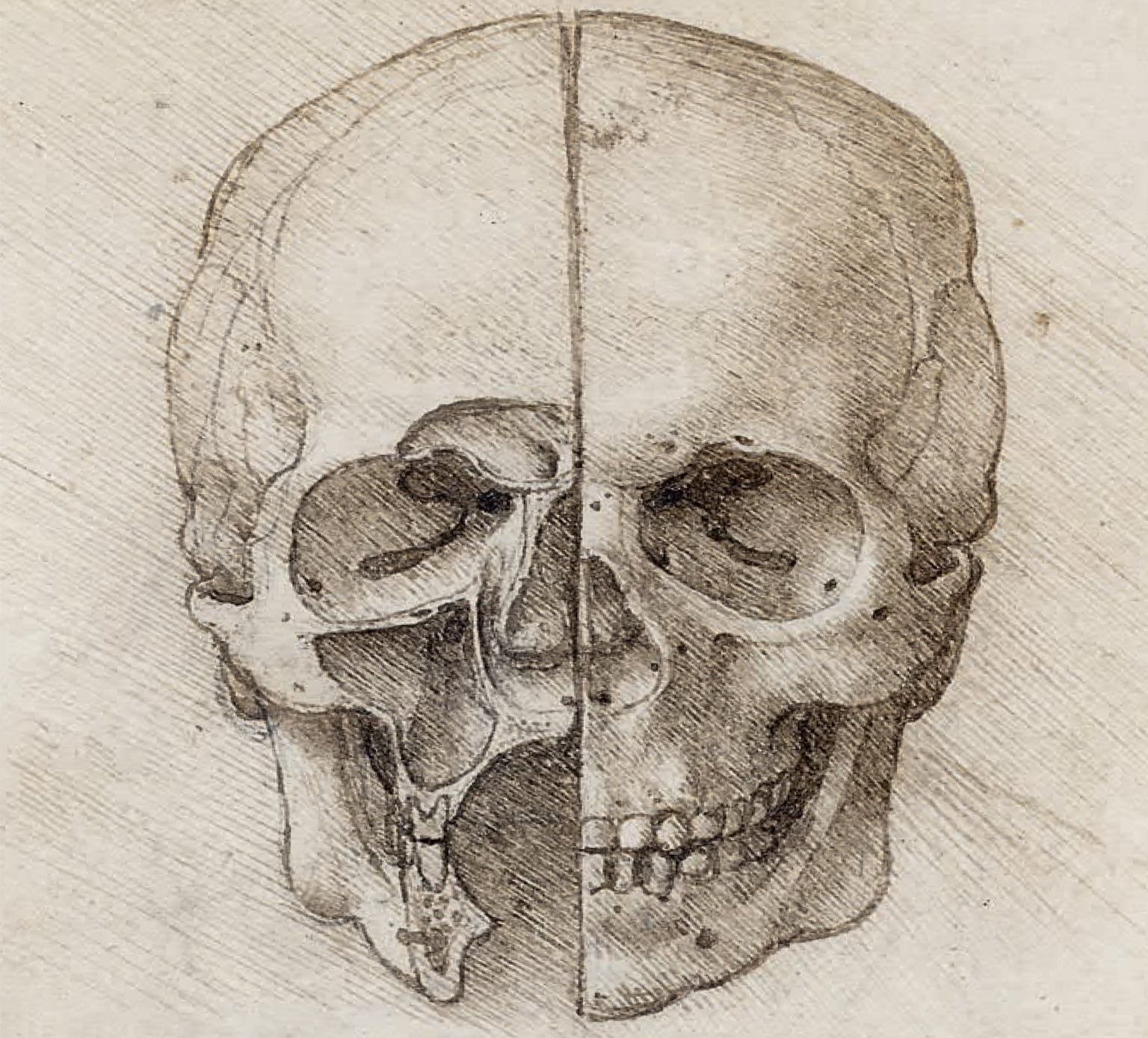
Martin Clayton and Ron Philo



Leonardo da Vinci
Anatomist

Martin Clayton is Head of Prints and Drawings, Royal Collection Trust. He is well known as an authority on the drawings of Leonardo da Vinci and his previous publications include the award-winning *Leonardo da Vinci: The Divine and the Grotesque* (2002) and (with Ron Philo) *Leonardo da Vinci: The Mechanics of Man* (2010). He is also the author of the multi-award-winning app *Leonardo da Vinci: Anatomy*.

Ron Philo is Adjunct Associate Professor in the Graduate School of Biomedical Sciences at the University of Texas Health Science Center, San Antonio.

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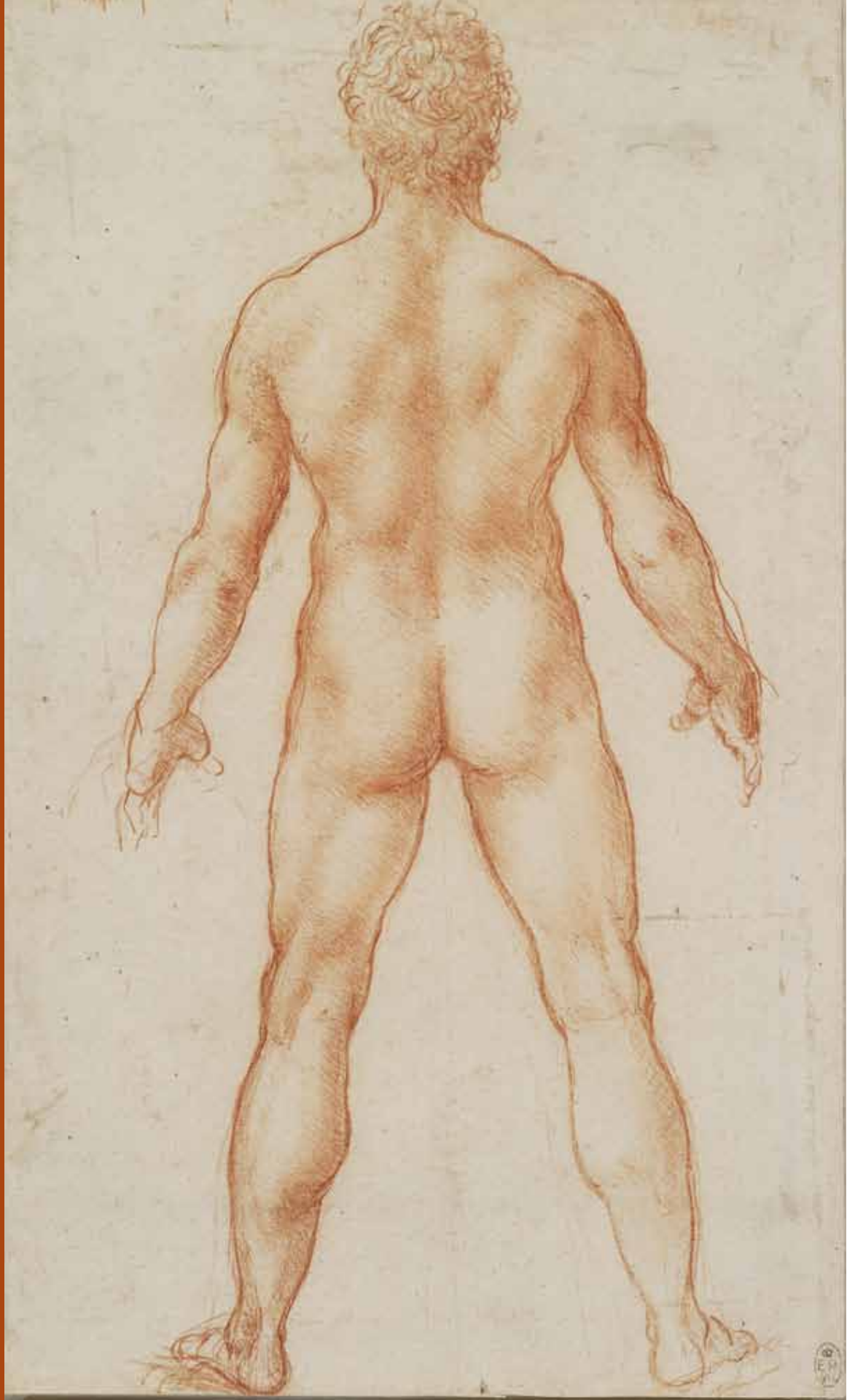

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Martin Clayton
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Front cover: *The skull sectioned,* 1489 (no.13b, detail)
Back cover: *The foetus in the womb, c.*1511 (no. 71, detail)
Frontispiece: *A male nude from behind, c.*1504–6 (no. 22)
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The Anatomical Studies of Leonardo da Vinci

At the time of his death, in France in 1519 at the age of 67, Leonardo da Vinci (fig. 1) was renowned as an artist across Western Europe. His scientific researches, however, were hardly known or understood beyond his immediate circle, and it was not until the nineteenth and twentieth centuries that the thousands of pages of his notebooks were properly examined. As a consequence, his reputation as the archetypal 'Renaissance Man' has been as a painter who also happened to practise in the sciences.

Leonardo himself would not have recognised this image. From the 1480s onwards his scientific studies were at least as important to him as his artistic activity. During the last decade of his life he seems not to have begun a single new painting, and in the years from 1508 to 1513, in particular, he worked essentially as a scientist who occasionally put his hand to paintings that he had begun in earlier years. And of all his scientific endeavours – optics, geology, botany, hydrodynamics – the field that engaged him most fully, and that in which he made the most far-reaching discoveries, was that of human anatomy.

In a few years of intense work he dissected around thirty human corpses, combining manual dexterity in dissection with an acute understanding of physical structure, great skill as a draughtsman and an eloquent literary style to produce some of the finest anatomical studies ever made. He fully intended to publish this work, and had he done so he would have transformed the study of human anatomy in Europe. But at his death in 1519 the drawings remained among his private papers, and they were essentially lost to the world for four centuries.

Fig. 1. Attributed to Francesco Melzi
*A portrait of Leonardo, c.*1515
Red chalk, 27.5 × 19.0 cm
RL 12726

Leonardo was born on 15 April 1452 near the central Italian town of Vinci, 15 miles west of Florence. He was the illegitimate son of a notary, Ser Piero da Vinci, and a peasant girl named Caterina, and was raised in his paternal grandfather's house. We have very little knowledge of the first 20 years of Leonardo's life. He learned to read and write, but his arithmetical skills were always shaky; and though as an adult he tried to learn some Latin, he never became comfortable with the language of most scientific writings.

Leonardo's illegitimacy prevented him from following his father into the legal profession. Instead he trained as a painter and by 1472 he had joined the painters' guild in Florence, the Company of St Luke, and was probably working in the large studio of the great sculptor and painter Andrea del Verrocchio. Leonardo executed some works entirely by himself, such as the *Annunciation* (Florence, Uffizi), while putting his hand to collaborative products of Verrocchio's workshop – most famously painting an angel's head in the *Baptism* (Uffizi). Leonardo thus began his career as a conventional (if remarkably talented) painter. There was a sense in fifteenth-century Florence that a painter or sculptor could gain the knowledge that would elevate his standing above that of a mere craftsman: in his *First Commentary,* written about 1450, the sculptor Lorenzo Ghiberti wrote: 'it is necessary . . . to have seen dissections, in order that the sculptor wishing to compose a *statua virile* knows how many bones are in the human body, and the muscles and all the tendons and their connections.' But there is little prefiguring, in Leonardo's output of this period, of the scientific researches that were to blossom in the second half of his life.

By 1483 Leonardo had moved to the northern Italian city of Milan. There his interests steadily widened to encompass architecture and engineering, and he began to assemble notes towards a treatise on painting. Leonardo was left-handed, and throughout his life he habitually wrote these notes in mirror-image, from right to left. This was not an attempt to keep his researches secret, as has been claimed, for his mirror-writing is relatively easy to read, with a little practice. Mirror-writing is a common developmental quirk in childhood, and what may have begun as an entertaining trick became a habit that Leonardo never had cause to discard.

Leonardo's treatise on painting was not to be a technical manual, in the manner of Cennino Cennini's *Libro dell'arte* of *c.*1400. Rather, he planned to lay out the scientific and theoretical basis of painting – its status as a liberal art *vis-à-vis* other forms of representation (such as sculpture or poetry), the nature of perspective, shadows and colour, and so on. Leonardo's treatise was thus to have much more in common with Leon Battista Alberti's *De pictura,* written in Florence in 1435, translated from Latin into Italian as *Della pittura* the following year, widely distributed in manuscript copies and surely known to the young Leonardo. But he planned to go much further than Alberti, encompassing every topic that would enable an artist to produce works that were 'true to nature'. He was concerned not just with appearances but with the underlying causes of these appearances, and the scope of his researches thus widened inexorably. While Leonardo always strove to determine general principles in his scientific studies, he also had an instinctive mistrust of abbreviation: in the fields of optics and hydrodynamics, for example, he attempted

to analyse every possible scenario, in both images and words. During the course of his career Leonardo was to compile many thousands of pages of studies – today we know some 5,000 pages, an intellectual legacy quite without parallel from the period, and even this is only a fraction of what Leonardo must have generated.

Several of Leonardo's fields of study soon broke free from the confines of the treatise on painting to become independent projected treatises in their own right. Among these was his work on the principal subject matter of the Renaissance artist, the human body, and as early as 1489 we have an outline of his projected treatise on anatomy:

> On the Order of the Book
>
> This work should begin with the conception of man, and describe the form of the womb, and how the child lives in it, and to what stage it resides in it, and in what way it is given life and food. Also its growth, and what interval there is between one stage of growth and another; and what it is that pushes it out of the body of the mother, and for what reason it sometimes comes out of the mother's belly before due time.
>
> Then you will describe which parts grow more than others after the infant is born, and give the measurements of a child of one year.
>
> Then describe the grown man and woman, and their measurements, and the nature of their constitution, colour and physiognomy.
>
> Then describe how they are composed of veins, nerves, muscles and bones. This you will do at the end of the book.
>
> Then in four drawings you will depict the four universal conditions of man, that is: joy, with different ways of laughing, and draw the cause of the laughter; weeping in different ways, with their cause; fighting, with the different movements of killing; flight, fear, ferocity, boldness, murder, and everything belonging to such events.
>
> Then draw labour, with pulling, pushing, carrying, stopping, supporting and similar things.
>
> Attitudes
>
> Then describe attitudes and movement.
>
> Effects
>
> Then perspective through the function of the eye; on hearing, I shall speak of music; and describe the other senses.
>
> Senses
>
> Then describe the nature of the five senses.[1]

Leonardo thus wished to examine every aspect of the human body – not just structural anatomy and physiology, but also conception and growth, the expression of the emotions, the nature of the senses and so on. Unsurprisingly, he was unable to get very far with most of these subjects: not only were they intrinsically problematic, but Leonardo had only a little access to human material at this stage of his career. In 1489 he managed to obtain a human skull (or skulls) for sectioning, and his drawings of the skull on the pages of the notebook now known as the

Anatomical Manuscript B – nos 11a–13b – are astonishingly accurate. A drawing and note on no. 5 also seem to demonstrate that during the late 1480s he was able to dissect a human leg (or at least observe a leg being dissected) – flaying the skin to show the muscles, removing the sartorius muscle to reveal the nerves and veins in the adductor canal, and cutting the leg through in cross-section to display the spatial relationship of the muscles (no. 6).

Where Leonardo might have been able to carry out this work is unclear. Milan had no university and thus no medical school at this time – the only university in the Duchy of Lombardy was in Pavia, 20 miles to the south (and it was there that Leonardo was probably to work with Marcantonio della Torre twenty years later – see below). In any case, the dissections that did take place in the universities were expository rather than investigative (fig. 2): a prosector removed the organs for inspection while the professor read from the canonical books – primarily Mondino de' Luzzi's *Anathomia corporis humani,* written around 1316, and the *Canon of Medicine* of the eleventh-century Persian polymath Avicenna (Ibn Sīnā), one of the principal sources for European Renaissance knowledge of the writings of the ancients. We do not know what access Leonardo had to such works at that time, but Mondino's *Anathomia* was still the most widely used treatise on anatomy in Leonardo's day, and around 1489 he had noted (on RL 19019r) 'Galen, *De utilita*',

Fig. 2. Anatomy lecture, from Joannes de Ketham, *Fasciculus medicinae,* Venice 1495
Woodcut
Wellcome Library, London

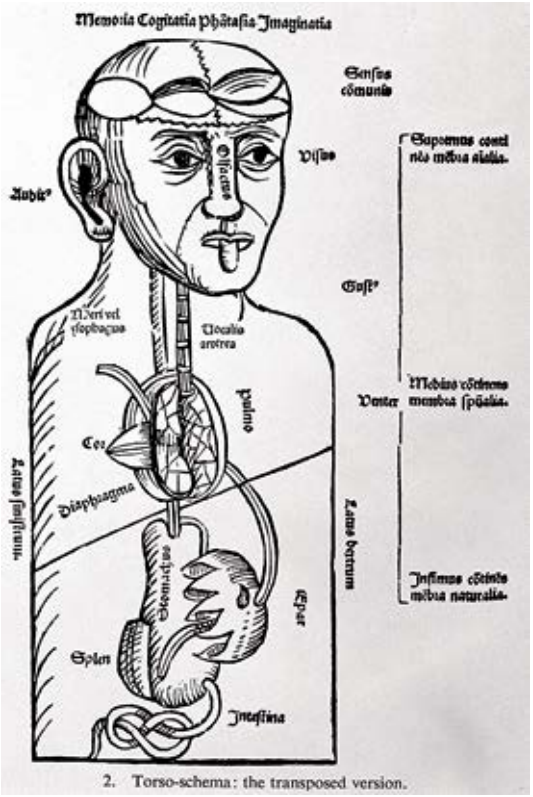


Fig. 3. Situs figure, from Johann Peyligk, *Philosophia Naturalis Compendium*, Leipzig 1499
Woodcut
Wellcome Library, London

Fig. 4. The head of a man showing the cerebral ventricles, from Albertus Magnus, *Philosophia naturalis*, Basle 1506
Woodcut
Wellcome Library, London

probably a reference to Galen's *De usu partium corporis humani,* the most important anatomical treatise to survive from antiquity. Those works were textual: anatomical illustrations even in Leonardo's day were little more than schematic diagrams (figs 3, 4) and though he occasionally adopted elements of those schemata, they were of almost no use to his researches.

More practical anatomical work may have been possible in the hospitals of Milan. The Ospedale Maggiore, one of the largest hospitals in Europe, was under the patronage of the Sforza rulers of Milan (and by the late 1480s Leonardo was court artist to Ludovico Sforza), and there were many other charitable hospitals in the city, run by religious houses and lay confraternities, where the right contacts could have allowed Leonardo access to an unclaimed corpse for dissection. This would not have been a unique case of a well-connected artist carrying out human dissection: a few years later the young Michelangelo was reportedly allowed to dissect corpses in the hospital of Santo Spirito in Florence, a privilege no doubt facilitated by his Medici patronage.

Though Leonardo's use of human material was limited, he did have unfettered access to animals for dissection. Then as now, animals were used as surrogates for

investigations of the human body: it was commonly supposed that the anatomy of all mammals was basically the same, the only difference being in the proportions and stance. Dissections of monkeys and dogs seem to lie behind Leonardo's drawings of the arm (no. 3), which concentrate on the nerve pathways. On the same sheet he drew the viscera of (probably) a pig and recorded an experiment in which he pierced the spinal cord of a frog that had been decapitated and yet retained a semblance of life. His drawings of dissections of the foot of a bear – the only large quadruped that walks on the soles of its feet, like man – are among the most impressive of Leonardo's early anatomical studies (nos 7–10). He was struck by the interpenetration of the flexor tendons of its toes, and twenty years later, when he found the same structure in the hands and feet of man (nos 65b–67), he recalled his studies of the bear.

The animal that Leonardo worked on most fully was the horse. In part this was prompted by a commission (received some time in the 1480s) to model and cast a huge equestrian monument to Ludovico Sforza's father, Francesco. Writing in the mid-sixteenth century, the biographer Giorgio Vasari stated that Leonardo compiled a treatise on the anatomy of the horse, lost when Milan was invaded by French forces in 1499. One drawing of the viscera of a large quadruped, probably a horse (fig. 5, on the reverse of no. 2), goes some way to supporting Vasari's statement, but we do not have enough material to know how extensive Leonardo's

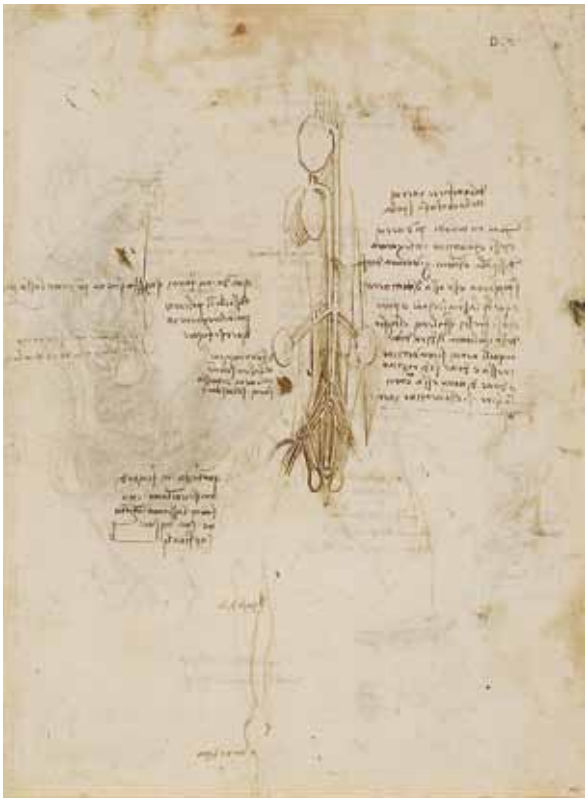


Fig. 5. Leonardo da Vinci
The viscera of a horse, *c.*1490–92
Pen and ink, 27.6 × 20.4 cm
RL 19097r

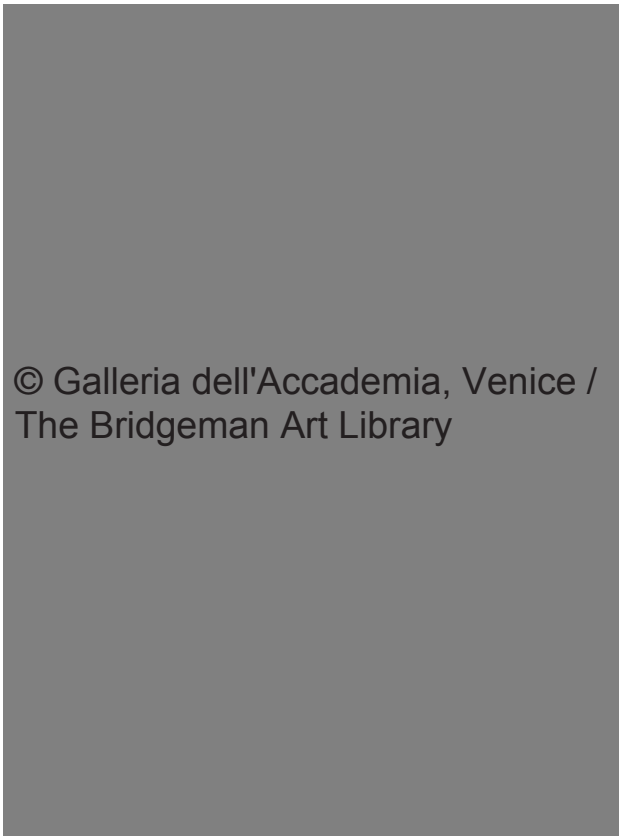


Fig. 6. Leonardo da Vinci
The proportions of the human body according to Vitruvius, *c.*1490
Pen and ink with touches of wash, 34.4 × 24.5 cm
Gallerie dell'Accademia, Venice

work was. More numerous are his surviving drawings of the external form of the horse (nos 18–19), made in the stables of the Milanese army. Leonardo concentrated on the musculature of the horse and its dimensions, often recording the breed, as different breeds of horse have different proportions.

When studying the human form, however, Leonardo was less willing to make such concessions to individual variation. Man was in principle an 'ideal body', divinely created and divinely proportioned. The treatise on architecture written by Vitruvius in the first century BC – the only treatise on the arts surviving from Classical times, well known in the fifteenth century and listed by Leonardo among a handful of his books around 1508 – discussed human proportion as analogous to architectural proportion. Just like a well-designed and harmonious building, the body should be divisible into equal units and all its measurements should be expressible either in terms of that unit or as simple fractions of the whole. Vitruvius stated that the body when standing with arms outstretched fits into a square, and, with all limbs splayed, into a circle centred on the navel: this fit of the human body with the perfect forms of the circle and the square was an inevitable consequence of the perfection and harmony of the universe and was the subject of Leonardo's most famous drawing (fig. 6). That drawing is highly finished, yet the inscriptions are in Leonardo's usual mirror-writing, and so it was presumably executed for his own eyes only, Leonardo presenting the material to himself as if to test its validity. The drawings on no. 15

embody several of the same precepts, and on no. 16 Leonardo attempted to go much further than Vitruvius, analysing seemingly insignificant dimensions of the body in proportional terms.

Many of Leonardo's early anatomical observations, therefore, were based on a blend of traditional (and often ancient) beliefs, animal dissection, proportional analysis and mere speculation. A striking example is his drawing of a hemisected man and woman in the act of coition (no. 2), of around 1490. Leonardo had not observed any of these structures: this is a diagrammatic rendering of traditional beliefs – a second channel in the penis carrying 'animal spirit' (loosely 'soul') from the spinal cord; a bifurcated spinal cord in the woman to transmit her 'animal spirit' to the uterus; a vessel from the testes, the source of ardour, to the heart, where the emotions are felt; a vessel from the uterus to the breasts, so that the menses retained on conception could be converted into milk; and so on.

As Leonardo's skill as an anatomical draughtsman increased, so he became ever more adept at illustrating structures that he had only inferred and not seen. Another example is no. 14, which studies the layers of the scalp and cerebral ventricles. Leonardo had clearly been able to investigate the head of some animal (and, as mentioned, he had in 1489 sectioned a human skull), and the cross-section of the cranium, the layers of the scalp, the membranes of the brain and their continuity with the optic nerve are therefore more or less accurate. But within the brain Leonardo placed the three globe-like ventricles that were traditionally supposed to house the mental faculties (cf. fig. 4) – the *senso comune* (where the sensory nerves converged), fantasy, reasoning, memory and so on. And in a detail at the bottom of that sheet Leonardo shows the head sectioned horizontally at the level of the eyes, with the crown of the head flipped back to reveal these ventricles: he has drawn what he imagined he would see, not what he actually did see.

But in the early 1490s Leonardo's anatomical work petered out. The reasons for this are not clear and there may have been external factors of which we have no knowledge. Certainly he was busy with the Sforza equestrian monument, and when that project was suspended in 1494 he threw himself into the mural of the *Last Supper,* also a Sforza commission and the greatest of Leonardo's artistic projects to reach completion (see no. 20). In the *Last Supper* Leonardo achieved instinctively what he had failed to formulate through scientific study – a means of relating the external forms of the body to an individual's state of mind – and it may be that frustration at his lack of progress with the topics he had outlined in 1489, such as the phenomena of the senses, led to his gradual abandonment of these studies. It was to be more than ten years before Leonardo resumed his anatomical work.

In 1499 Ludovico Sforza was overthrown by French forces. Having lost his patron, Leonardo soon afterwards left Milan and returned to Florence. Now aged 48, he quickly re-established himself as one of the city's leading artists – though in truth he was painting little and it is hard to get a clear picture of his activities at that time. In 1502 Leonardo spent a few months travelling through central Italy as a military engineer and map-maker, but in the spring of 1503 he received a

Fig. 7. Italian sixteenth-century artist, after Leonardo, retouched by Peter Paul Rubens
The Battle of Anghiari, *c.*1612–15
Black chalk, pen and ink, wash, white and grey bodycolour, 42.8 × 57.7 cm
Louvre, Paris

commission to paint a huge mural of the *Battle of Anghiari* in the council chamber of the Florentine Republic. This was the most prestigious commission of Leonardo's career and also the most dynamic composition that he ever worked on: the only portion that he executed, known as the *Fight for the Standard* (fig. 7), was a wild struggle of man and horse. The size of the painting, some 20 m (65 ft) wide, required Leonardo to prepare the composition meticulously. He devoted much effort to background research before beginning work on the mural, making many studies of horses and of male nudes, in action and at rest (nos 21–4).

Leonardo's investigations were now conditioned by their practical purpose, towards a painting rather than a theoretical treatise. There was no attempt to derive or impose a system of proportions, and initially he concentrated on the topics that would be of immediate use – the superficial musculature of man, the horse galloping, rearing and bucking, the expressions of fury in man and horse (fig. 8). But Leonardo's scientific studies throughout his life were characterised by an urge to go ever deeper, to discover fundamental causes, and he was soon drawn back to the study of human anatomy, independently of the specific requirements of the *Battle of Anghiari*.

While Leonardo's early interest in the phenomena of life remained, he was now primarily concerned with the physical structure of the body. And he had evidently

Fig. 8. Leonardo da Vinci
Expressions of fury in horses, lions and a man, *c.*1503–4
Pen and ink with touches of wash, 19.6 × 30.8 cm
RL 12326

been trying to get to grips with the literature on the subject. A list, probably not exhaustive, of 116 books (both printed and in manuscript) owned by Leonardo around this date includes Johannes de Ketham's medical compendium, *Fasciculus Medicinae* (the Latin edition of 1491, not the Italian translation of 1493), which included Mondino's *Anathomia;* Guy de Chauliac's fourteenth-century manual on surgery, *Cyrurgia* (first published in Venice in 1498); Bartolomeo Montagnana's *Tractatus de urinarum judiciis* (Padua 1487); another *libro di notomia,* otherwise unidentified; and, not forgetting Leonardo's earlier studies of horses, a *libro di medicina di cavalli*.[2] And these were just the books that Leonardo owned: though he rarely quotes his sources directly, the content of his later anatomical notes demonstrates that he was becoming increasingly familiar with the works of his predecessors. Around five years later (on no. 49) he made a note to 'have Avicenna translated' and cited the names of two contemporary anatomists, Gabriele Zerbi and Alessandro Benedetti, presumably referring to their *Liber anatomie corporis humani* (Venice 1502) and *Historia corporis humani sive Anatomice* (Venice 1495, 1502) respectively; a note on the cover of Leonardo's Manuscript F in Paris, compiled around 1508, also lists the 'Anatomy of Alessandro Benedetti' among a handful of his books.

Work on the *Battle of Anghiari* proceeded with interruptions until September 1506, when Leonardo was called back to Milan, and the painting remained unfinished. Over the next couple of years he travelled repeatedly between Milan and Florence, and reconstructing the development of his anatomical studies at this time is difficult due to the lack of datable works. Had Leonardo died at the age of 55, his anatomical work would be regarded as a passing interest, almost insignificant in the context of his many other scientific pursuits. But the next five years were to see a sustained campaign of dissection and exposition that would mark him out as one of the greatest anatomists ever to have lived.

Our first sign of this activity, if not its spark, is a description of a post-mortem conducted by Leonardo, probably in the winter of 1507–8 (no. 25):

> This old man, a few hours before his death, told me that he was over a hundred years old, and that he felt nothing wrong with his body other than weakness. And thus, while sitting on a bed in the hospital of Santa Maria Nuova in Florence, without any movement or other sign of any mishap, he passed from this life. And I dissected him to see the cause of so sweet a death.

This remarkable page goes on to provide the first clear description of coronary vascular occlusion, arteriosclerosis and cirrhosis of the liver in the history of medicine. It indicates that by 1508 Leonardo was already sufficiently experienced in human dissection to identify without hesitation the pathology of this particular case. A casual reference on the same page to 'the other dissection … of a child of two years' suggests that human dissection was now almost routine for Leonardo. Executed criminals were the usual subjects of public dissections, but the centenarian and probably the two-year-old died in the charitable hospitals of Florence, presumably with no relatives to claim their bodies for burial. It is plain that Leonardo had now sufficient reputation as an anatomist to be permitted by the authorities to conduct such dissections as a matter of course.

The description of the centenarian's death was added to the notebook in which Leonardo had made his sequence of skull studies almost twenty years before (nos 11a–13b). These notes and the resulting drawings were not made during the dissection itself – they probably date from after Leonardo's definitive return to Milan in the spring of 1508 – and indeed we probably do not have a single sheet that was compiled as Leonardo actually carried out a dissection of soft tissue. Dissection of embalmed, fixed material, as performed today, is quite different from dissection of the unembalmed, as practised by Leonardo. Without fixatives or preservatives this is a messy process, which would have been compounded by the rudimentary nature (compared with the modern period) of his dissection instruments – on no. 49 he listed among other possession a bistoury (a fine surgical knife), forceps, a fine-tooth bone saw and a scalpel, and on the other side of the same sheet he sketched a handful of his tools (fig. 9). There are a few glimpses in Leonardo's notes of the gruelling nature of the activity, such as a reminder on no. 57a to 'break the jaw from the side so that you can see the uvula in its position'.

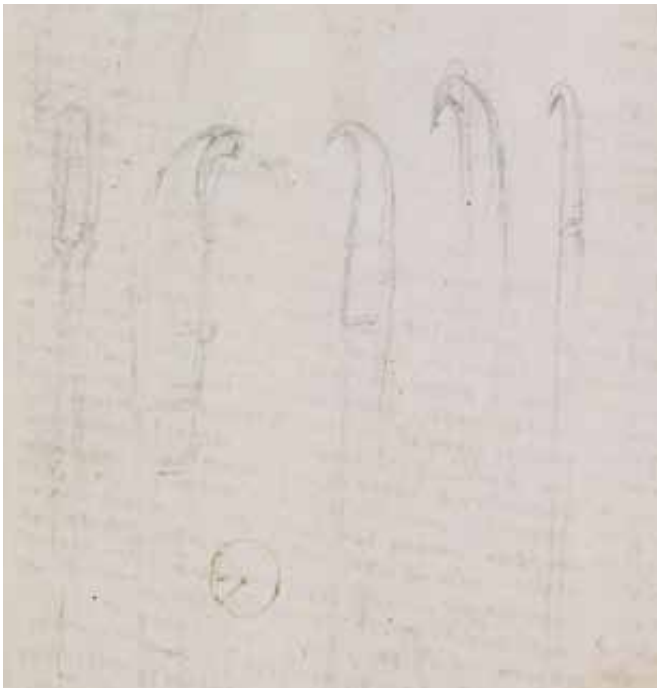


Fig. 9. Leonardo da Vinci
Dissection tools,
*c.*1508–10
Black chalk
RL 19070r (detail)

The paper on which Leonardo made his dissection notes would unavoidably have become soiled with body fluids (drawings of prepared bones could however have been made directly, under clean conditions); either he discarded those notes and sketches once he had processed them, or his successors did not deem them worthy of preservation.

We cannot know what medium Leonardo would have used for his dissection notes. The drawings that do survive were mostly constructed with a detailed underdrawing in black chalk (or sometimes possibly charcoal) that was erased once the outlines had been fixed with pen and ink; in a couple of cases the drawings did not proceed beyond the underdrawing, which was consequently not erased. The drawings were usually shaded using a variety of techniques: pen hatching curving around the form of a bone and muscle; lighter pen lines following the direction of the muscle fibres; delicately applied wash to capture the sheen of the fascia or the curvature of the spine. These 'fair copies' are carefully considered, partly diagrammatic representations of the body's structures, synthesised from the dissection notes. Indeed, Leonardo stated on no. 49, a sheet of *c.*1508–10, that he combined the findings of several different dissections to arrive at these drawings:

> You who say it is better to see a dissection than to see these drawings would be right, if it were possible to see all those things which in such drawings are demonstrated in a single figure. In [dissection], with all your ability, you will not see nor obtain knowledge of more than a few vessels; to obtain a true and full knowledge I have dissected more than ten human bodies, destroying all other organs, and taking away in its minutest particles all the

> flesh which was to be found around the vessels without causing them to bleed, except for the imperceptible bleeding of the capillary vessels. And one single body was not sufficient for enough time, so that it was necessary to proceed little by little with as many bodies as would render a complete knowledge. This I repeated twice in order to observe the differences.

This last sentence demonstrates, incidentally, that Leonardo was aware of variations in anatomy between individuals. Some of his drawings incorporate oddities that must have been derived from a single dissection, such as the enlarged spleen and umbilical vein of the cirrhotic 'centenarian', but in general he attempted to iron out such variations.

The Anatomical Manuscript B was wide-ranging and, in consequence, relatively unfocused. Within a single notebook he dealt with aspects of the bones and muscles, the nervous system, the cardiovascular system and many of the internal organs; some of these studies, such as those of the bladder (no. 33a), were close to definitive, but many of the others seem somewhat arbitrary both in subject and in depth of analysis. As if wishing to draw a line under these studies, Leonardo compiled the celebrated sheet that combines many of his discoveries and observations in a single complex image, depicting the cardiovascular system and principal organs of a woman (no. 47a). This was pricked for transfer, so that he could produce 'clean copies' and elaborate on areas that remained unresolved, but the goal of a complete, coherent treatise on anatomy must have seemed as far away as ever. Around 1510, however, we see a marked shift in the basis of Leonardo's anatomical researches.

During the winter of 1510–11 he compiled a series of 18 sheets, mostly double-sided, and collectively known as the Anatomical Manuscript A (including nos 52a–67). On those pages Leonardo crammed more than 240 individual drawings and notes running to over 13,000 words. The bones and muscles were now the focus of Leonardo's investigations and he illustrated in detail every bone in the body except those of the skull, and many of the major muscle groups. The nerves and blood vessels are occasionally included, but it was the mechanics of the body, rather than biochemical or 'spiritual' considerations, that primarily interested Leonardo. On no. 63b he stated: 'Provide that the book on the elements of mechanics [*delli elementi machinali*], with its practice, comes before the demonstration of the movement and force of man and other animals; and by means of these you will be able to prove all your propositions.' And it does appear that he had indeed composed, or at least laid out, such a treatise, for on no. 65a he refers to 'the fifth [chapter] of the fourth [book] on the elements of mechanics'.

The structural, mechanical perfection of the body was therefore the guiding principle for Leonardo in this campaign of investigation. Though God is never directly invoked, on no. 56 he lauds 'the first composer of such a machine' ('*il p° conponitore di tal machina*') and on no. 53b he attributes a feature to 'the master' ('*il maesstro*'). More frequently however 'nature' ('*natura*') is given as the author of a particular feature – for example 'here you see the wisdom of nature in providing

two causes of movement in each limb' (no. 65a; *natura* is cited on seven other occasions in the manuscript). But if Leonardo's drawings convey 'the marvellous works of nature' ('*l'opere mirabile della natura*'), he stated that 'if this his composition appears to you a marvellous piece of work, you should regard this as nothing compared to the soul that dwells within that architecture; and truly whatever that may be, it is a thing divine' (no. 53b). Perhaps one of the keys to Leonardo's achievement in Manuscript A was his willingness to put to one side spiritual matters, and indeed any concern with the processes of life, allowing him to analyse the muscles and bones in purely physical terms.

To some extent this methodological shift was a consequence of Leonardo's increasing experience, stemming from his greater access to human material. The number of corpses he dissected grows from 'more than ten' to 'more than thirty' towards the end of his life, and the abundance of drawings based on human dissection confirms that Leonardo now had no shortage of subjects. In his earlier studies, an enquiry that proceeded from effect to cause allowed him to map a way through the complexity of the body, seeking the structures that would give rise to certain physiological functions. Now much more familiar with the body, he was able to comprehend how the details fitted into the whole, and in general to work outwards from cause to effect, trying to understand the purpose of the structures that his dissections exposed. Consequently almost every drawing and statement in Leonardo's notes at this time is based on direct investigation. The efficacy of his dissections increased exponentially: as he became more familiar with the body, so he was better able to formulate his questions, dissect the relevant part accurately and efficiently, understand what he uncovered and synthesise his discoveries in drawings of a clarity rarely matched to the present day.

But Leonardo may not have arrived at this methodological position alone. The physician and historian Paolo Giovio – who would have known Leonardo when both were in Rome between 1513 and 1516 – wrote in a short biography of the artist, composed around 1527:

> In order that he might be able to paint the various joints and muscles as they bend and stretch according to the laws of nature, he dissected the corpses of criminals in the medical schools, indifferent to this inhuman and disgusting work. He then tabulated all the different parts down to the smallest veins and the composition of the bones with extreme accuracy, in order that this work on which he had spent so many years should be published from copper engravings for the benefit of art.[3]

This information was expanded in Vasari's biography of Leonardo:

> Leonardo then applied himself with great diligence to human anatomy, helped in this by (and in turn helping) that excellent philosopher Marcantonio della Torre, who was then lecturing at Pavia and who wrote on this subject, and who was one of the first (as I have heard) to begin to illustrate matters of medicine by the teachings of Galen and to throw true light on anatomy, which up to then had been obscured by the great shadows of ignorance. In this he was wonderfully served by the intelligence, work and hand of Leonardo, who

> composed a book drawn in red chalk and finished in pen, of bodies he had dissected himself. He depicted with great diligence all the bones and to what they are joined, and then in order all the nerves, covering them with the muscles – the first that are attached to the skeleton, the second that hold it firm and the third that move it. In places he wrote his observations in crude letters, done in reverse with the left hand, which cannot be read by anyone who does not know the trick of reading them in a mirror. These papers on human anatomy are in large part in the hands of Francesco Melzi, a Milanese gentleman who in Leonardo's day was a handsome boy and much loved by him.[4]

There are no more than a couple of passing references to Leonardo's anatomical work in the first edition of Vasari's *Vite* (1550) and it is likely that Vasari obtained the detailed information quoted above directly from Melzi, Leonardo's heir, after the publication of the first edition. While the mention of drawings in red chalk is puzzling – very few of Leonardo's anatomical drawings are in that medium – the statement that Leonardo collaborated with Marcantonio della Torre at the university of Pavia should probably be taken at face value. There are only a few scraps of evidence in Leonardo's notes that may support this: no. 71 carries both a reminder to give a 'book on water to Messer Marcantonio' and – on the reverse – a passage on the membranes surrounding the foetus, in a hand otherwise unknown among Leonardo's papers and which may well be that of Della Torre. But the strongest support for Vasari's statement is the radically different nature of Manuscript A from anything that Leonardo had produced before.

As Vasari stated, Marcantonio della Torre was a leading figure in the revival of the teachings of Galen; while the majority of Galen's many books (which had survived from Antiquity in Arabic translations, thence translated into Latin in the Renaissance) were not printed until the 1520s, Della Torre could have had access to a number of his works in manuscript. The abundance and range of Galen's writings make it hazardous to try to identify specific points that Leonardo may have gleaned from Galen through Della Torre (and Leonardo very rarely quoted any source directly), but the compelling message of works such as *De usu partium corporis humani* was that a command of detail had to precede any attempt to comprehend a system.

It is thus entirely plausible that Leonardo was working alongside Marcantonio della Torre in the medical school of the university of Pavia in the winter of 1510–11. Such a collaboration would explain both Leonardo's ready access to human material and the methodological stance inherent in Manuscript A. It would also explain Leonardo's new sense of purpose, for this is the only period in his anatomical career during which he was able to attain a balance between detail and coverage – it is as if the professional anatomist standing at his shoulder was able to save Leonardo from his habit of going ever further into the details of a physical scenario.

On no. 66 Leonardo commented, 'this winter of 1510 I believe I shall finish all this anatomy', by which he presumably meant the compilation of material towards his proposed treatise. This would begin with the mature male as the 'perfect' body,

then treat the variants – the old man, the infant and the reproductive organs of the woman (the rest of a woman's body being treated as essentially the same as a man's): 'Begin your book on anatomy with a perfect man, and then draw him old and less muscular, then stripping him in stages down to the bone. And then draw the infant, with a diagram of the womb' (no. 55). The intended or imaginary reader of the treatise was in the forefront of Leonardo's mind throughout, and in every case the aim was to make the drawing as clear as possible. Anatomical illustration is not a simple matter of depicting what is found upon conducting a dissection. Other than the bones, which can be shown undiagrammatically, any representation of a part of the body requires a degree of stylisation to be legible. There is no space in the musculoskeletal system: to convey the structure of a system clearly, some space must be introduced, the muscles must be differentiated and the nerves and vessels separated to some degree. Thus Leonardo adopted and developed a wide range of illustrative techniques to make his drawings as clear as possible.

From architecture Leonardo took the principles of elevation, plan and section, repeatedly insisting that structures should be shown from multiple directions to convey complete spatial information (e.g. nos 62, 64b; on nos 58b–59a he depicts the muscles of the arm and shoulder in eight views through 180 degrees). From engineering he took the device of the 'exploded view', depicting the elements pulled apart to show their articular surfaces and how they connect (nos 53b, 62). He perceived some structures as composed of distinct layers: the structures of the palm of the hand are built up sequentially in six drawings on nos 63b–64a; the shoulder is progressively stripped down on nos 52a–54. He tried to analyse 'complex movements' as composed of 'simple' elements, combining the engineer's or architect's orthogonal analysis of space and form with the physiologist's attempt to isolate the movements caused by each individual muscle. And having analysed the full complexity of a structure in a sequence of drawings, Leonardo then sometimes tried to convey the whole of this structure in a single diagram, reducing the muscles to threads such that the interrelationship of every muscle and bone could be seen (nos 52b, 53b).

With some rearrangement and amplification, and through the medium of a sensitive reproductive engraver, these drawings would have served magnificently as illustrations to the published treatise on anatomy that Leonardo always intended to produce. But the text is a different matter. The larger drawings dictate the layout of the page, and smaller details and neat blocks of text are then fitted in around them. On each page a range of inks and pen-nibs can be seen in the notes as Leonardo moved from sheet to sheet, adding explanations and observations over a period of time as his understanding of the anatomy evolved. Relatively few of the notes comprise definitive statements on a particular structure of the body; the majority were Leonardo's attempt to keep track of a flood of partially resolved information – his comments to himself on how to depict a certain structure or on a feature that required further investigation.

The lucidity of the drawings may convey the impression that these are final expressions of Leonardo's understanding, but this is belied by the notes, which

emphasise the fact that Manuscript A was a work in progress. And the hope, expressed on no. 66, that Leonardo would conclude his anatomical work in the winter of 1510–11 was to be confounded. Marcantonio della Torre died of the plague in 1511, aged around thirty, and whether or not this loss affected Leonardo's methodology directly, he never again attained the balance between coverage and detail that is found in Manuscript A. Towards the end of the same year the French occupiers of Milan, Leonardo's employers, were partly ousted by Swiss forces. The city remained in turmoil for many months and for much of the period 1512–13 Leonardo stayed at the family villa of his young assistant Francesco Melzi, at Vaprio d'Adda, 15 miles east of Milan.

At Vaprio, Leonardo had no access to human material for his anatomical work and he had to use animals as his subjects, just as he had done at the start of his anatomical career 25 years before. His dissections of the ribcage and diaphragm of dogs and oxen (nos 72–4) and of a bird's wing (nos 75–6) were meticulous and insightful, but there is no sign that he had the completion of his treatise in mind: a period of retreat that could have allowed him the time to put his papers in order was instead taken up with a miscellany of unrelated pursuits. Among these was his investigation of the (bovine) heart, in some respects the most brilliant of Leonardo's many scientific investigations.

In no. 29a, a few years earlier, Leonardo had satisfied himself that the heart (and not the liver) was the centre of the vascular system. He now set about analysing the physical structure of the heart, and in a long series of densely annotated sheets (including nos 78–87) he drew and described with great accuracy the ventricles and atria, the structure of the valves, and the papillary muscles and chordae tendineae. He made a glass model of the aortic valve (no. 85) so that he could reproduce and observe the fluid flow in the sinus (widening) at the root of the aorta, correctly deducing that vortices of blood in the sinus are in part responsible for the closing of the valve when the heart relaxes and expands in diastole. Leonardo understood that the right side of the heart takes in blood from the venous system, that the left side pumps blood into the arterial system and that each of the valves attains perfect closure. But he never followed this through by observing that the right side of the heart expels blood into the pulmonary artery, that the left side takes in blood from the pulmonary veins (see fig. 21), and deducing that the only way to avoid rapidly emptying the venous system and overfilling the arterial system is for blood to pass from the arteries into the veins at their very ends. (Indeed, the emptying of the venous system by the heart, and the amount of blood that the liver would have to produce to compensate for this, was one of William Harvey's principal arguments against the traditional system when he first posited the circulation of the blood in his treatise *De motu cordis* of 1628.)

Instead Leonardo tried to make his discoveries fit with the accepted physiology of the heart, which held that it was the source of heat and 'vital spirit' (a sort of 'life force') in the body. Leonardo argued that the heat was generated by the churning of blood in and out of the ventricles and atria; this 'subtilised' the blood, allowing a portion of it to pass through the interventricular septum, the dividing

wall of the heart between the right and left ventricles, during diastole, thus acquiring the 'vital spirit' that was distributed throughout the body by the arterial system. The lungs existed to cool the heart, preventing it from overheating, otherwise 'the heart is suffocated; once I saw a man who burst in fleeing from his enemies: he poured out sweat mixed with blood through all the pores of his skin' (as Leonardo noted on no. 82r).

Leonardo had no conception of circulation of the blood, either systemic or pulmonary, and it would be wrong to claim that he was on the threshold of discovering the circulation system. His work on the heart is a disconcerting mix of physiologies, in part ancient and in other aspects on a par with modern understanding. But his work reflects, in general, how science proceeds, through incremental improvements in description and theory rather than solely by grand discoveries and accompanying paradigm shifts. Leonardo's 'failure' to discover the circulation system was a failure only if that is seen as the only criterion by which study of the cardiovascular system can be judged. His astonishingly accurate account of the cardiac valves was far more detailed than the work of William Harvey, for example. And Harvey's theory, it should be noted, replaced the invisible pores of the interventricular septum with a different set of invisible pores, the capillaries between the arterial and venous systems, whose existence was not verified until Marcello Malpighi was able to use a sufficiently powerful microscope several decades later.

There is a pervading sense in Leonardo's notes on the heart, running to many thousands of words, that he could go no further. Faced with an impasse between his physical understanding and the accepted physiology of the heart, he was doomed to keep on describing the motion of the blood through the valves in ever more detail (see nos 86–7). And there, apparently, his anatomical work came to an end.

In September 1513 Leonardo and his assistants left Milan for Rome, where they lodged in the Vatican palace under the patronage of Giuliano de' Medici, brother of Pope Leo X. Leonardo may have attempted to resume his anatomical researches at the hospital of Santo Spirito, close to the Vatican, but in a draft letter he complains of having been 'hindered in anatomy, denounced before the Pope and likewise at the hospital' by a troublesome German mirror-maker with whom he was forced to work. Leonardo's three years based in Rome were generally unproductive on all fronts and after the death of his patron he probably welcomed an invitation to move to the French court. By the end of 1516 Leonardo had settled at Amboise, one of the chain of royal residences in the Loire valley, where he held a privileged position as painter, engineer and architect to King Francis I. Leonardo worked on a few artistic projects, advised on technical matters, provided designs for entertainments and generally served as an ornament to the court.

There is no evidence that Leonardo pursued his anatomical researches during these last years in France, but he had with him the hundreds of sheets of drawings and notes on the subject that he had compiled over the previous three decades. A diary entry by Antonio de Beatis records a visit to Leonardo's studio by Cardinal

Luigi d'Aragona on 10 October 1517. After describing some paintings that Leonardo showed the party, Beatis (the cardinal's secretary) noted that:

> This gentleman has written in great detail on anatomy, with illustrations of the members, muscles, nerves, veins, joints, intestines, and of whatever else can be discussed in the bodies of men and women, in a manner that has never yet been done by anyone else. All this we have seen with our own eyes; and he said that he had dissected more than thirty bodies, both male and female of all ages. He has also written on the nature of water, on diverse machines and on other things, which he has set down in countless volumes, all in the vulgar tongue, which if they are published will be profitable and very delightful.[5]

But Leonardo's researches were not to be published for several centuries. He died on 2 May 1519, a couple of weeks past his 67th birthday, at the chateau of Cloux, having bequeathed his notebooks and drawings to the young Francesco Melzi. Though periodically Leonardo had stated his intention to put his notes into order, Melzi returned to Italy with a mass of undigested material, dense, repetitive and disorganised.

Melzi settled at his family home at Vaprio and over the next 50 years he attempted to make sense of this daunting legacy. His ownership of Leonardo's anatomical studies was no secret, as Vasari's account quoted above demonstrates, and a few early copies of the anatomical drawings show that artists did have occasional access to them. Melzi copied out passages from the theoretical writings in Leonardo's notebooks in an effort to construct the treatise on painting that Leonardo himself had never completed; abridged copies of Melzi's resulting manuscript circulated in Italy in the sixteenth and seventeenth centuries and a version was first published in 1651. But there is almost nothing on the subject of anatomy in Melzi's version of the treatise, beyond generalities on the dynamics of the body in motion, and indeed no evidence that he made any sustained attempt to investigate the anatomical papers. Beyond the walls of the Villa Melzi fresh anatomical enquiry gained pace, culminating in the publication of Andreas Vesalius's groundbreaking *De humani corporis fabrica* in 1543, a model of what Leonardo's projected treatise could have been. The history of anatomical study may conveniently be divided into pre-Vesalian and post-Vesalian periods; had Leonardo published his treatise, we would today refer to pre-Leonardian and post-Leonardian periods.

Melzi died around the year 1570, and by 1590 his son had sold the majority of Leonardo's papers to the sculptor Pompeo Leoni, who preserved the notebooks intact and mounted the loose drawings into several large albums. Among the contents of one of these albums (fig. 10) were almost all the anatomical studies now known to us, which suggests that those drawings (including the so-called Anatomical Manuscripts A and B) had been acquired by Leoni as loose sheets, not as bound codices. Leoni spent much of his later career in the service of the King of Spain and divided his time, and his art collection, between Milan and Madrid. Peter Paul Rubens saw Leonardo's papers while they were in Leoni's possession, probably in 1603 in Madrid; he was reported to be particularly interested in Leonardo's

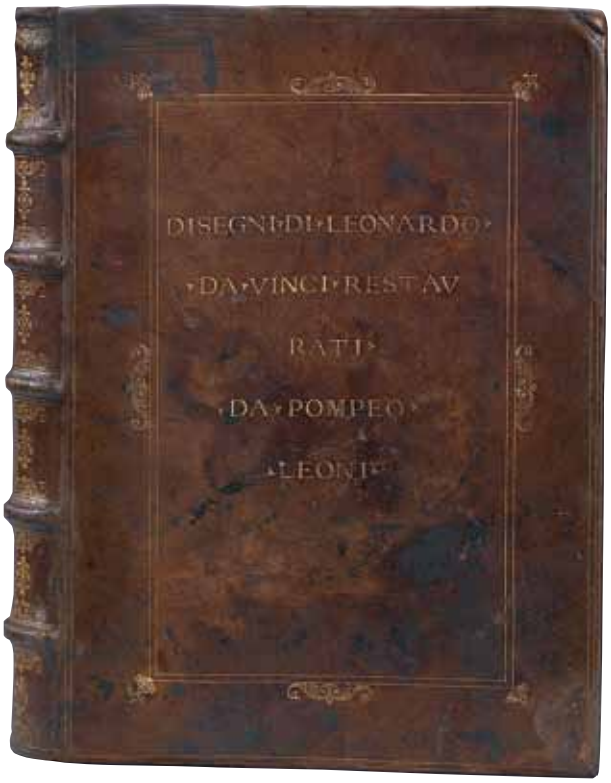


Fig. 10. *The Leoni binding*, *c.*1590–1600
Leather, 47 × 33 × 6.5 cm
RL 33320

anatomical drawings, though there is no direct reflection of them in the anatomical studies that Rubens himself made a few years later.

Inventories of Leoni's estate compiled after his death in Madrid in 1608 list (among many other items) the Leonardo volumes he had had with him in Spain. By 1630 one of these was in England, in the possession of Thomas Howard, 2nd Earl of Arundel, one of the great collectors of seventeenth-century Europe. While the album was in Arundel's possession a few of the anatomical drawings (nos 13a, 42, 43, 57b, 64a and an amalgam of nos 12a and 12b) were copied and later reproduced in etchings by Wenceslaus Hollar (fig. 11), but they seem to have been regarded as curiosities rather than repositories of knowledge. Arundel left England for the Low Countries shortly before the outbreak of the Civil War, travelling on to Italy, where he died in 1646, and it is not known whether he took the Leonardo album with him into exile. The album is next recorded in 1690, when it was seen in London in the possession of William III and Mary II. The means by which the volume entered the Royal Collection is unknown but it is probable that, along with many other Renaissance drawings, the Leonardos had been acquired, by purchase or gift, by Charles II (reigned 1660–85).

There was only sporadic interest in the album of Leonardos during the eighteenth century and it was forgotten about and 'rediscovered' at least twice. But by 1773 the physician and anatomist William Hunter had examined the anatomical drawings in George III's library and recommended in a letter to Albrecht von Haller that

they should be included in his great work on the history of anatomy, *Bibliotheca anatomica* (published in 1774). Hunter seems to have been the first person to appreciate fully the content and significance of the drawings since Leonardo's death two and a half centuries before, and in one of his lectures he noted that Leonardo's drawings enabled him

> to carry the history of the improvement of Anatomy farther back than has been generally done by our own writers; and to introduce into the annals of our art, a genius of the first rate, Leonardo da Vinci, who has been overlooked, because he was of another profession, and because he published nothing upon the subject. I believe he was, by far, the best Anatomist and physiologist of his time … and Leonardo was certainly the first man we know of who introduced the practice of making anatomical drawings …
>
> Those very drawings and the writing, are happily found to be preserved in his Majesty's great collection of original drawings. Mr Dalton, the King's librarian, informed me of this, and at my request procured me the honour of leave to examine them …
>
> In due time, as I doubt not of being honoured with the permission of the King, who loves and encourages all the arts, I hope to engrave and publish the principal of Leonardo's anatomical designs. They will be a curious and valuable acquisition to the history of Anatomy.[6]

Hunter died in 1783, before he could carry out his plan; but in 1796 John Chamberlaine published his *Imitations of Original Designs by Leonardo da Vinci,* including good etchings by Francesco Bartolozzi of 52b, 54 and 64b (fig. 12),

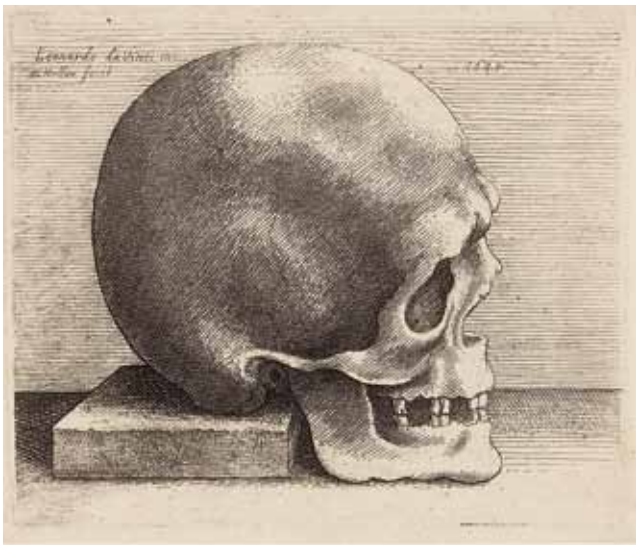


Fig. 11. Wenceslaus Hollar, after Leonardo da Vinci
A skull, 1645
Etching, 7.8 × 9.2 cm
British Museum, London

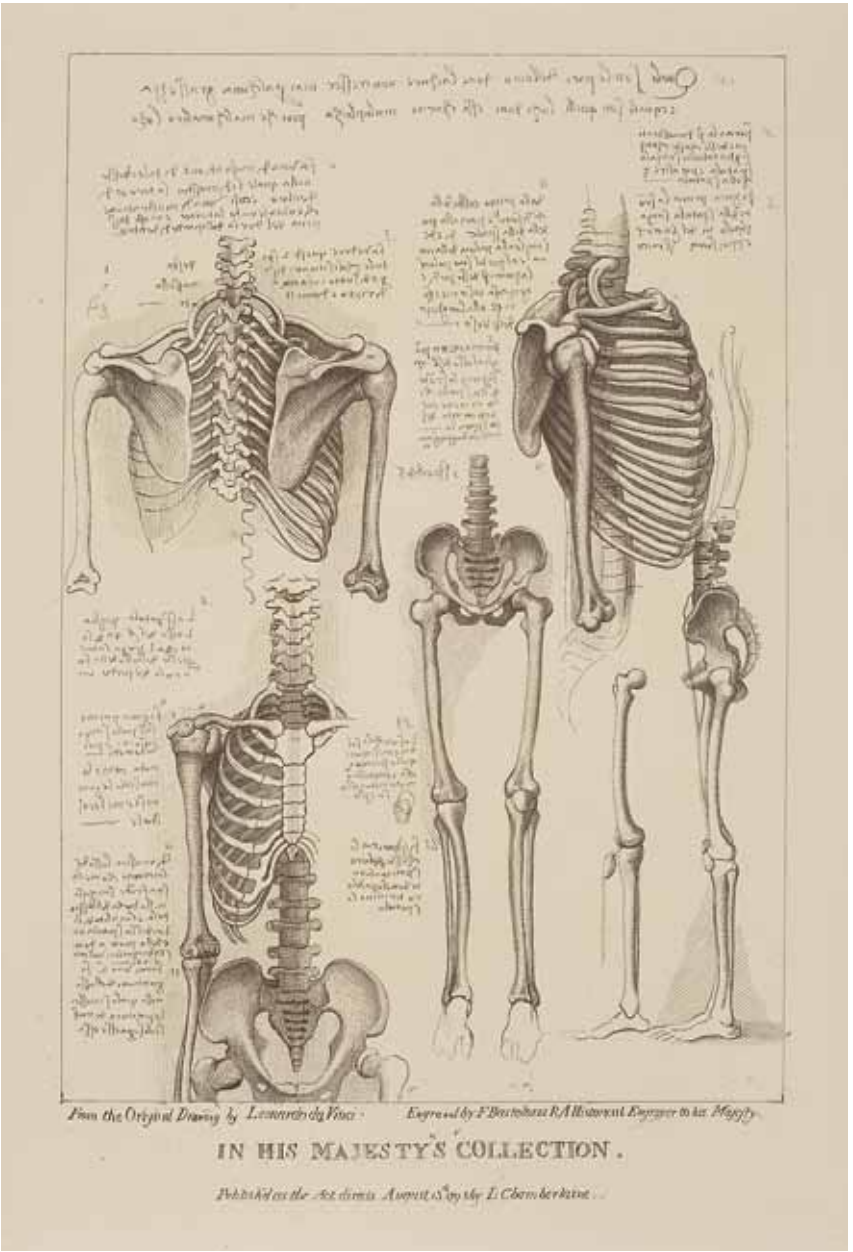


Fig. 12. Francesco Bartolozzi, after Leonardo da Vinci
The skeleton, 1795
Etching, 33.6 × 23.5 cm
RCIN 809368

with Leonardo's notes transcribed and reliably translated; two of these had been published individually the previous year, and subsequent editions added etchings of nos 2, 64a and RL19013r. For the first time the beauty and accuracy of at least some of Leonardo's anatomical drawings could be witnessed by a wider public. In 1797 the artist James Barry attempted to persuade the Committee of the Royal Academy to revive Hunter's intentions. This initiative came to nothing and the publication of most of Leonardo's anatomical work had to wait yet another century.

Finally, all of Leonardo's anatomical papers were published in a series of facsimile editions between 1898 and 1916 (see Further Reading). In the 1970s a conservation programme was begun in which all the Leonardo drawings at Windsor, beginning with the anatomical sheets, were lifted from their nineteenth-century mounts and suspended between ultraviolet-filtered acrylic sheets, and a complete facsimile edition of the anatomical drawings was published in 1979. Selections of Leonardo's drawings have now been seen by millions of people in exhibitions around the world.

Since 1900 students of Leonardo, and many anatomists and physicians specialising in particular aspects of the body, have attempted to come to terms with the legacy of his anatomical researches. He is an oddity – a scientist who made great strides in his field and yet had no perceptible influence on its wider development. Perhaps all we can do is to attempt to understand fully his thinking, to admire some of the finest anatomical drawings ever made, and to reflect on the different course that European anatomical study would have taken, had Leonardo published his researches.

We will leave the last word to Leonardo himself, writing around 1508–10 on the difficulties facing the anatomical draughtsman (no. 49):

> Though you may have a love for such things, you will perhaps be impeded by your stomach; and if this does not impede you, you will perhaps be impeded by the fear of living through the night hours in the company of quartered and flayed corpses, fearful to behold. And if this does not impede you, perhaps you will lack the good draughtsmanship which such a depiction requires; and even if you have skill in drawing, it may not be accompanied by a knowledge of perspective; and if it were so accompanied, you may lack the methods of geometrical demonstration and of calculating the forces and strengths of the muscles; or perhaps you will lack patience so that you will not be diligent. Whether all these things were found in me or not, the 120 books composed by me will give the verdict, yes or no. In these I have been impeded neither by avarice nor negligence but only by time. Farewell.

Notes

1 RL 19037v.

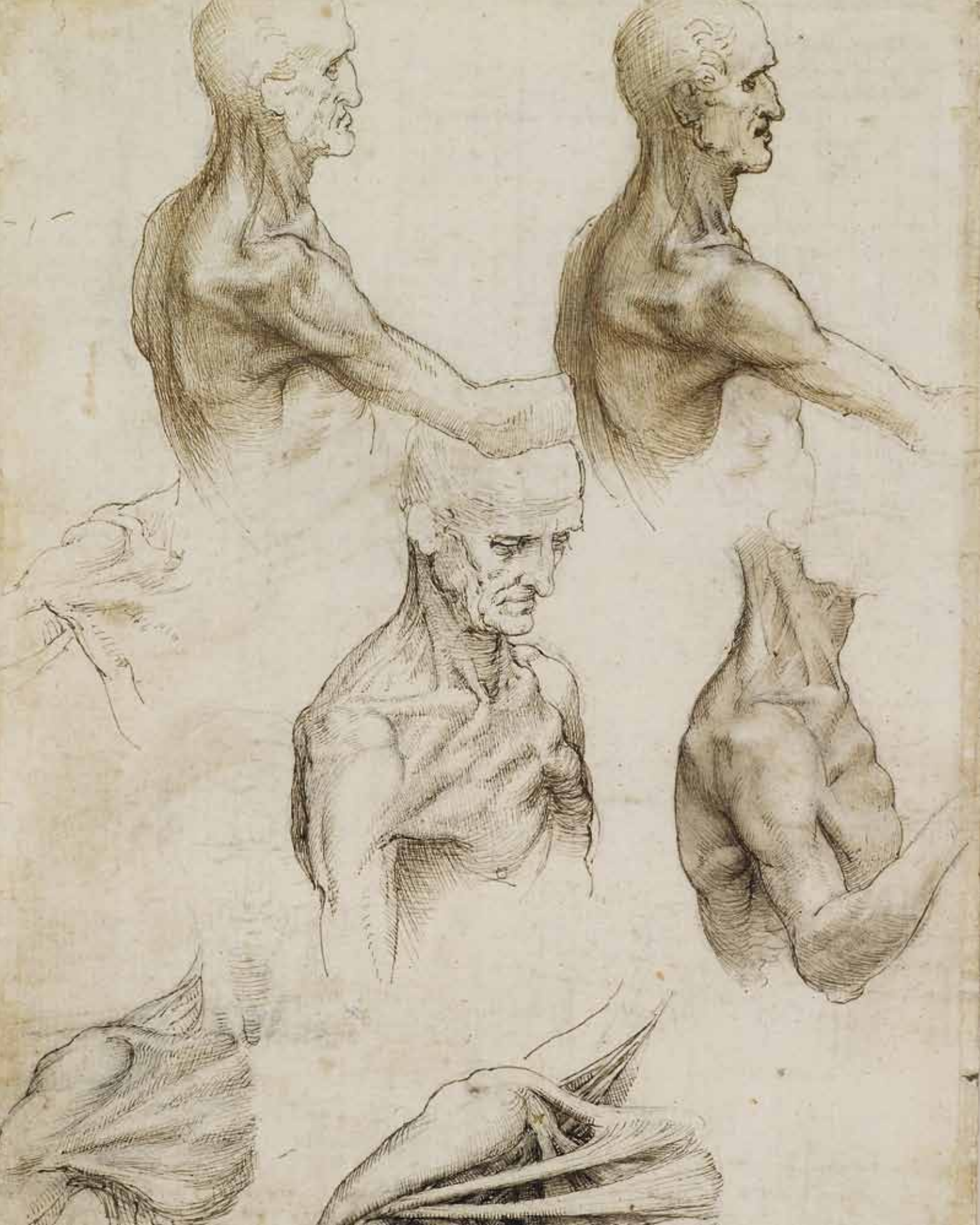
2 L. Reti, 'The two unpublished manuscripts of Leonardo da Vinci in the Biblioteca Nacional of Madrid – II', *Burlington Magazine,* CX (1968), pp. 81–9.

3 J.-P. Richter, *The Literary Works of Leonardo da Vinci,* 2nd edn, Oxford 1939, I, p. 3.

4 G. Vasari, *Delle vite de' più eccellenti pittori, scultori et architettori,* 2nd edn, Florence 1568, III, p. 7.

5 L. Beltrami, *Documenti e memorie riguardanti la vita e le opere di Leonardo da Vinci,* Milan 1919, p. 149.

6 *Two Introductory Lectures, Delivered by Dr William Hunter, to his Last Course of Anatomical Lectures, at his Theatre in Windmill Street,* London 1784, pp. 37–9.



Notes to the reader

All of the drawings in this book, and indeed the great majority of Leonardo's surviving anatomical studies, are housed in the Royal Library at Windsor Castle. Most of these sheets have drawings and/or notes on both sides of the paper. Where only one side of a sheet is catalogued here, it is given a simple catalogue number; where both sides are catalogued, they are numbered e.g. '31a' and '31b'.

All drawings are on white paper unless stated otherwise. In dimensions, height precedes width.

References are given to the following standard catalogues (see also Further Reading):

RL
K. Clark and C. Pedretti, *The Drawings of Leonardo da Vinci in the Collection of Her Majesty The Queen at Windsor Castle*, 2nd edn, 3 vols, London 1968–9

MS A
G. Piumati, *I manoscritti di Leonardo da Vinci della Reale Biblioteca di Windsor. Dell'anatomia: Fogli A,* Paris 1898

MS B
G. Piumati, *I manoscritti di Leonardo da Vinci della Reale Biblioteca di Windsor. Dell'anatomia: Fogli B,* Turin 1901

QA
Leonardo da Vinci. Quaderni d'Anatomia, 6 vols, Christiania 1911–16

O'M&S
C.D. O'Malley and J.B. Saunders, *Leonardo da Vinci on the Human Body,* New York 1952 and later edns

K&P
K. Keele and C. Pedretti, *Leonardo da Vinci. Corpus of the Anatomical Studies in the Collection of Her Majesty The Queen at Windsor Castle,* 3 vols, London and New York 1979–80

In describing the drawings, directions are normally given as for the viewer: e.g. 'to the left of' is to the left as we look at the drawing. But 'left kidney' etc. means anatomical left, and thus on the *right* as we look at the drawing.

Early anatomical and proportion studies

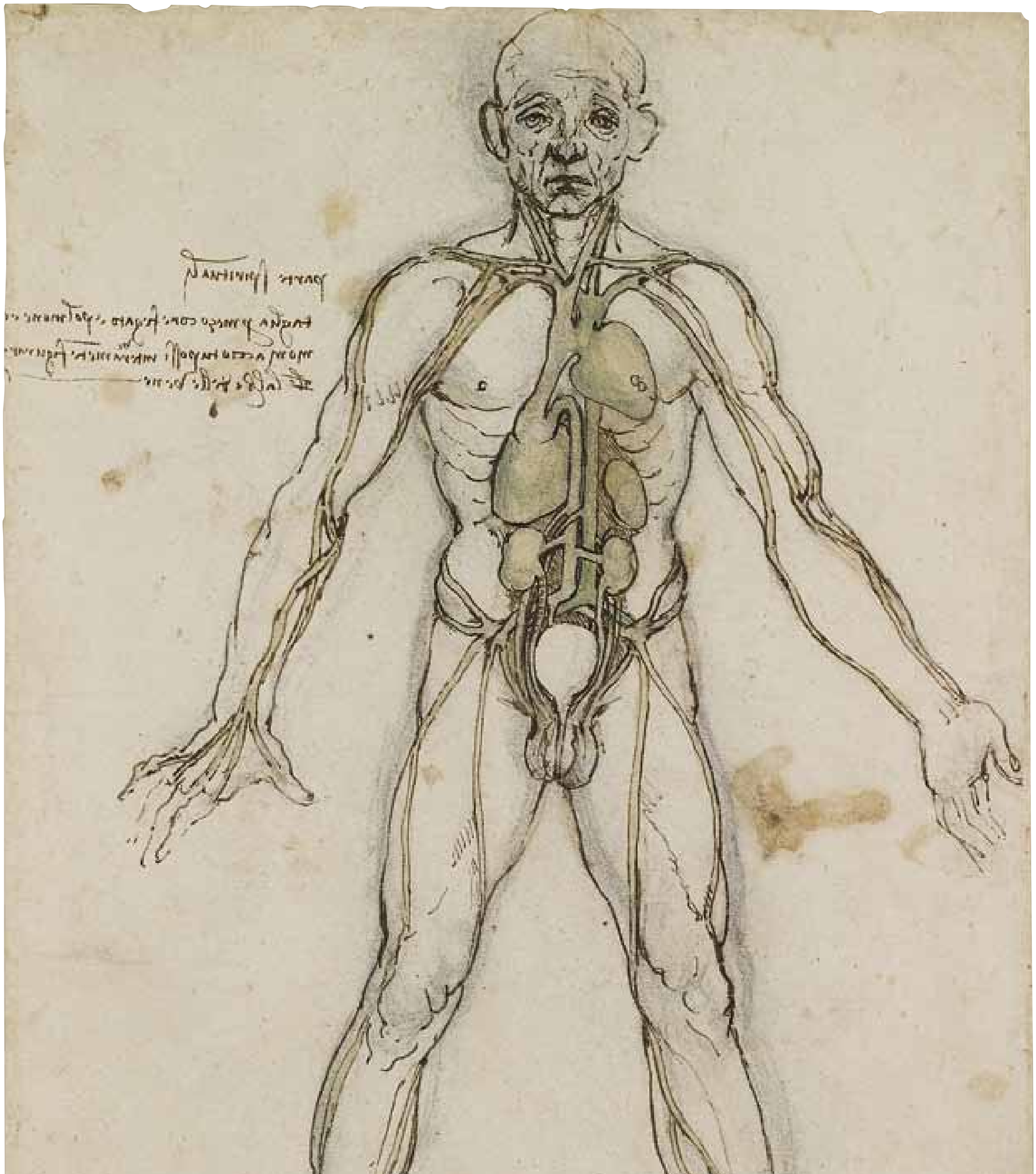
1 The major organs and vessels

*c.*1485–90
Pen and ink with brown and greenish wash, over black chalk
27.8 × 19.7 cm
RL 12597r; QA V.1r; O'M&S 116; K&P 36r

The drawing summarises Leonardo's early understanding of the layout of the major organs and vessels, before he had carried out any significant human dissection. It is an amalgam of two medieval traditions: the 'situs figure' showing the position of the major organs within the trunk and the 'bloodletting figure' showing the recommended sites for venesection and, occasionally, the paths of the superficial vessels.

Since ancient times the heart had been acknowledged as of primary importance in the body. Aristotle wrote of it not only as the centre of life and heat, but also of intelligence and the emotions. In the second century AD Galen refined these theories: observation of vessels travelling from the intestines to the liver supported the notion that the liver was the source of nutrition or 'natural spirit', creating blood that was distributed by the veins to nourish the body and, in doing so, was consumed. There was no notion of circulation or return of the blood. A portion of the blood was thought to pass from the right ventricle of the heart through the interventricular septum into the left ventricle, thus acquiring 'vital spirit', the 'life force', which was distributed through the body by the arterial system. The lungs existed to cool the heart. Variations on these basic ideas were espoused by the medieval followers of Aristotle and Galen, both Arab and European, and Leonardo's drawing embodies these principles.

Though the colour difference is now hard to distinguish, Leonardo used a brown wash for the venous system and a greenish wash for the arterial system – the contrast is most evident in the inferior vena cava and aorta. Whereas the origin of the vena cava from the liver is simply wrong, the relationship of the vena cava to the aorta and their bifurcations are essentially correct, and the right testicular artery and vein are present. The superior vena cava is shown splitting into the brachiocephalic veins and thence into the subclavian and internal jugular veins; the aortic arch is also drawn as a symmetrical structure, as it is in cattle but not in humans. The great saphenous vein can be followed from its origin on the upper side of the foot, running up the inside of the calf and knee and across the thigh. In the left arm, the cephalic vein (on the thumb side of the limb) is shown as part of the venous system, but the vessel on the little finger side of the limb, which should be the basilic vein, leads to an artery. The great saphenous, cephalic and basilic veins are among those most easily visible in a living subject, and were those most used in Leonardo's day for bloodletting.



2 The hemisection of a man and woman in the act of coition

*c.*1490–92
Pen and ink
27.6 × 20.4 cm
RL 19097v; QA III.3v; O'M&S 204; K&P 35r

The principal drawing records Leonardo's early beliefs about conception, as derived from the writings of his forerunners, who differed on whether the process involved a material union, a spiritual union, or both. Plato, for example, recorded in the *Timaeus* the belief that the 'seed' was a spiritual entity in the brain and spinal cord, possessing a will of its own and compelling men and women to procreate. Here Leonardo notes that 'Avicenna claims that the soul begets the soul, and the body the body'; elsewhere he recorded that 'Hippocrates says that the origin of men's sperm derives from the brain, and from the lungs and testicles of our parents, where the final decoction is made; and all the other limbs transmit their substance to this sperm by means of transpiration, because there are no channels through which they might come to the sperm' (MS Forster III, fol. 75r).

Leonardo seems here to depict an arrangement whereby *three* components are involved in conception. In the male he has drawn channels into the penis from the lumbosacral plexus at the bottom of the spinal column (to transmit an 'animal', i.e. soul, element), from the heart (a 'spiritual' element), and from the testes (a 'material' element), thus following Mondino's division of the body into animal (head), spiritual (thoracic) and material (abdominal) regions. The channels from heart and testes unite with the urethra and pass through one duct in the penis, while the channel from the spinal cord remains separate. A simple dissection would have ascertained that the penis has just one channel. Leonardo may also have believed that his fictive channel in the male between the heart and the testes had a secondary function: the notes include the reminder to consider 'how the testes are the cause of ferocity' – as the emotions were believed to be felt in the heart, the tube between the testes and the heart would also allow this ferocity to be transmitted from its source.

The arrangement in the female is less clear. The spine bifurcates and a branch of the spinal cord passes directly into the uterus, but the ovaries and heart are not drawn; it is thus questionable whether at this stage of his career Leonardo believed that there was an equal contribution to conception from the female. He did, however, introduce a channel from the uterus to the breast, to allow the menses retained during pregnancy to be converted into milk.

The main drawing and the subsidiary study to the left also display Leonardo's crude understanding of the gastrointestinal system at that date. The smaller drawing distinguishes between the small and large intestines, but the coiling of the intestines is abbreviated and in the middle of the intestines there is a second stomach-like organ (perhaps an exaggerated cecum) connected to the umbilicus; in the notes Leonardo reminds himself to investigate 'how [the infant] is nourished through the umbilicus'.

3 The bones and nerves of the arm

*c.*1485–90
Metalpoint (faded) and pen and ink on blue-grey prepared paper
22.2 × 30.4 cm
RL 12613r; QA V.21v; O'M&S 152; K&P 1v

Several of Leonardo's earliest anatomical sheets are executed in the medium of metalpoint on paper coated with a blue preparation. In many cases the metalpoint has faded badly, perhaps at an early date, for some of them were reinforced in pen by Leonardo himself. The faded metalpoint lines are, however, still clearly visible in ultraviolet light (fig. 13).

Most of the anatomical studies on this sheet (there are some architectural sketches too) are concerned with the bones and nerves of the arm. These are based on animal dissection and Leonardo made no attempt to adjust the proportions to those of a human. The short, thick and strongly curved humerus is suggestive of a dog or other quadruped; the hand at lower right is labelled by Leonardo as that of a monkey and erroneously shows five roughly equal fingers each with the same number of bones. It exhibits the characteristics of the skeleton of a young individual, with the epiphyses (rounded ends) of the radius, ulna, metacarpals and phalanges shown as distinct small bones.

The drawings to the top of the page examine the pathways of the nerves from the spine down the arm, and in the largest drawing the radial, median and ulnar nerves can all be distinguished as they traverse the length of the limb. The brachial plexus, where the nerves of the arm leave the spinal column (see nos 37–39b), is shown as formed from just four spinal nerves – fewer than in a monkey, human or dog. In the drawing immediately above, the relationship of the median and ulnar nerves to the muscles at the surface of the arm can be seen. Perhaps the most astute drawing is the small study at centre left, almost invisible in normal light, which illustrates the formation of a spinal

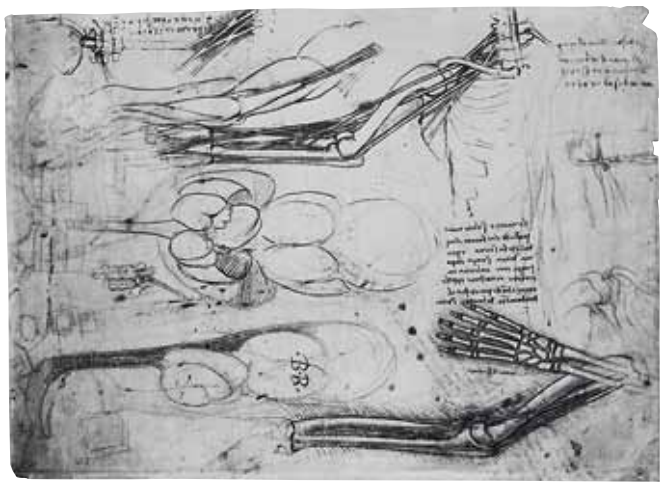
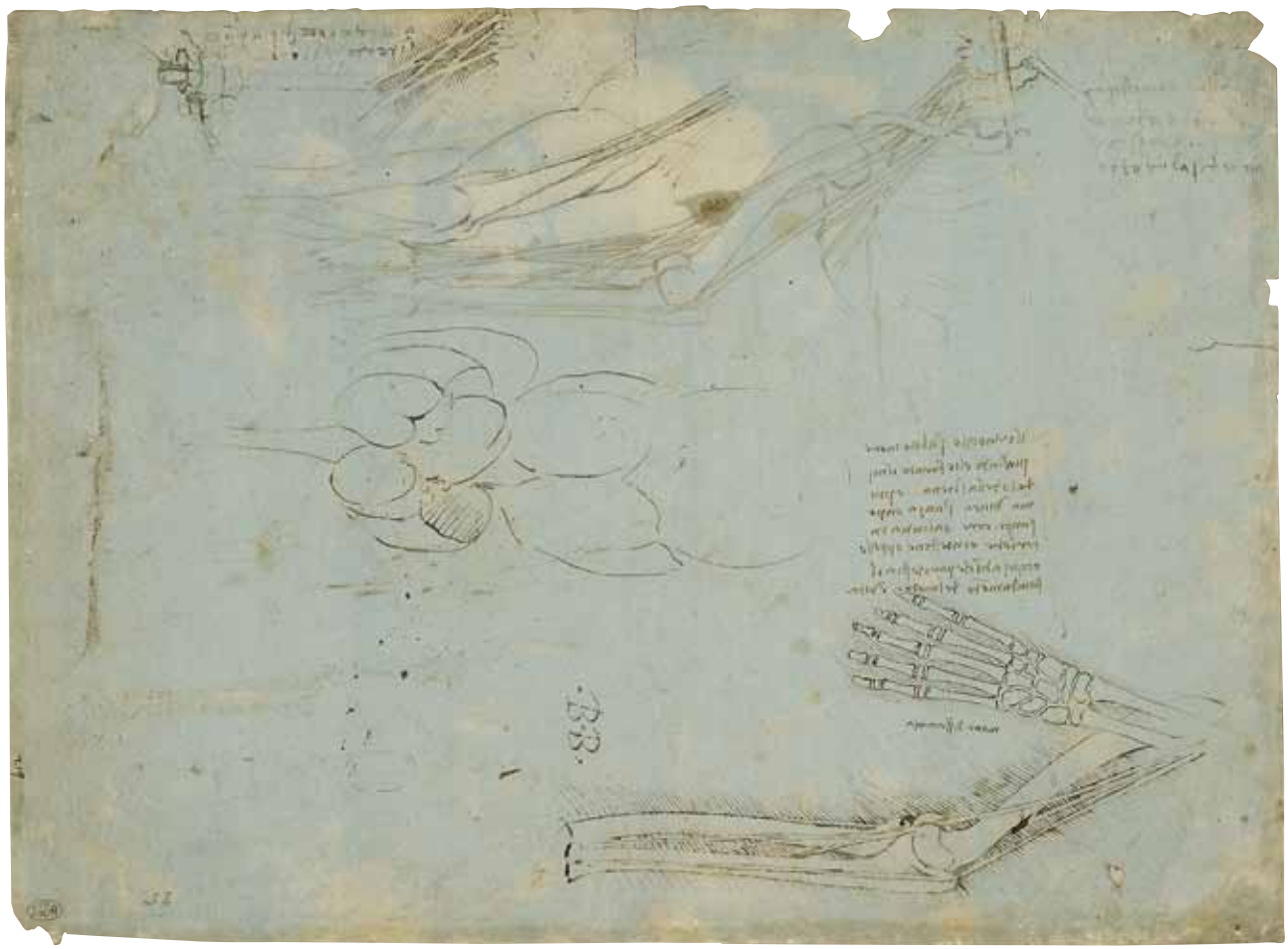


Fig. 13. Ultraviolet image of no. 3



nerve (cervical in this case) from the merger of two roots – one dorsal and one ventral – emerging from the spinal cord and passing through an intervertebral foramen.

Leonardo was particularly interested in the spinal cord as crucial to life: it contains neural circuits that can function independently of the brain, and in the note at centre right he observed that a decapitated frog can continue to exhibit a semblance of life until the cord itself is destroyed: 'The frog dies instantly when its spinal medulla is perforated. And previously it lived without head, without heart or any interior organs, or intestines or skin. Here therefore it appears lies the foundation of movement and life.'

The large drawing at the centre of the sheet depicts the thoracic and some abdominal organs of what appears to be a pig, repeated in a rough lateral view (with the addition of the tongue, trachea and so on) at lower left.

4 The neck

*c.*1485–90
Metalpoint (faded), pen and ink, leadpoint, some discoloured white heightening, on pale blue-grey prepared paper
20.2 × 28.7 cm
RL 12609r; QA V.16r; O'M&S 34; K&P 3r

The principal drawing depicts a variety of structures in the neck. The hyoid bone and laryngeal apparatus are not human, and the proportions of the smaller study to centre right – faded, and visible only in ultraviolet light (fig. 14) – suggest that a monkey was again Leonardo's subject. Such is the density of detail that Leonardo provided key letters on the clavicle, though it is not always clear to which structures these letters refer. Prominent are the diagonal sternocleidomastoid muscle (*M*) and the external jugular vein (*P*), with its branches outlined in pen in the smaller study to the right. *R S T* are at approximately the positions where the internal jugular vein, common carotid artery and vagus nerve pass behind the clavicle (collarbone). A portion of the temporalis muscle is seen passing deep to the zygomatic arch (cheekbone), and at the back of the neck there is an odd depiction of what might be the trapezius muscle reduced to two 'strings' to show the deeper muscles such as splenius.

In the delicate metalpoint sketch to the left, temporalis is seen again, and Leonardo has indicated the zygomaticus major muscle and part of the complex of levator muscles which lift the upper lip.

To lower right is a head and neck of a type drawn habitually by Leonardo. The sternocleidomastoid muscle is again prominent, though Leonardo has depicted it travelling backwards to the shoulder rather than forwards to the clavicle and sternum. At lower left is what may be a first attempt to understand the oblique muscles of the anterior abdominal wall, shown travelling between the iliac crests and the opposite lower ribs and thus crossing the midline of the body, which they do not do (cf. no. 70).

Fig. 14. Ultraviolet image of no. 4

5 The muscles and nerves of the leg and head

*c.*1485–90
Metalpoint (faded) and pen and ink on blue-grey prepared paper
21.3 × 30.0 cm
RL 12626r; QA V.15r; O'M&S 159; K&P 6r

The study at upper right, reinforced in pen and ink, depicts the front of the thigh with the sartorius and gracilis muscles cut and shown as stumps at the top of the thigh and the knee. This has exposed some of the adductor and quadratus femoris muscles, and the femoral nerve and vessels as they begin to course into the adductor (Hunter's) canal. The accompanying note states: 'I have lifted off the muscle *a n* [sartorius] which is half a *braccio* long [30 cm – the longest muscle in the human body] and I have uncovered *r t* [rectus femoris]. Now attend to what lies below *m o* [vastus lateralis].' This drawing and note probably constitute the earliest evidence for human dissection in Leonardo's anatomical investigations.

Much of the rest of the sheet is filled with studies of the leg, mostly in faded metalpoint (fig. 15), with particular emphasis on the branches of the femoral nerve. In the studies at centre right and far left, the sciatic nerve can be seen dividing into the tibial nerve in the midline of the leg and the common fibular nerve laterally. At lower right is a study of the head and neck, with portions of the temporalis muscle indicated and trapezius and sternocleidomastoid reduced in width for diagrammatic clarity. In the sketch at lower left, trapezius is reduced to a pair of threads meeting in a large inverted 'V' at the back of the cranium but seems to travel around to the front of the neck.

The horizontal section through the head at lower centre shows the orbits and the cerebral ventricles. In medieval physiology these ventricles were thought to be three bulbs arranged in a row, which housed the mental faculties (cf. nos 12b–13a, 14, 48–50). The first was where the mind's 'raw material' was gathered – the *senso comune,*

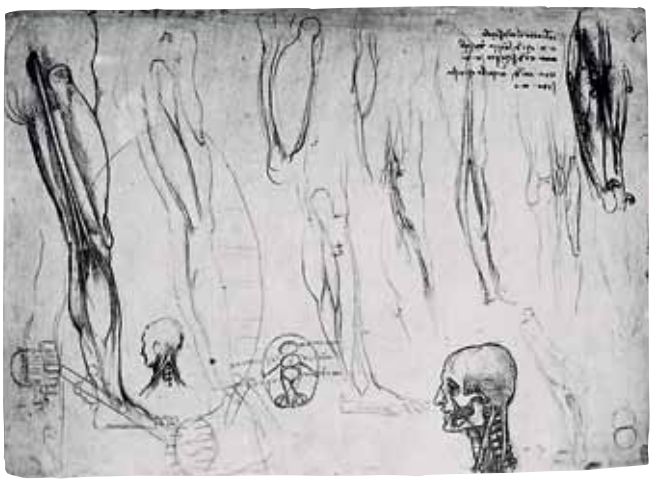
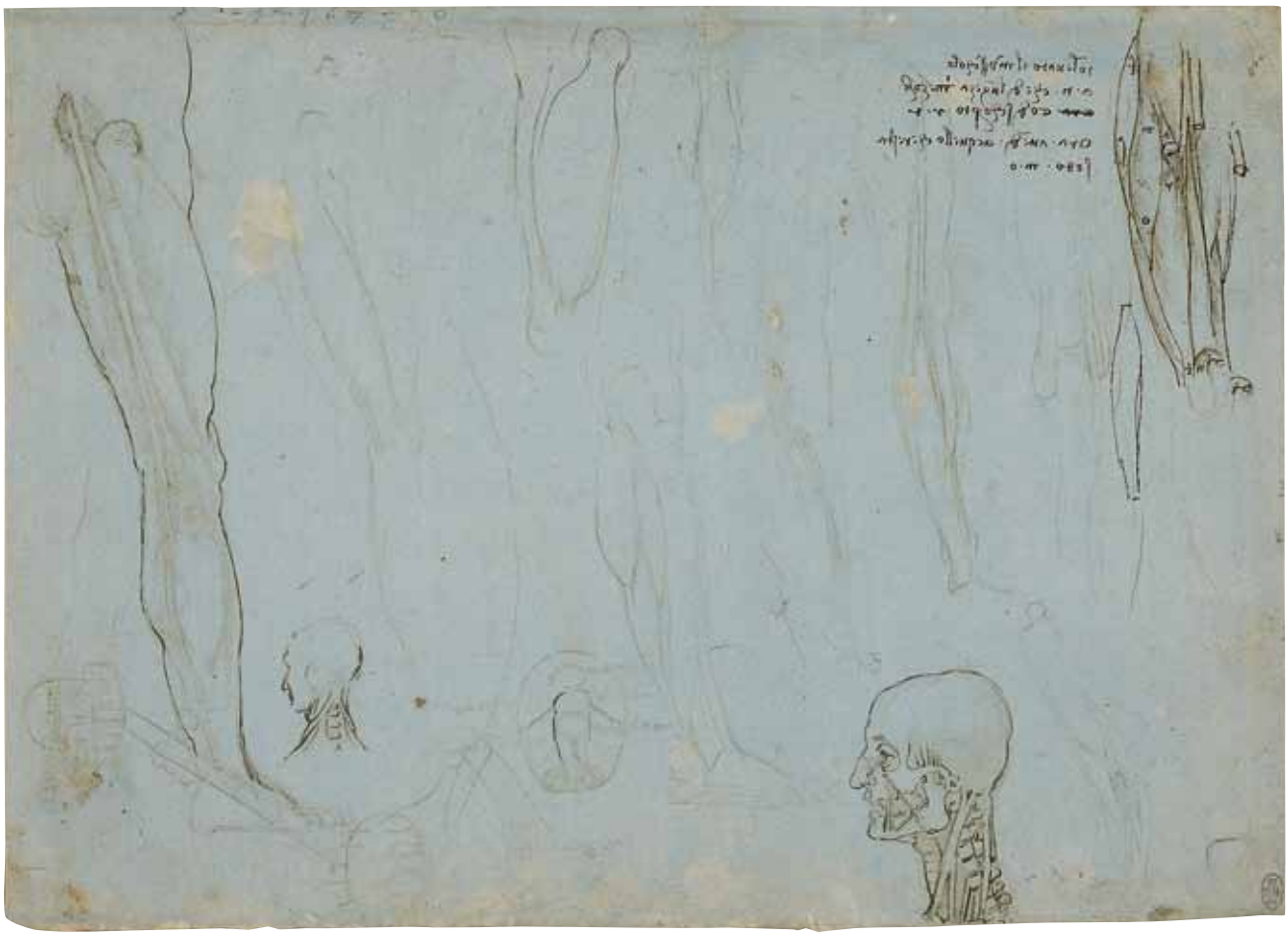


Fig. 15. Ultraviolet image of no. 5



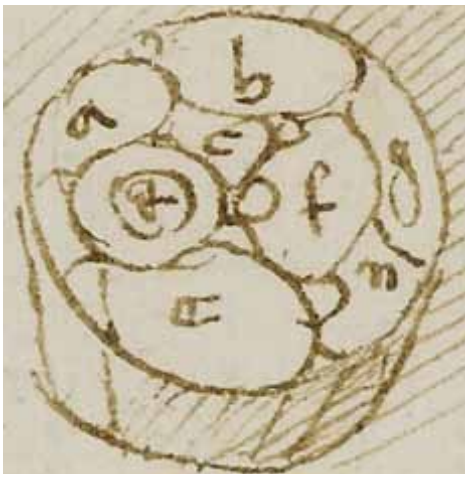
where the sensory nerves converged, together with imagination and fantasy; the second was where this information was processed, through reasoning and so on; and the third was where the results were stored, in the memory. Leonardo was unconvinced by this sequence, and repeatedly tried different arrangements. Here the optic nerves alone travel to the first ventricle, labelled *'imprensiva'* and *'inteletto'* (intellect); the middle ventricle, to which the auditory nerves travel, is labelled *'senso comune'* and *'volonta'* (will); the third ventricle is labelled *'memoria'* (memory), as usual. The *imprensiva* was the 'receptor of impressions' and its distinction from the *senso comune* is not entirely clear; but Leonardo clearly wished to accord a special status to visual information, with the optic nerves travelling directly to the site of the intellect and the other sensory nerves passing to a more generalised clearing house for the brain's activity.

6 The leg sectioned

*c.*1485–90
Pen and ink
22.2 × 29.0 cm
RL 12627v; QA V.20r; O'M&S 72; K&P 4v

Cross-sectional anatomy is commonplace today, in computed axial tomography (CAT) and magnetic resonance imaging (MRI), but Leonardo's use of this representational technique for the human body was unprecedented. Here, most of the larger muscles of the upper leg can be identified in position, suggesting that Leonardo did indeed section a human leg in this manner – it would not be possible to infer this arrangement from surface examination or from animal material. The lack of fixatives (or freezing) to harden the tissues so that they could easily be sawn into discs must have hampered him – soft, unfixed tissue tends simply to fall apart when cut, and the relative sizes and positions of the muscles here are thus not entirely correct, but the detail to the left still bears comparison with an equivalent modern image (fig. 16).

For ease of reference the detail is here enlarged and reversed. Surrounding the femur (with its marrow) at *d* are vastus medialis at *a,* the adductor muscles at *b* and *c,* vastus lateralis at *e,* the short and long heads of biceps femoris at *f* and *n* respectively, and semimembranosus and semitendinosus merged at *g*. Rectus femoris and sartorius are probably the unlabelled muscles to the front of the femur; gracilis is not indicated.



Detail of no. 6, reversed

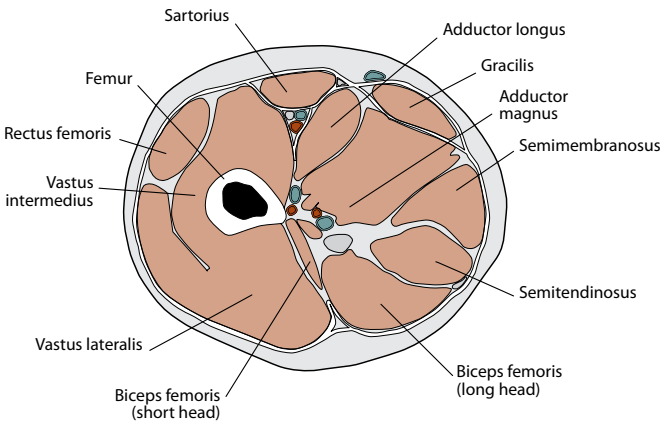
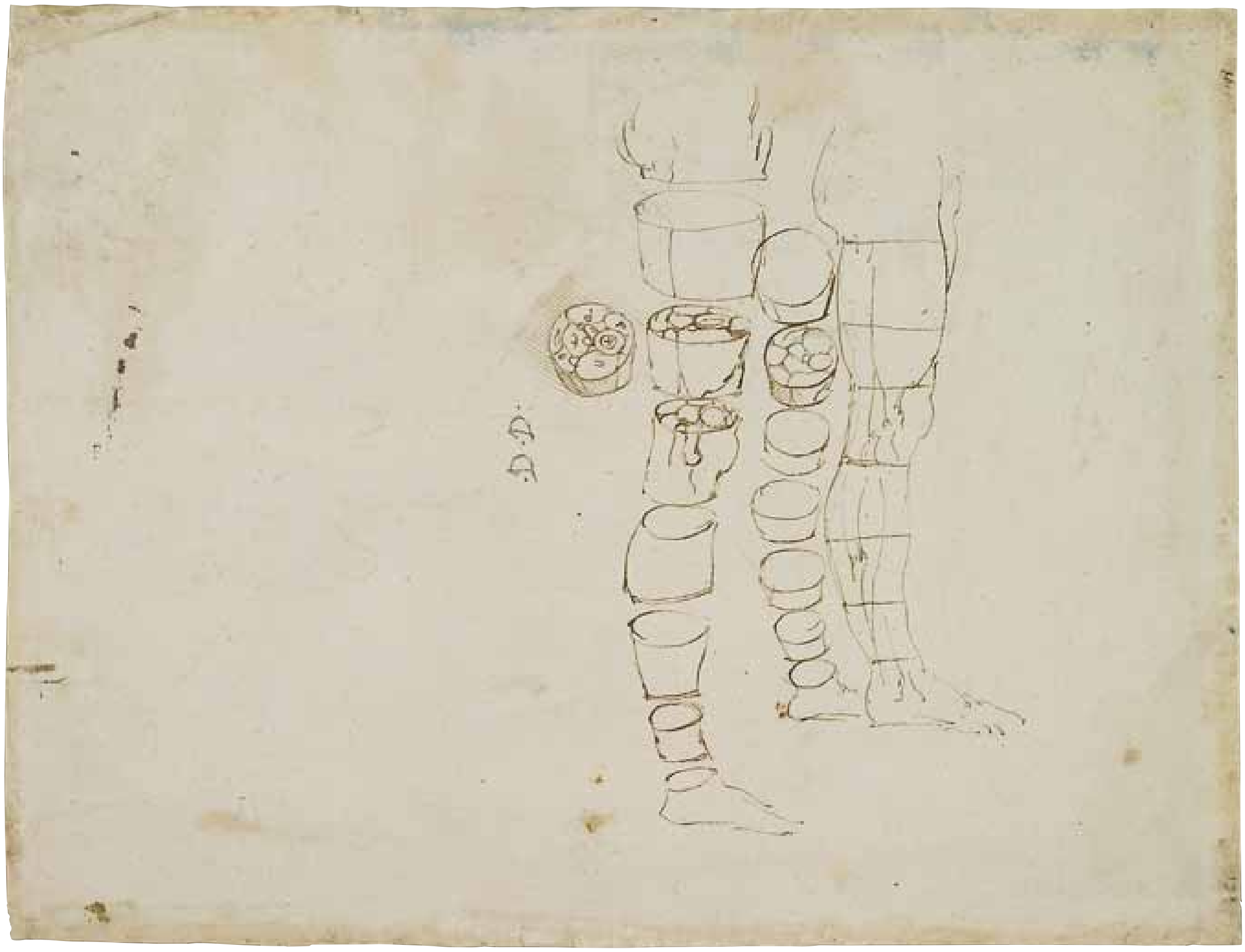


Fig. 16. Cross-section of a human leg


D.D.

7 A bear's foot

*c.*1488–90
Metalpoint with pen and ink and white heightening,
on blue-grey prepared paper
16.1 × 13.7 cm
RL 12372r; QA V.11r; O'M&S 81; K&P 12r

8 A bear's foot

*c.*1488–90
Metalpoint on blue-grey prepared paper, with
pen and ink and white heightening in the detail
13.6 × 18.6 cm; a fragment 4.8 × 12.1 cm
pasted behind an aperture at upper left
RL 12373r; QA V.12r; O'M&S 82; K&P 13r–14r

During the latter part of the 1480s Leonardo dissected the left hind leg of a bear. At that time bears were common in the mountains of Italy; they were hunted for sport and kept in captivity for entertainment, and Leonardo could thus easily have obtained a specimen for dissection. His particular interest in the animal was probably due to its plantigrade gait – like humans, bears walk with their feet flat on the ground (digitigrade animals such as dogs and cats walk on some portion of the digits, while unguligrade animals such as horses or cattle walk on the tip of a digit, usually in the form of a hoof). Leonardo's dissection would therefore have given him an insight into the anatomy of the human foot at a time when he had little access to human material.

The drawings show the bones, muscles and tendons of the lower leg and foot. Three of the drawings (nos 7–9) give a lateral or outside view of the foot, the last of these partially from below; no. 10 is a medial or inside view of the foot; and set into no. 8 is a detail of the large toe from the medial side. These drawings can be compared directly with Leonardo's studies of the human foot executed more than twenty years later: nos 7–8 give essentially the same view as no. 66; no. 9 is very similar to no. 65b, but seen from the other side of the foot; and no. 10 gives the same view as no. 65a.

The side views show the extensor retinaculum ligament holding in place the tendons of extensor digitorum longus on the front surface of the ankle. The omission of this ligament was to be an odd feature of Leonardo's later studies of the human foot; on a page of notes also of around 1510 he reminded himself to 'make a discourse on the hands of each animal in order to show in what way they vary, as with the bear in which the ligament joins the tendons of the toes together over the neck of the foot' (RL 19061r), suggesting that he thought this ligament was peculiar to the bear.

In nos 7–9 the tendons of fibularis longus and brevis pass behind the lateral malleolus (ankle bone) and the superficial fibular nerve can be seen running diagonally above the lateral malleolus and entering the dorsum or upper surface of the foot (cf. key diagram to no. 66). In no. 7 the Achilles or calcaneal tendon appears to pass right around the calcaneus and along the sole of the foot; its insertion on the calcaneus is more correctly shown on no. 9. There the multiple tendons of flexor digitorum brevis

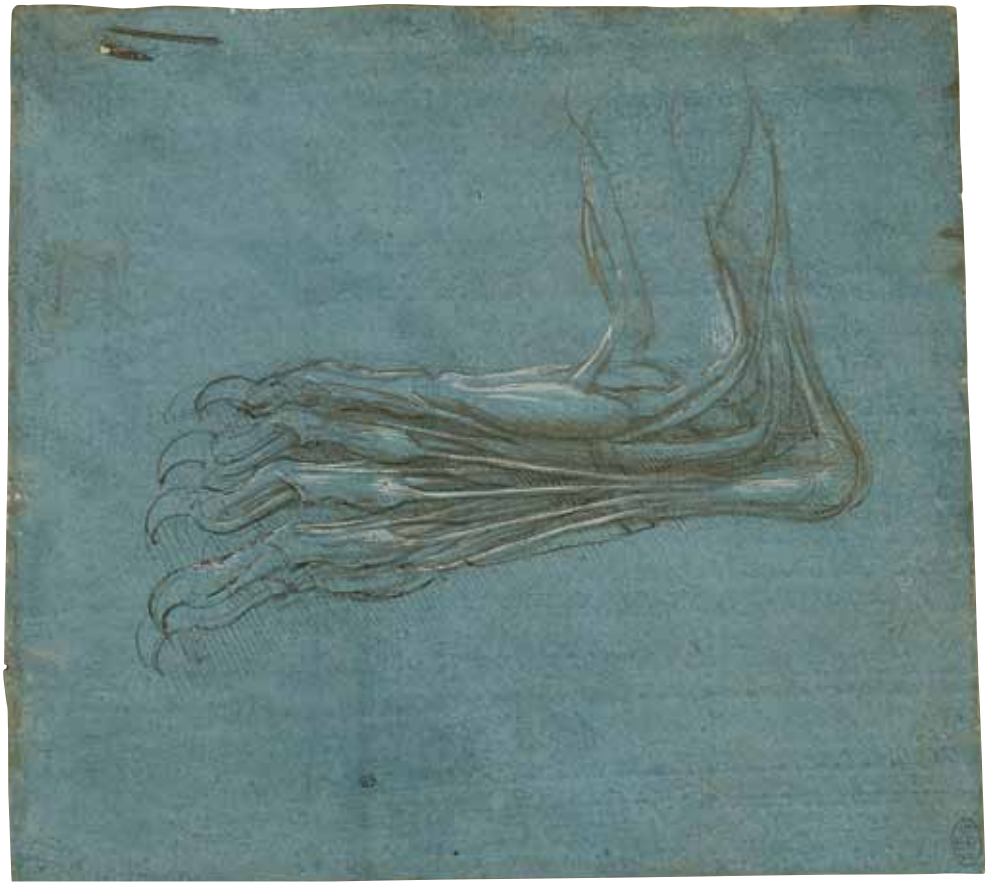
9 A bear's foot

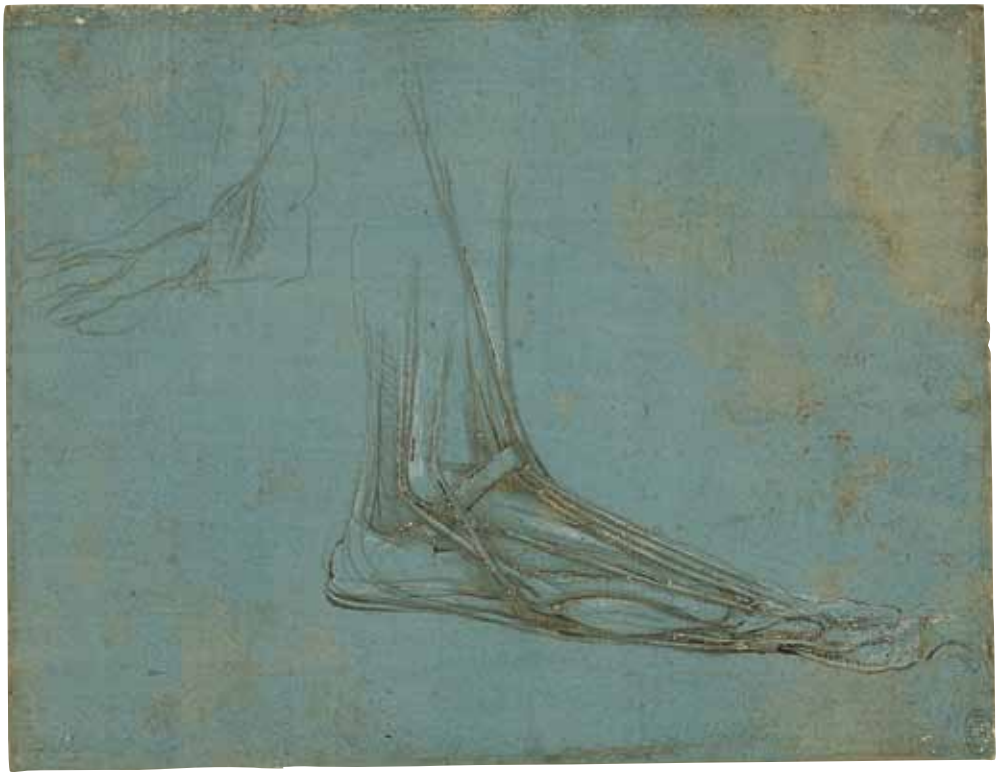
*c.*1488–90
Metalpoint with pen and ink and white heightening,
on blue-grey prepared paper
15.5 × 17.3 cm
RL 12375r; QA V.14r; O'M&S 84; K&P 15r

10 A bear's foot

*c.*1488–90
Metalpoint with pen and ink and white heightening,
on blue-grey prepared paper
14.1 × 18.1 cm
RL 12374r; QA V.13r; O'M&S 83; K&P 16r

are prominent, forming broad expansions at the sites of their insertion, and the tendons of flexor digitorum longus are visible beneath them (cf. key diagram to no. 65b). The relationship of the brevis and longus tendons is not entirely apparent in no. 9, but this relationship is studied in detail in the fragment pasted on to no. 8, where the longus tendon is shown passing through a bifurcation in the (reduced) brevis tendon. Leonardo was to pay particular attention to that feature when he found it in the human hand 20 years later (no. 63b). The tendon of extensor digitorum longus, and muscles and tendons possibly of extensor digitorum brevis and/or an interosseous or lumbrical muscle, can also be seen inserting on the upper side of the toes.





11a The cranium

1489
Pen and ink
18.8 × 13.9 cm
RL 19059r; MS B.42r; O'M&S 5; K&P 40r

At the head of the page Leonardo wrote 'On the 2nd day of April 1489', adding later 'Book entitled On the Human Figure'. With this sheet he thus began the compilation of what has been designated the 'Anatomical Manuscript B' (hereafter simply Manuscript B), a notebook of 44 folios used for anatomical studies during two periods around 1489 and 1508 (for the later drawings see nos 25–46).

It may have been the acquisition of a human skull (or skulls) that prompted Leonardo to begin this notebook. While we have seen that he dissected a human leg before this date, Leonardo would have regarded the head as the key to a number of the more subjective, phenomenological issues that he wished to investigate, such as the senses and the emotions. Here, however, his drawings and notes are entirely material, tracing the paths of the maxillary and superficial temporal veins.

It is difficult to determine how many skulls Leonardo had access to – the differing dentition seen in the drawings is not necessarily indicative of different specimens, for he was not simply depicting what was in front of him. Nonetheless, the skull studies are exquisitely observed and modelled. Leonardo's use, in his contemporary metalpoint drawings, of dense parallel hatching to capture the effects of light on solid surfaces had honed his draughtsmanship to an astonishing level of refinement, and here he was able to depict the nuances of the cranium using the unforgiving medium of pen and ink alone.

The drawings and accompanying note trace the path of the maxillary vein (labelled *m* in the upper drawing), passing under the zygomatic arch (cheekbone) and entering the orbit posteriorly, engaging the infraorbital groove and canal and emerging through the infraorbital foramen (labelled *n* in the upper drawing). There it ramifies with the angular vein and other veins around the orbit. Meanwhile, the superficial temporal vein is shown coursing parallel to the maxillary vein under the zygomatic arch, then ramifying around the temple. The union of the two veins to form the retromandibular vein just below the level of the jaw is not shown.

[illegible]

[illegible]

11b Notes on topics to be investigated

1489
Pen and ink
18.8 × 13.9 cm
RL 19059v; MS B.42v; K&P 40v

On this page of his newly commenced notebook Leonardo listed some of the topics that he wished to investigate, as they occurred to him and in no particular order – this is not a cogitated programme for his intended treatise (see p. 9). The themes are found repeatedly in his drawings and notes at this period: facial expression, the phenomena of life, and the paths of the nerves in the limbs (see more potential subjects on no. 41):

What nerve is the cause of movement of the eye and makes the movement of one eye draw the other
on closing the eyelids
on raising the eyelids
on lowering the eyelids
on shutting the eyes
on opening the eyes
on raising the nostrils
on opening the lips with the teeth closed
on bringing the lips to a point
on laughing
on [the expression of] wonder

describe the origin of man when he is generated in the womb
and why an infant of eight months does not live
what is sneezing
what is yawning
epilepsy
spasm
paralysis
trembling with cold
sweating
tiredness
hunger
sleep
thirst
lust

on the nerve which causes movement from the shoulder to the elbow
on movement from the elbow to the hand
from the wrist to the beginning of the fingers
from the beginning of the fingers to their middle
and from the middle to the last joint
on the nerve which causes movement of the thigh
and from the knee to the foot and from the ankle to the toes
and also to their middle
and of the rotation of the leg

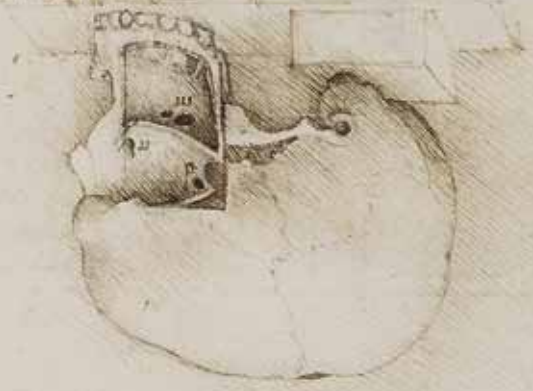
12a The cranium

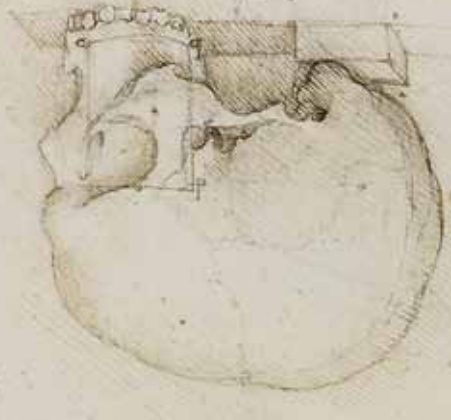
1489
Pen and ink over black chalk
18.8 × 13.4 cm
RL 19057v; MS B.40v; O'M&S 4; K&P 43v

The drawings show a cranium as if resting on a table, supported by a block under the occipital bone. There is no one angle of view: some features are seen as if from slightly above, some from slightly behind, and some from slightly to the front. Among other features, Leonardo has shown the suture lines of the major cranial bones, the infratemporal crest, the pterygopalatine fossa, the sphenopalatine foramen, and the foramen for the zygomaticofacial nerve on the zygomatic bone.

In the second drawing Leonardo has removed the lateral orbital wall and the lateral portions of the zygomatic and maxilla bones, using the superior and inferior orbital fissures as targets for his saw-cuts. We now see the full depth of the orbit, with the optic foramen at *b* and the fossa for the lacrimal duct at *n,* and the maxillary sinus (whose first description is usually credited to Nathaniel Highmore in his *Corporis humani disquisitio anatomica* of 1651), with openings into the middle meatus of the nasal cavity at *m*. On the floor of the sinus are small elevations, like stalagmites in a cave; these are portions of the thin capsule of alveolar bone covering the roots of the maxillary teeth (particularly noticeable in older individuals).

The notes record physiological interpretations of these structures based on the ancient theory of the humours: the ethmoid bone 'discharges superfluous humours of the head into the nose'; the maxillary sinus contains 'the humour that nourishes the roots of the teeth'; and the fossa for the lacrimal sac is 'the place through which the tears rise up from the heart [seat of the emotions] to the eye, passing through the canal of the nose'.



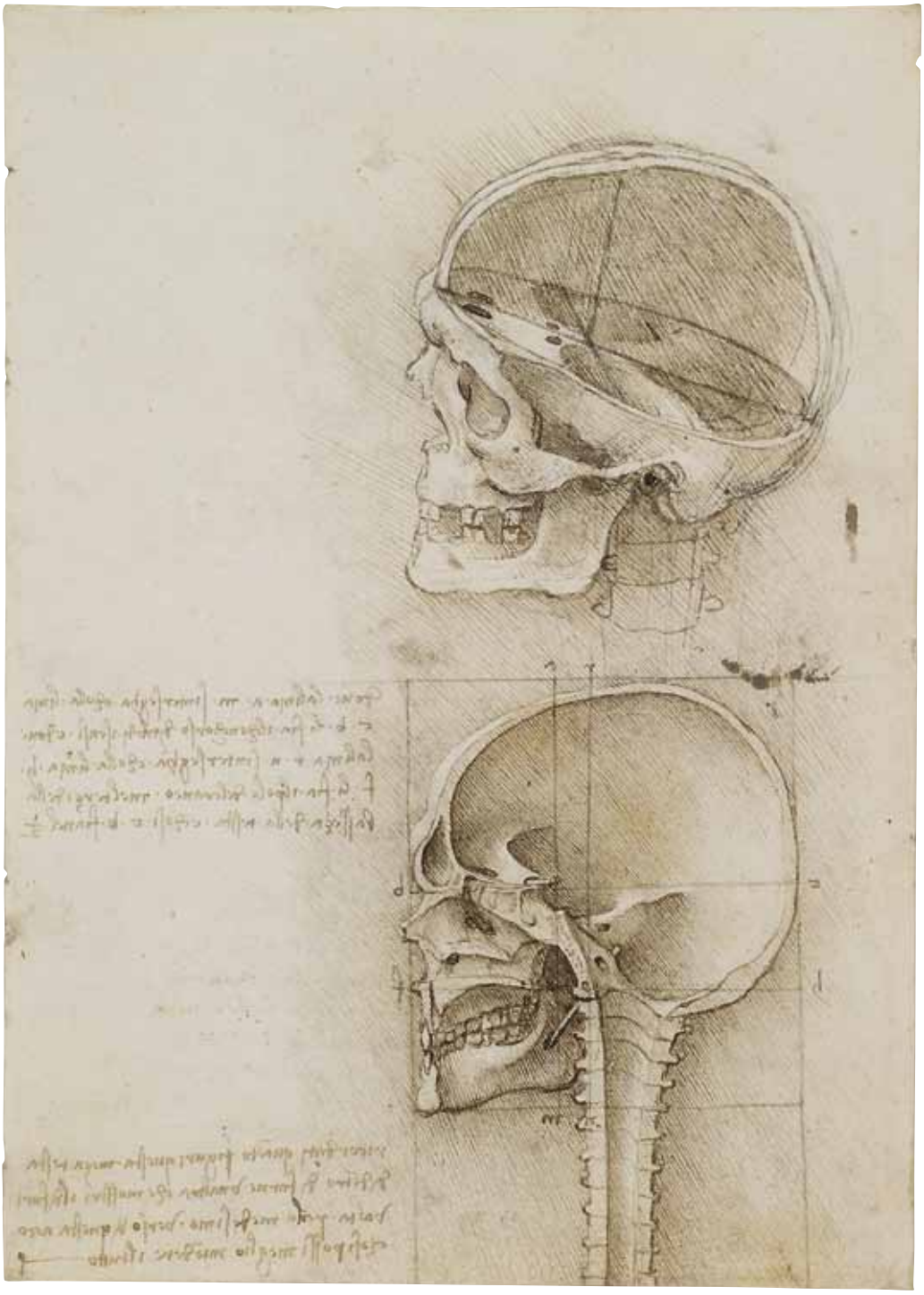


12b The skull sectioned

1489
Pen and ink over black chalk
18.8 × 13.4 cm
RL 19057r; MS B.40r; O'M&S 7; K&P 43r

Both drawings give the location of the *senso comune,* the confluence of the senses within the brain (see no. 5). The upper drawing places it at the intersection of three orthogonal lines – an anterior-posterior axis, a vertical axis through the upper point of the skull, and a lateral axis roughly along the ridge of the dorsum sellae. Just in front of this intersection are the optic foramina; at the front of the orbit is the fossa for the lacrimal sac, and Leonardo's attention to detail can be seen in the inclusion of the small zygomaticofacial foramen on the zygomatic arch (the dot on the cheekbone).

The lower drawing shows the skull in a full sagittal section, with the cervical vertebrae included schematically. The grid and accompanying notes locate the *senso comune* at the intersection of the lines *am* and *cb* (at the mid-point of the height of the skull), and the 'fulcrum of the cranium' at the intersection of the lines *rm* and *hf* (at one third of the height of the skull, though the grid seems to show it at one quarter). Of the many features accurately depicted, one may note the prominent frontal sinus; the optic nerve emerging from the optic foramen; the internal acoustic meatus and hypoglossal canal; the inferior alveolar nerve entering the mandibular foramen; the incisive canal piercing the anterior hard palate; and the opening of the nasolacrimal canal into the nasal cavity. It appears that a portion of the inferior nasal concha was removed to reveal the ostium of the nasolacrimal canal, and the middle and superior nasal conchae appear similarly to have been left off to indicate the opening into the maxillary sinus – this is somewhat large and the ethmoidal bulla is only vaguely indicated, and this area may have been damaged during the preparation of the skull. The dorsum sellae and crista galli are omitted.



13a The cranium sectioned

1489
Pen and ink
19.0 × 13.7 cm
RL 19058r; MS B.41r; O'M&S 6; K&P 42r

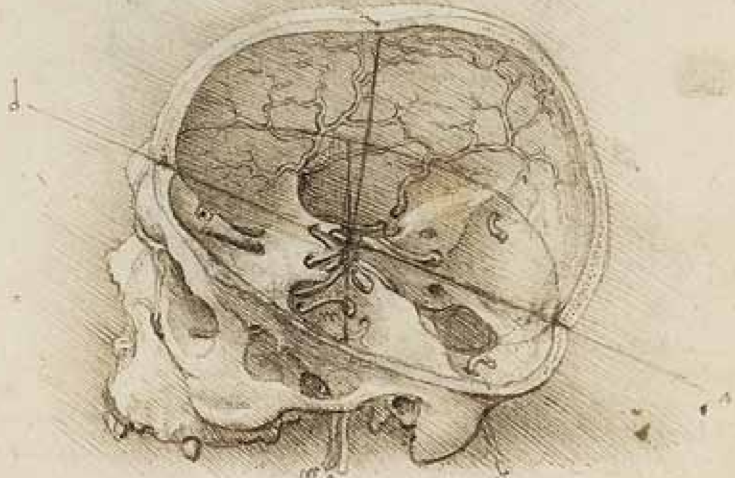
The cranium is in the same section as in the upper drawing of no. 12b, with the floor of the cranial cavity tilted a little further towards the viewer. Again, the site of the *senso comune* is indicated at the intersection of orthogonal axes. The note defines this position in proportional terms:

> The confluence of all the senses has below it in a perpendicular line the uvula, where one tastes food, at a distance of two fingers; and it is directly above the windpipe of the lung and the orifice of the heart by a space of one foot. And it has the junction of the bones of the head half a head above it; and in front of it in a horizontal line is the lacrimator of the eye at one-third of a head.

Leonardo was in all probability working with a dry skull, with the dura mater absent, and he attempted to infer the pathways of some of the nerves and vessels, with variable success. He drew the mastoid emissary vein *n* passing through the mastoid foramen, with its pair on the other side of the cranium, though he does not indicate their origin or destination. Two vessels labelled *a* and *m* travel to the middle of the cranium from below: *a* is probably the middle meningeal artery, seen entering the cranium through the foramen spinosum; *m* enters the cranium through the foramen ovale, where it then turns through 90 degrees and travels forwards to the floor of the orbit. That should be the infraorbital artery, which arises from the maxillary artery; but the artery that passes through the foramen ovale is the accessory meningeal, a separate branch of the maxillary artery.

Around the nose are the angular and dorsal nasal veins, with their connections to the frontal (supratrochlear) vein. Further vessels are shown ramifying on the inside of the frontal and parietal bones, and Leonardo discusses how these are partially embedded in the bone and covered by the meninges: 'The veins [they are in fact arteries] which are drawn within the cranium proceed in their ramification, imprinting half their thickness into the bones of the cranium, and the other half is hidden within the membranes which cover the brain.'

The optic nerves can be seen emerging from the optic foramina and converging on the supposed site of the *senso comune.* Immediately below are two further structures: the first is probably the oculomotor nerve (CNIII), with its pair just visible on the other side of the optic chiasm; the second is probably the maxillary (or possibly the ophthalmic) division of the trigeminal nerve (CNV; the mandibular division, which should pass downwards through the foramen ovale, is not shown).



13b The skull sectioned

1489
Pen and ink over traces of black chalk
19.0 × 13.7 cm
RL 19058v; MS B.41v; O'M&S 3; K&P 42v

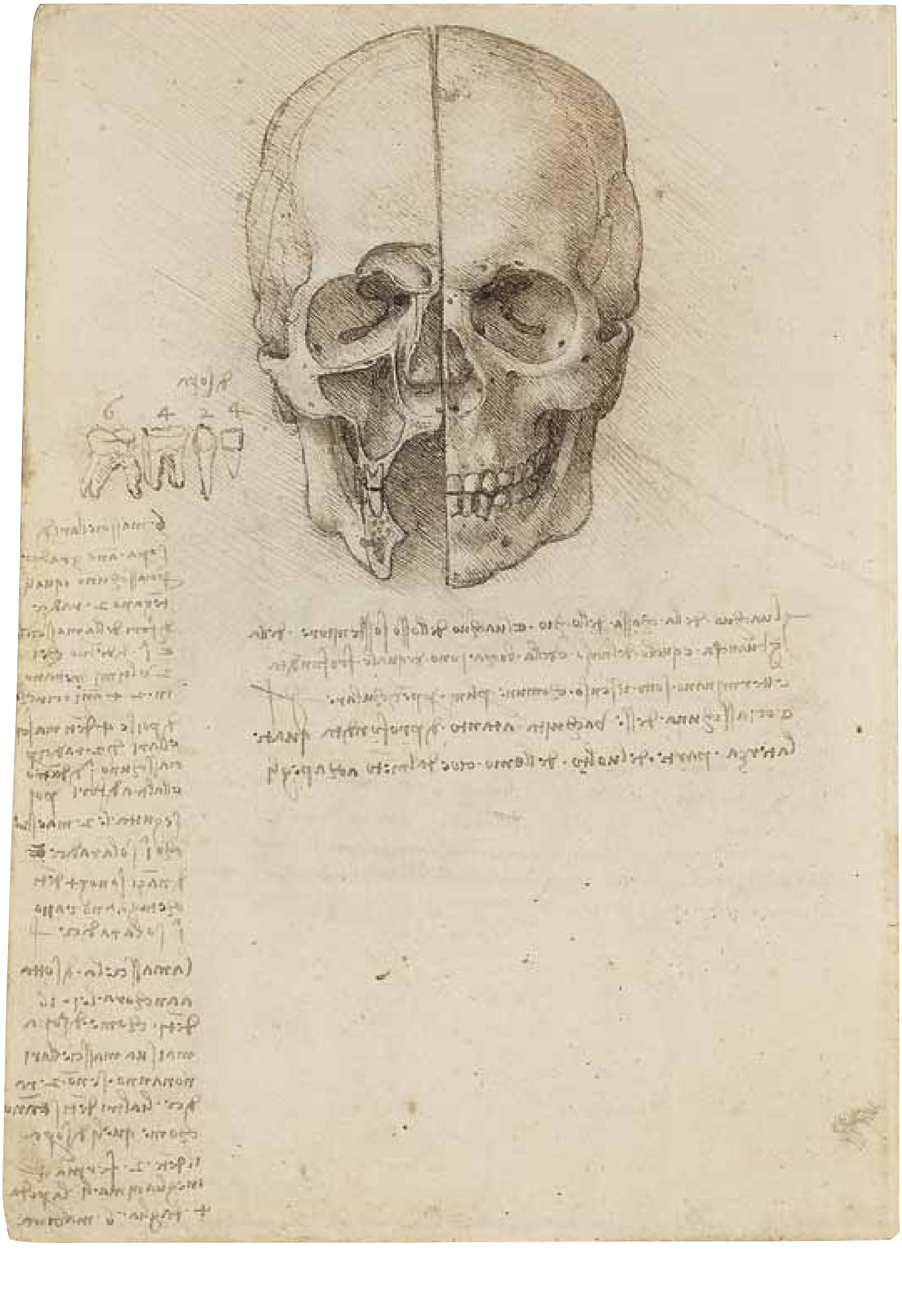
Here Leonardo first sawed the skull in the median plane, dividing it into equal left and right halves; then he sawed away the front of the right side of the skull – a very difficult operation, given the delicacy of the bones between the facial sinuses. By juxtaposing these two halves, the viewer is able to locate the cavities of the skull in relation to the surface features; covering the left (proper) side of the skull dramatically reduces the legibility of the demonstration.

The sectioned right side shows the frontal sinuses (at the level of the eyebrows) and the opening into their drainage duct. In the orbit of the eye can be seen the superior and inferior orbital fissures, the nasolacrimal canal leading into the inferior meatus of the nasal cavity, the infraorbital groove, and on the cut margin, the infraorbital canal. Below the orbit is the maxillary sinus and its opening into the nasal cavity. Two teeth are shown sectioned, with their roots. In the mandible or jawbone can be seen the mandibular canal and the mental foramen (the small hole connecting the mandibular canal with the surface of the mandible), and on the inside of the mandible is the profile of the mylohyoid line. On the intact left side of the skull are the supraorbital notch, the fossa for the lacrimal sac on the intact orbital rim, the canine fossa, the oblique line of the mandible, and the mental foramen.

In his note Leonardo relates the site of the *senso comune* to these cavities:

> The cavity of the eye socket, and the cavity of the bone that supports the cheek, and those of the nose and mouth, are of equal depth and terminate in a perpendicular line below the *senso comune*. And each of these cavities is as deep as the third part of a man's face, from the chin to the hair.

In the left margin Leonardo added stylised drawings of each of the different types of teeth – molar, premolar, canine and incisor – counting them in the note below to a total of 32, including the last molars or 'wisdom teeth'. While the correctness of this figure may seem trivial, there was no consensus at the time (probably due to the sporadic eruption of wisdom teeth), with some commentators repeating Aristotle's assertion that women have fewer teeth than men.



14 The layers of the scalp, and the cerebral ventricles

*c.*1490–92
Pen and ink, and red chalk
20.3 × 15.3 cm
RL 12603r; QA V.6v; O'M&S 142; K&P 32r

The principal drawing imagines the head sectioned through the middle, and in the left margin its layers are likened to those of an onion. Leonardo lists the layers in order: 'hair; scalp; muscular flesh; pericranium arising from the dura mater; cranium, that is, bone; dura mater; pia mater; brain'. This is essentially repeated in the detail to lower right, with dura mater and pia mater transposed. While most of these layers correspond with modern usage, Leonardo used the term pia mater to refer to what is now called the arachnoid mater (named as such by Frederik Ruysch in 1664); what we now call the pia mater is practically inseparable from the underlying brain and neural tissue, and Leonardo would have been unable to differentiate it as a separate layer of the brain. He correctly shows the dura mater extending along the optic nerve to the posterior surface of the eye. Even the globe of the eye is comprised of layers, as indicated; the lens, however, is not located in the center of the vitreous body as shown, but immediately behind the iris.

While the shape and extent of the cranial cavity are not particularly accurate, Leonardo has prominently indicated the frontal sinus, one of his discoveries from sectioning the skull in 1489 (no. 12b). The arrangement of the cerebral ventricles and sensory nerves is more conventional than in no. 5 and corresponds closely to contemporary images of the sensory apparatus (fig. 4). The diagram at lower right shows the head sectioned horizontally at eye level and the crown of the head flipped back: all the sensory nerves, not just the optic, converge on the first ventricle. It must be supposed that this last diagram was imaginary rather than recording an actual sectioning of the head performed by Leonardo, but its resemblance to a modern MRI scan (fig. 17) is remarkable.

production: please photosop background to lose edges of scan

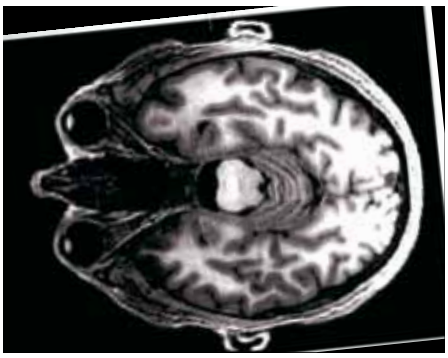
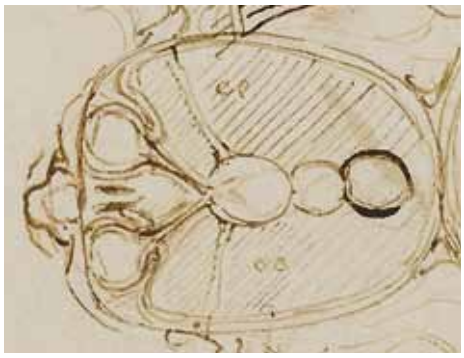


Fig. 17. MRI scan of the author's head
Image acquired by the Wellcome Laboratory of Neurobiology



Detail of no. 14

15 The proportions of a standing, kneeling and sitting man

c.1490
Pen and ink
16.1 × 21.8 cm
RL 19132r; QA VI.8r; K&P 27r

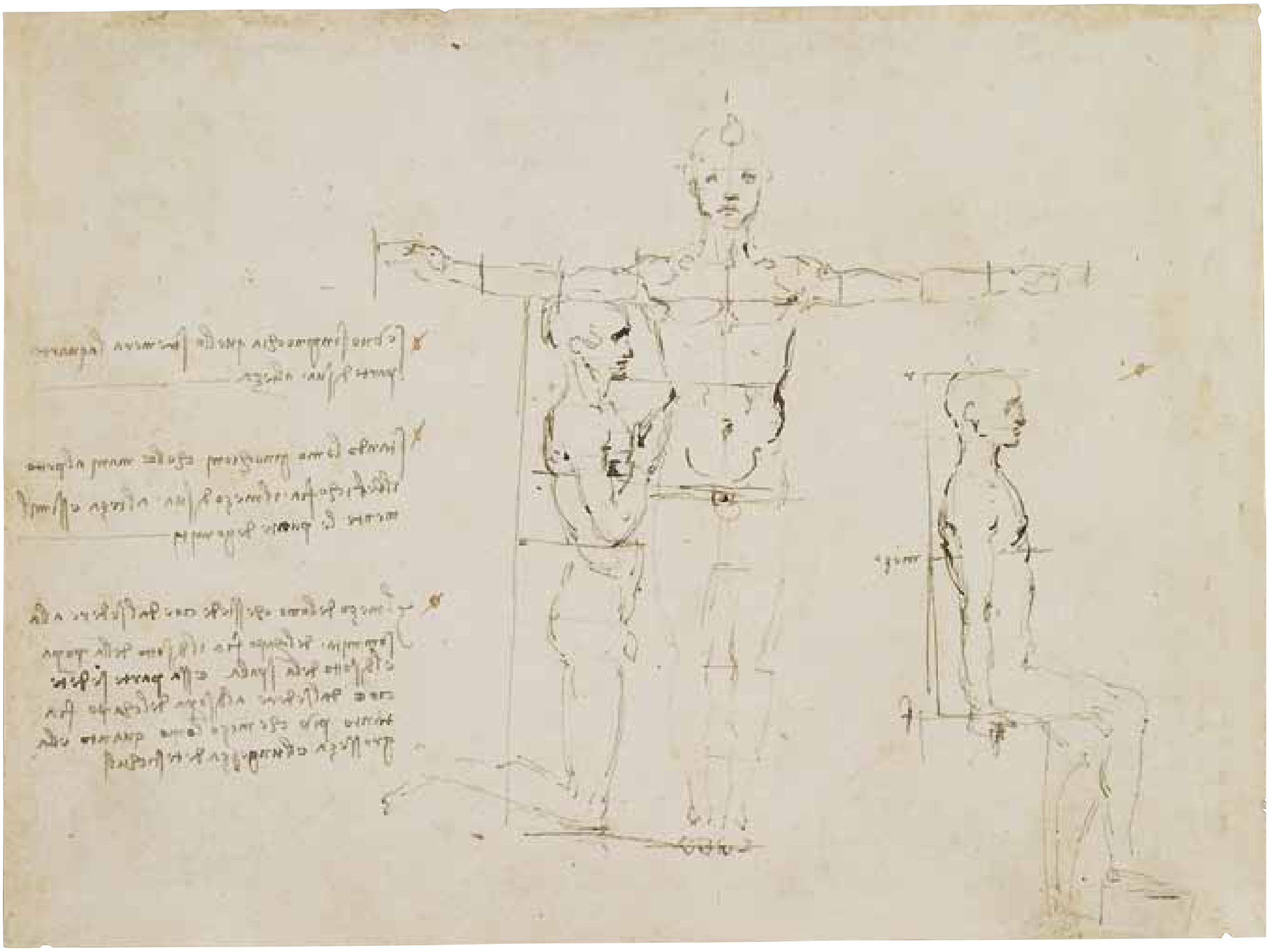
Nos 15 and 16 belong to a series of sheets that form Leonardo's earliest and most sustained study of human proportion. All the drawings in this series are executed schematically in pen and ink with no underdrawing and are neatly laid out on the page, suggesting that Leonardo was making a 'fair copy' of rough notes compiled elsewhere.

The system of proportions in the central drawing follows that of Vitruvius (see p. 13 above). The height of a man was the basic unit, equivalent to the span of the outstretched arms. A quarter of the height was the cubit, and Leonardo marked off the cubits horizontally at the knee, the pubis and between the armpits, and vertically at the elbows and the centre of the chest. These divisions are also shown and explained on Leonardo's drawing of the 'Vitruvian man' (fig. 6), along with the statements that the head is an eighth of the height, the face and the length of the hand a tenth, the width of the palm a twenty-fourth, and the finger a ninety-sixth. Leonardo departed from Vitruvius only in stating that the foot is a seventh of the height, whereas Vitruvius held it to be a sixth.

The notes to the left of the sheet explain the two subsidiary diagrams:

> If a man kneels he will diminish by a quarter part of his height.
>
> When a man is kneeling with his hands on his chest, the umbilicus is the middle of his height, and similarly the points of his elbows.
>
> The middle of a man who sits, that is, from the seat to the top of his head, is below the breast and below the shoulder. This sitting part, that is, from the seat to the top of the head, is as much more than half the man as is the size and length of the testicles.

Although the figures are sketchily drawn, Leonardo has accurately positioned the muscle masses and other landmarks such as the nipples, the umbilicus and the crease of skin over the inguinal ligament, which demarcates the boundary between abdomen and thigh; his predecessors (both artists and anatomists) had frequently erred in this basic topography.



16 The proportions of the leg and foot

*c.*1490
Pen and ink
40.4 × 28.1 cm
RL 19136–9v; QA VI.11v; K&P 31v

The simplicity of the Vitruvian precepts illustrated in no. 15 was abandoned when Leonardo began to measure an individual. Here his model is named twice as 'Caravaggio', taking his name from that town to the east of Milan.

The drawing is one of the earliest examples of overwhelming detail in Leonardo's scientific investigations. The notes beside the leg seen from the front read:

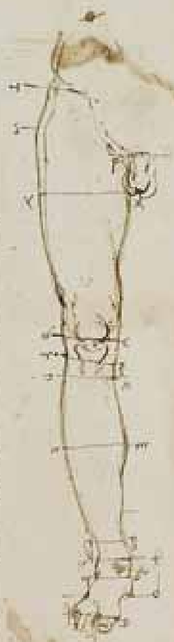
> *ac* is half a head, and is the same as *db,* and to the attachment of the five toes *ef.*
>
> *dk* diminishes a sixth in the leg at *gh.*
>
> *gh* is one-third of a head.
>
> *mn* increases by one-sixth from *ac* and is seven-twelfths of a head.
>
> *op* is one-tenth less than *dk* and is six-seventeenths of a head.
>
> *a* is in the middle between *q* and *b* and is one-quarter of a man.
>
> *r* is in the middle between *s* and *b.*
>
> The hollow on the outside of the knee at *r* is higher than the hollow on the inside at *a* by half the thickness of the leg at the foot.

And so on. However the study of a pulley to lower right is accompanied by a note on simple mechanics:

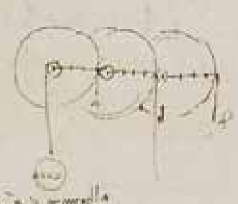
> Five men against one thousand pounds in one hour; one man in five hours; a fifth of the force of one man in twenty-five hours. And in this way it always goes, he who lightens the work prolongs the time.

In his later anatomical studies (e.g. no. 65a) Leonardo was to realise that such simple principles were a more productive application of proportional analysis than measuring the ankle in terms of seventeenths of the head.

Although the sheet is ostensibly concerned with external anatomy, Leonardo has in the drawing at upper left indicated some detail of the knee joint, and in the other two principal studies loose scribbles represent the position of the greater trochanter at the head of the femur. The drawings of a standing leg demonstrate the importance of aligning the parts when depicting stance, as was studied more explicitly in no. 23.



16.



17 The proportions of the head, and a standing nude

*c.*1490
Metalpoint and pen and ink on blue-grey prepared paper
21.3 × 15.3 cm
RL 12601r; QA VI.1r; K&P 19r

Here Leonardo attempts to find correspondences of length between parts of the face, without the use of fractions:

> It is as far from *a* to *b,* that is, from the start of the hair at the front to the line of the top of the head, as it is from *c* to *d,* that is, from the lower end of the nose to the junction of the lips at the front of the mouth.
>
> It is as far from the tearduct of the eye *m* to the top of the head *a,* as it is from *m* to below the chin *s*.
>
> *s c f b* are equal to one another as to distance.

Leonardo inked over the metalpoint outlines to clarify the diagram, adjusting the line of the back of the cranium to make the depth of the head (from the line touching the brow, lips and chin, thus omitting the nose) equal to the height of the face. He placed the eye at the mid-point of the head and divided the face into three equal sections, from the base of the chin to the base of the nose, thence to the brow, and thence to the hairline. Though we now tend to regard such proportional studies as trivial, a close attention to facial proportion is in fact of great importance to the profession of plastic and reconstructive surgery.

The head also displays prominently anatomical landmarks typical in Leonardo's work – the sternocleidomastoid and trapezius muscles, the superciliary arch and the angle of the mandible. The rough metalpoint sketch to the right again emphasises the importance of alignment of the parts in a convincing depiction of a standing individual.

v
v
p
f
m
c
d
s

18 A horse in left profile, with measurements

*c.*1490
Metalpoint and pen and ink on blue-grey prepared paper, the upper half damaged
32.4 × 23.7 cm
RL 12319; P.I.89

Alongside his studies of human proportion around 1490, Leonardo worked intensively on the proportions of the horse, prompted by a commission to sculpt a huge bronze equestrian monument to Francesco Sforza, the former Duke of Milan. Leonardo surveyed different breeds of horse, and the note above the main drawing here, '*gianecto grosso di messer galeazo*', records that his subject was a 'large jennet' belonging to Galeazzo da Sanseverino, the Captain-General of the Milanese army.

Leonardo's equine studies were fundamentally different from his contemporary studies of human proportion because the horse, unlike man, held no central place in the scheme of the universe, and could therefore not be expected to have any divinely harmonious relationships between its parts. To ascertain its form, abstract speculation was of no use: one simply had to measure the beast. The density of measurement in Leonardo's equine studies went far beyond what was of direct practical use to the artist, but they were methodologically in advance of his studies of the human form, for he was unencumbered by an urge to find correspondences and harmonic proportions.

Measuring a live horse must have been slow work, and it is probable that Leonardo annotated the drawings on the basis of measurements dictated to (or by) an assistant. The larger distances were presumably measured with a tape; the thicknesses of the legs were obtained with caliper compasses, four of which Leonardo drew in a notebook compiled at the end of the 1480s (Paris MS B, fols 52v, 57v, 58v). Leonardo used as his unit the horse's head or *testa* (measured from the tip of the muzzle to the base of the ears), divided into sixteenths and with subdivisions of these sixteenths expressed either as fractions (halves, thirds and quarters of a sixteenth, as seen here) or in terms of a unit itself one sixteenth of a sixteenth, and thus 1/256 of a head – less than 2 mm. This system is similar to that outlined by Leon Battista Alberti in his treatise *De statua* (*c.*1443–52), in which he moved away from a harmonic system of division of the human body, instead dividing each foot into 10 *unceolae* and 100 *minutae* of roughly 3 mm.

The sheet was folded in two before Leonardo began work on it, and further metalpoint studies in the upper half were effaced when the blue preparation was damaged by damp at some point in the sheet's history.

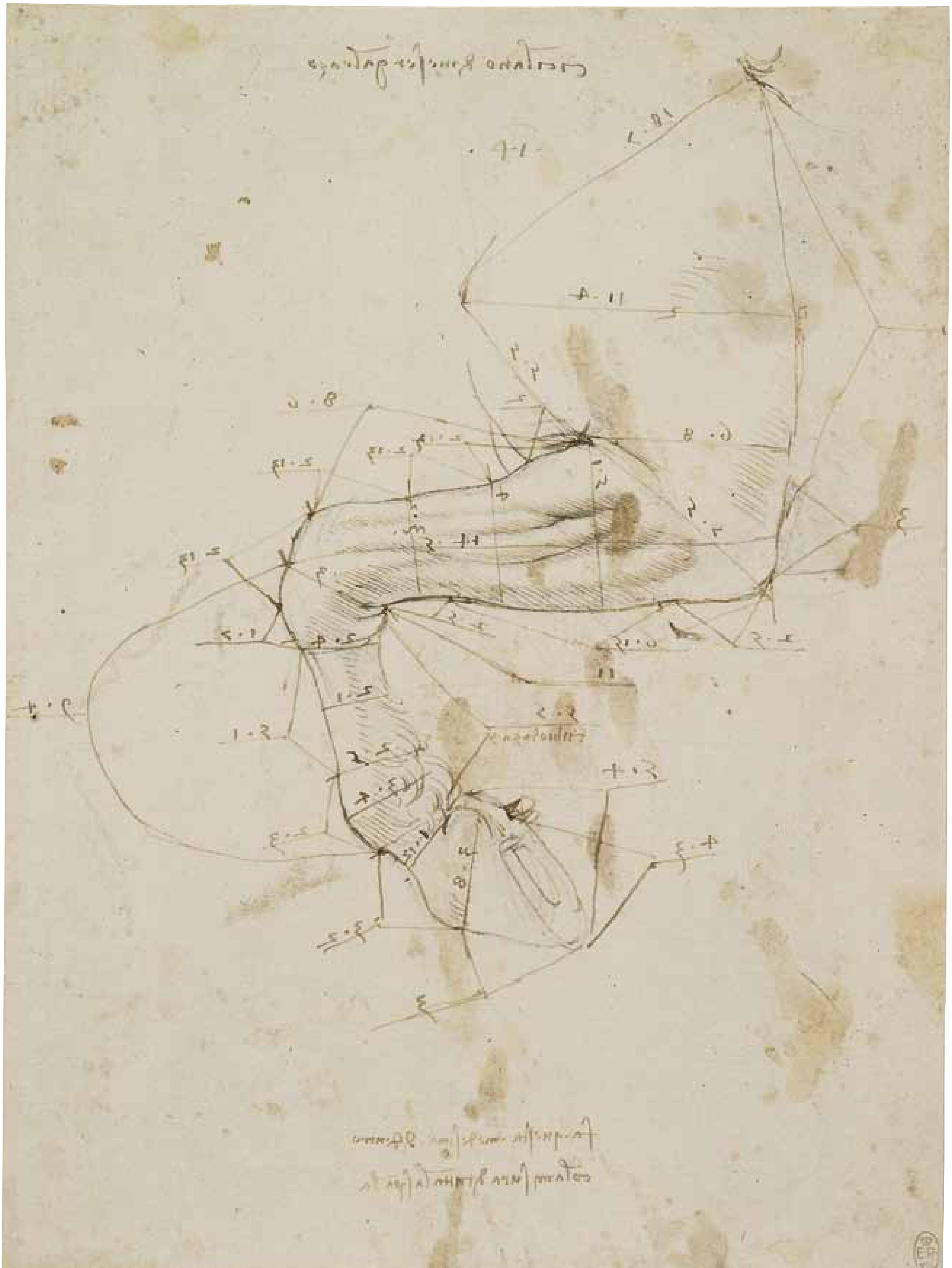
19 A horse's left foreleg, with measurements

*c.*1490
Pen and ink over charcoal
25.0 × 18.7 cm
RL 12294; P.I.94

Most of Leonardo's measured drawings of horses, such as no. 18, show the animal standing on all four legs, but several details study the dimensions of the raised left foreleg. This was the intended final form of the Sforza monument, as is seen in exactly this pose in a sketch of the frame for the transport of the clay model, where the hoof rests on a vase (Codex Atlanticus fol. 216v–a). In the note below the drawing Leonardo reminds himself to 'make this the same within [i.e. from the other side of the leg] with the measurement of the whole shoulder'. The drawing is also labelled '*Cicilano dj meser galeazo*', identifying the model as a 'Sicilian' belonging to Galeazzo da Sanseverino (see no. 18), and the subject of many of Leonardo's equine studies (as recorded in a manuscript known as the Codex Huygens in the Morgan Library, New York, fols 71–3, 77, 80, 84, 86).

Leonardo's surveys of horses were drawn freehand and the measurements added – the drawings were not constructed from these measurements. Thus Leonardo never had to confront the real problems that would face an artist attempting to put together a horse (whether drawn, painted or sculpted) from such a plethora of dimensions. If the measured drawings were used at all during Leonardo's preparations for the Sforza monument, it is more likely that they served as a check on the dimensions of the clay model. The statue was to be about three times life size, and errors of proportion would have been difficult to apprehend when working close to the clay model.

Here Leonardo used the same system of measurement as on no. 18, with the basic unit one sixteenth of a head, subdivided into further sixteenths; for example, he gives the length of the upper profile of the foreleg as '8.6', that is, eight sixteenths and six sixteenth-sixteenths, or 0.523 of a head. While his focus was on the dimensions, Leonardo was also careful to model the superficially visible muscles accurately, and extensor carpi radialis, common digital extensor and ulnaris lateralis are all prominent in the foreleg.



20 The head of Judas

*c.*1495 or later
Red chalk on red prepared paper
18.0 × 15.0 cm
RL 12547

In the earlier phase of Leonardo's anatomical researches the link between his studies and his proposed treatise on painting was still frequently in evidence, for one of the aims of his anatomical research was to equip the artist with the knowledge necessary to produce convincing, 'truthful' depictions of the human form. Thus on nos 12b and 17 he studied the proportions of the head, on no. 4 some of the muscles of facial expression, and on no. 11b he reminded himself to study the expressions of laughter and wonder. The ultimate ambition of his neurological research was to relate the movements of the body to those of the mind.

In no artistic project was this ambition more fully realised than in the *Last Supper,* painted on the end wall of the refectory of Santa Maria delle Grazie in Milan and the greatest of Leonardo's paintings to reach completion. It was also the most overtly cogitated of his paintings, with an intensely complex interplay of gestures and expressions intended to convey the emotional drama of the scene. In his preparatory studies for the painting Leonardo took great pains to individuate the Disciples, both their characters (as implied by the permanent cast of their features) and their emotions (as expressed by their fleeting expressions and poses).

The present drawing corresponds to the head of Judas in the *Last Supper,* though it is not entirely clear whether it is a study for the painting or a record of the motif. While the modelling is entirely by Leonardo, the profile has been strengthened at a later date (probably by Francesco Melzi), which has rather flattened the effect – covering the profile greatly enhances the plasticity of the drawing. Judas's guilty shock at Christ's announcement of the imminent betrayal is conveyed by his strongly raised eyebrows and the tension in his neck muscles. It is there that Leonardo's knowledge of the deeper structures is evident. As usual, the sternocleidomastoid muscle is prominent, though the sternal and clavicular portions seem strangely divided below the angle of the mandible and the attachment of the sternal portion only is shown. Due to the depressed shoulder, the contour of the levator scapulae muscle is also seen.

But it cannot be argued that Leonardo's anatomical work in the previous decade really paid dividends in his artistic projects. Here, and even in his most overtly anatomical painting, the *St Jerome,* there is little that could not be ascertained by superficial examination. By the middle of the 1490s Leonardo's anatomical work had apparently fizzled out. Its revival a decade later was prompted by another artistic project, but Leonardo's great achievements in the field of anatomy could come only when he severed the link to painting and studied the subject as an end in itself.

21 A male nude, and a partial study of the left leg

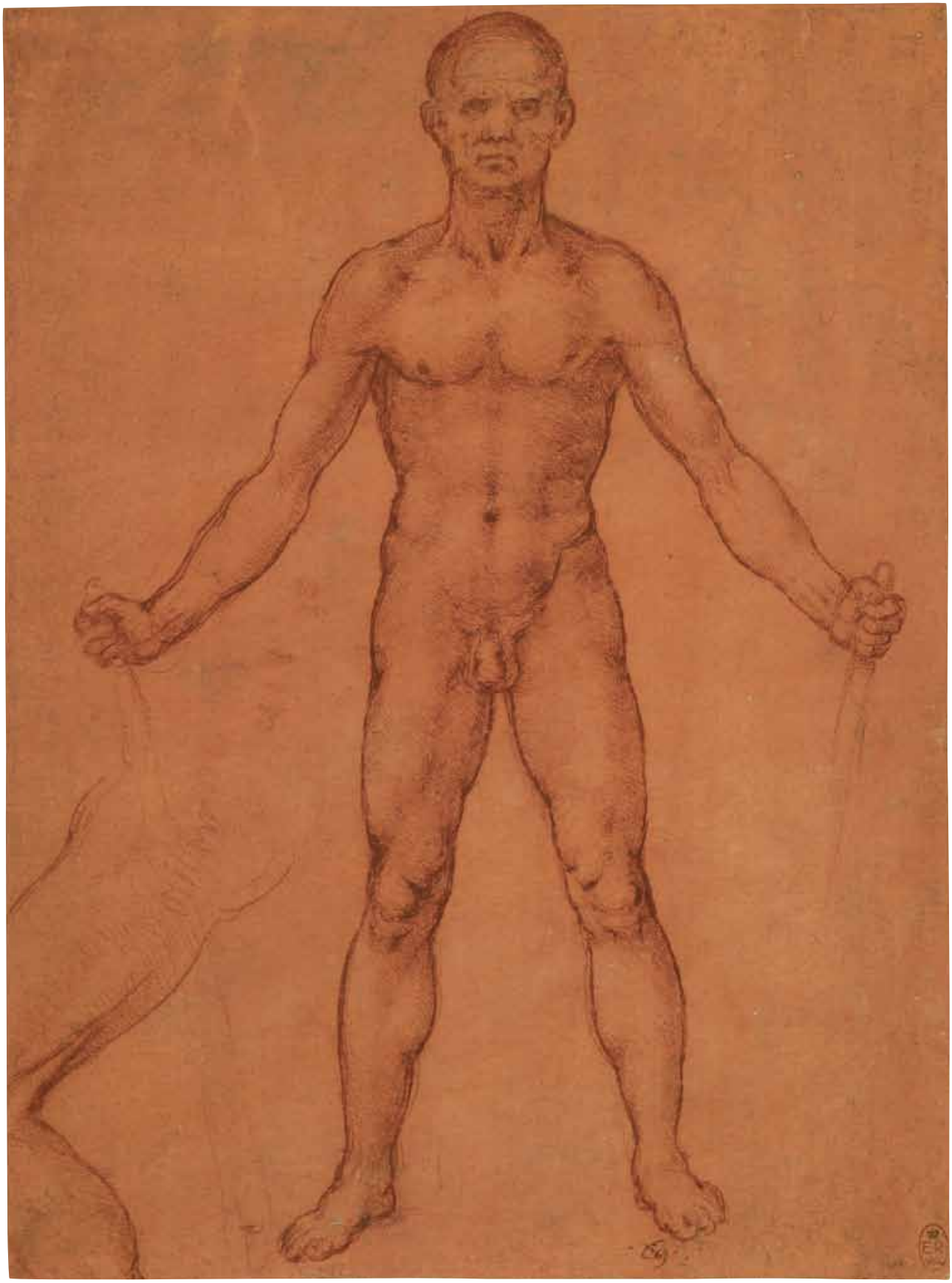
*c.*1504–6
Red chalk (partly wetted) on red prepared paper
22.6 × 16.7 cm
RL 12593r; K&P 85r

This drawing and no. 22 form part of Leonardo's background research towards the great mural of the *Battle of Anghiari,* commissioned for the Sala del Gran Consiglio of the Palazzo della Signoria in Florence in 1503. Here the model stands almost symmetrically, with his legs spread equally and his arms supported by sticks so as to put no strain on the shoulder muscles. Leonardo believed that while it was important for expressive purposes to know how to draw the muscles in tension, it was just as important to know how to draw them when relaxed:

> You should not make all the muscles of your figures conspicuous; even if they are shown in the correct place they should not be made too evident, unless the limbs to which they belong are engaged in the exertion of great force or labour; and the limbs that are not under strain should have no such display of musculature. If you do otherwise you will have produced a sack of nuts rather than a human figure.
>
> [Madrid MS II, fol.128r]

Numerous features demonstrate Leonardo's growing knowledge of the anatomical structures below the skin. In the neck the sternocleidomastoid and omohyoid muscles and the jugular notch are depicted; on the thorax are the anterior axillary folds caused by the underlying pectoralis major muscle; and on the abdomen can be seen the central linea alba, the prominences caused by the anterior superior iliac spines and the furrows of the underlying inguinal ligament. The long flexor tendons above the wrists are visible, and surrounding the knee are the vastus medialis and lateralis muscles, with rectus femoris between them. Below the patellas are protrusions caused by the tibial tuberosities.

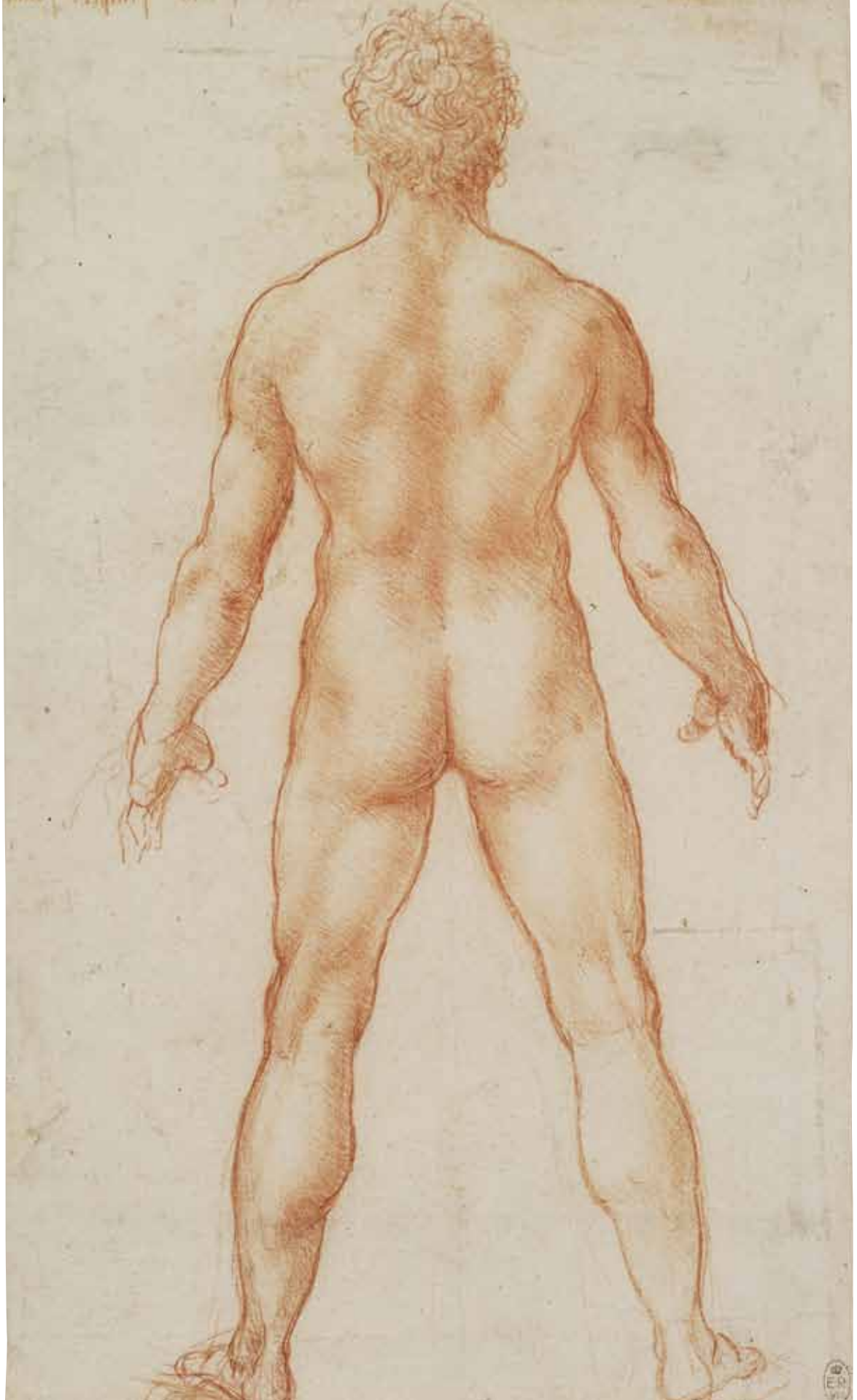
In the lower left corner is a cut drawing of a left leg flexed at the knee, emphasising the rounded inferior portion of vastus lateralis and the raised tendon of the long head of biceps femoris.



22 A male nude from behind

*c.*1504–6
Red chalk
27.0 × 16.0 cm
RL 12596r; K&P 84r

Though the shading of the body is very subtle, almost every superficially visible muscle mass is clearly depicted – artistic beauty and anatomical accuracy are here in perfect balance. In the back one can discern trapezius, latissimus dorsi and erector spinae; the inferior angle of the right scapula is emphasised, and in the arm, triceps is prominent. In the buttocks, gluteus maximus is well modelled, as are the 'hamstring' muscles of the posterior thigh – semimembranosus and semitendinosus medially and biceps femoris laterally. Below the popliteal fossa (the 'knee pit') are well-developed gastrocnemius and soleus muscles, and the elongated hourglass form of the Achilles or calcaneal tendon is accurately shown.



23 The muscles of the shoulder, torso and leg

*c.*1504–6
Pen and ink, and red chalk
16.1 × 15.3 cm
RL 12640r; QA VI.13r; K&P 82r

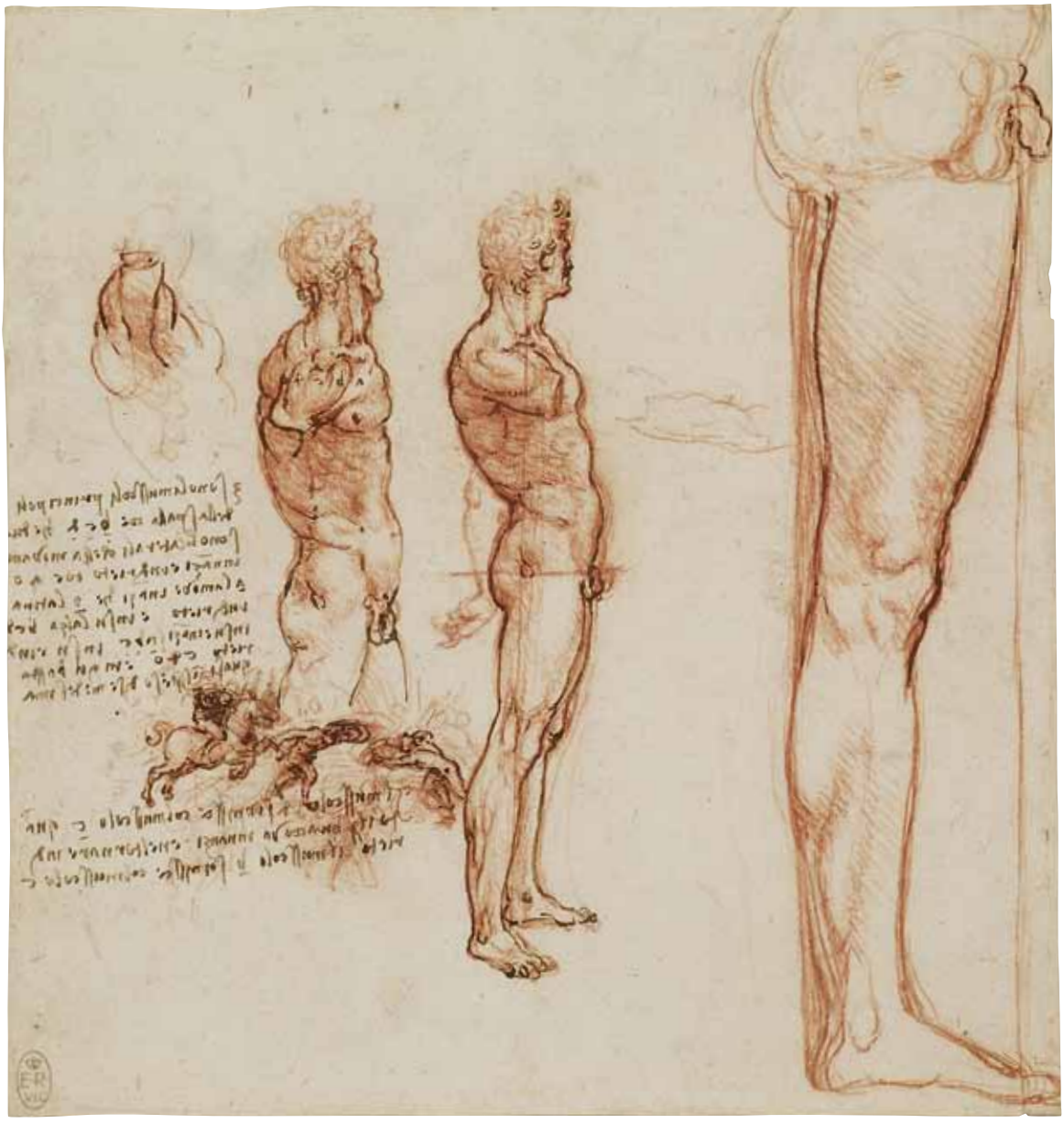
The sketch of a skirmish at lower left relates the anatomical drawings directly to Leonardo's work on the mural of the *Battle of Anghiari*. To the right is a study of the inside of the left leg, as if the body had been cut down the middle; a circle behind the genitalia is presumably intended to represent the bladder. In the lower thigh, the contour of the vastus medialis muscle can be seen, and behind the patella is a curving ridge probably due to the underlying tendons of sartorius, gracilis, semitendinosus and semimembranosus. On the lower leg the bulges of the gastrocnemius and soleus muscles can be distinguished.

Vertical lines travelling upwards from the heel and toe are connected with Leonardo's studies of posture; another vertical line in the drawing at the centre of the sheet demonstrates the principle that when a figure stands upright the head should be directly above the heel. A horizontal line on the same drawing, passing through the pubis and the greater trochanter of the femur, is at the mid-point of the body (cf. no. 15).

In the drawing to the left of this, the arm is again cut away to show the serratus anterior and external abdominal oblique muscles on the trunk. Five muscle bodies on the shoulder are labelled: *a* is the clavicular portion of pectoralis major and *b, c, d* and *o* are all portions of the deltoid, which Leonardo habitually treated as distinct fascicles (cf. no. 58b, in which the deltoid is divided up in an identical manner). Leonardo attributed different actions to the various portions of the deltoid:

> The principal muscles of the shoulder are three, that is *b c d;* and there are two lateral ones which move it forwards and backwards: *a* moves it forwards and *o* pulls it backwards; and *b c d* upwards; upwards and forwards, *a b c;* upwards and backwards, *c d o;* downwards, its own weight is almost enough.

While it is true that the portions of the deltoid have different actions, they do not in themselves explain the many actions of the shoulder. It would be five years before Leonardo dissected the deeper muscles of the shoulder, as depicted brilliantly on nos 52b–54.



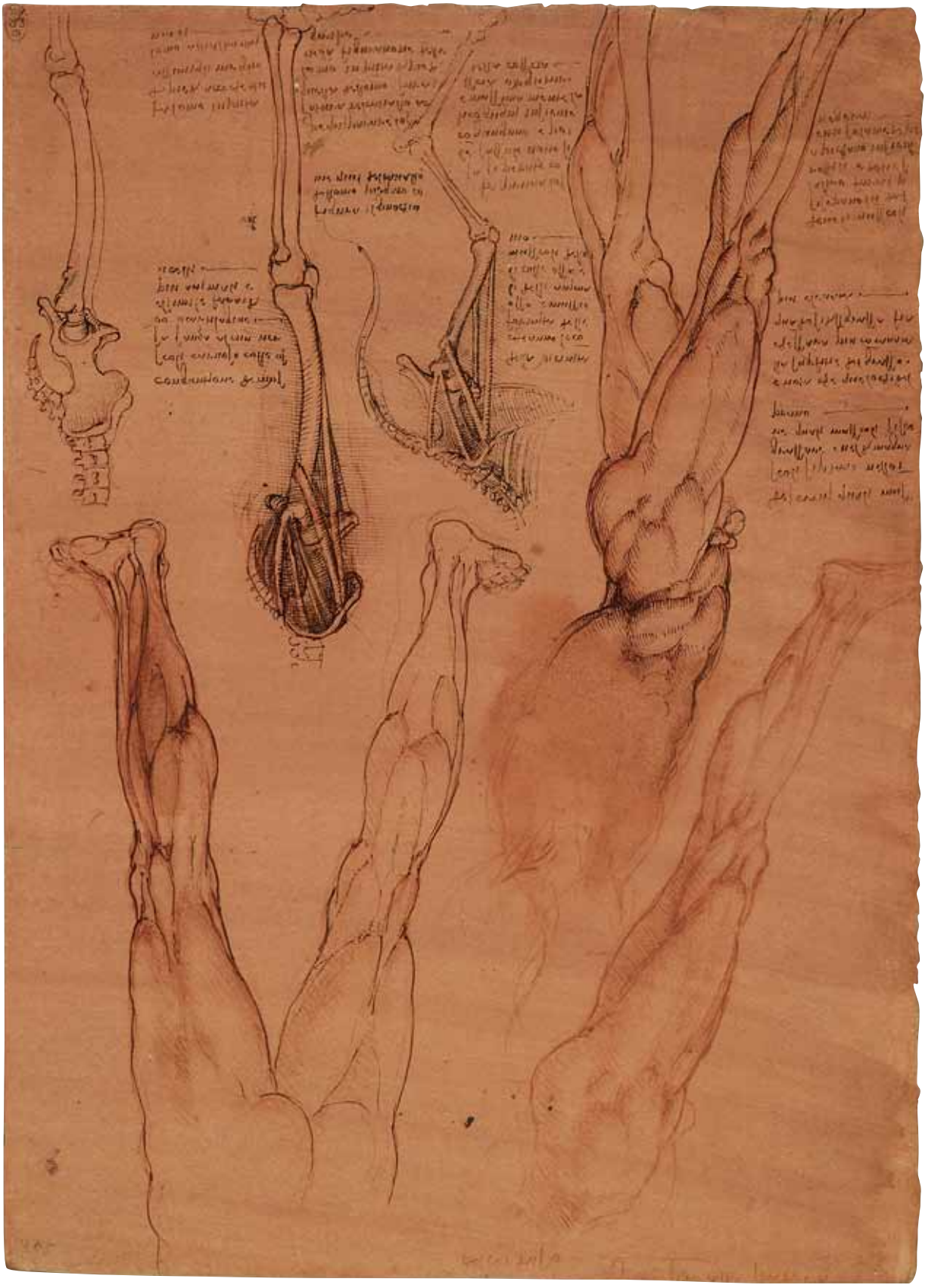
24 The leg muscles and bones of man and horse

*c.*1506–8
Pen and ink and red chalk on red prepared paper
28.2 × 20.4 cm
RL 12625r; QA V.22r; O'M&S 58; K&P 95r

The superficial drawings of legs belong to a long series of similar studies executed by Leonardo around the time of his work on the *Battle of Anghiari*. They are life studies informed by his knowledge obtained by dissection, though how much human dissection he had carried out by this date is unclear. He notes 'where the muscles are separated from one another you will draw in their borders', and he has thus exaggerated their boundaries. But as Leonardo was not able to differentiate easily between the subcutaneous fat and the muscle itself, the shapes of some of the muscles appear rather odd, especially the gluteal muscles in the buttocks and gastrocnemius and soleus in the lower leg.

The two studies at lower centre compare the pelvic and leg bones of man and horse – Leonardo notes astutely that 'to match the bone structure of a horse with that of a man you will have to draw the man on tip-toe in depicting his legs'. A few muscles are represented by threads: rectus femoris from the anterior iliac spine to the patella; tensor fasciae latae from roughly the same point towards the lesser trochanter of the femur (in the horse this trochanter is much more prominent than in the human); and the gluteal muscles, represented by a number of threads (two in the horse, four in the human) running from the iliac crest towards the greater trochanter. Leonardo had the same problem with the gluteal muscles as he did with the deltoid. The gluteals really are separate muscles, and usually the difference between gluteus maximus, gluteus medius and gluteus minimus is easily seen, but the more superior fibres of gluteus maximus can sometimes be confused with gluteus medius, and the cleavage fascia between gluteus medius and gluteus minimus continually confounded Leonardo.

The drawing at lower right has been called an 'anatomical fantasy', blending the bones of a horse with those of a man. It is much more likely that Leonardo intended it to be purely human, but incorporated errors (in particular the extended ischium below the coccyx; cf. no. 64b, in which the error is corrected) derived from his superior knowledge, at that date, of equine anatomy – the study of human bones and muscle threads to the left displays the same errors. Conversely, Leonardo's study of the horse here was to some degree compromised by his knowledge of human anatomy: the pelvis is too upright and not long enough, and the femur is too long and thin.



25 Notes on the death of a centenarian

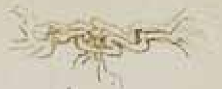
*c.*1508
Pen and ink over traces of black chalk
19.2 × 14.1 cm
RL 19027v; MS B.10v; O'M&S 128; K&P 69v

> And this old man, a few hours before his death, told me that he was over a hundred years old, and that he felt nothing wrong with his body other than weakness. And thus, while sitting on a bed in the hospital of Santa Maria Nuova in Florence, without any movement or sign of any mishap, he passed from this life.
>
> And I dissected him to see the cause of so sweet a death, which I found to be a fainting away through lack of blood to the artery which nourishes the heart and the other parts below, which I found very dry, thin and withered. I performed this dissection very diligently and with great ease because of the absence of fat and humours which greatly hinder the recognition of the parts. The other dissection was of a child of two years, in which I found everything contrary to that of the old man.

Thus Leonardo records, in the lower third of this sheet, the circumstances of the best-documented of his dissections, carried out probably during the winter of 1507–8. This is a page from the so-called Anatomical Manuscript B, which Leonardo had begun with his magnificent series of skull studies in 1489 (nos 11a–13b) and which had lain unused and mostly empty for almost twenty years. His resumption of the compilation of that notebook marks the beginning of five years' intense anatomical investigation.

As Leonardo describes above, he was able to make a thorough dissection of the 'centenarian', and several of the subsequent sheets in the notebook are labelled *'del vechio'*, 'of the old man' (nos 26, 30, 31a, 35, 37, and others not in the exhibition). Some of those drawings demonstrate that his subject had been suffering from cirrhosis of the liver and associated portal hypertension, and the passage at the head of the sheet gives the earliest known description of this condition:

> The artery and vein which in the old extend between the spleen and liver generate so thick a coat that it closes the passage of blood from the mesenteric veins through which blood passes to the liver and heart and to the two great vessels, and thus through the whole body. And these veins, as well as thickening the coat, grow in length and become twisted like a snake, and the liver loses the humours of the blood which was carried there by the vein, whence the liver is desiccated and becomes like congealed bran both in colour and substance, so that when but a little friction is made on it this substance falls away in minute particles like sawdust, leaving behind the veins and arteries.



26 The vessels of the neck and shoulder

*c.*1508
Pen and ink over black chalk
19.0 × 13.9 cm
RL 19049v; MS B.32v; O'M&S 121; K&P 58v

Leonardo labelled this drawing *'del vechio'* and thus it purports to show the arteries and veins of the neck, shoulder and upper arm of the 'centenarian' (see no. 25):

a are the ramifications of the artery
b is the ramification of the veins
c is the cephalic vein
n are the two vessels which enter the cervical vertebrae to nourish them
o is the basilic vein
s are the apoplectic vessels

The cut artery *a* is thus the aorta: its branching is symmetrically arranged (following a bovine rather than human pattern), giving rise to right and left common carotid and right subclavian arteries – the left subclavian is not visible in this drawing but its presence can be inferred. The superior vena cava, *b,* is formed from the union of the left and right brachiocephalic veins. The vertebral arteries *n* are a long way out of position, placed too high in the neck. The common carotid artery and internal jugular vein are the straight vessels passing to the right of *s;* to the left of *s* are the external jugular vein (receiving a branch from the posterior external jugular, running around the back of the neck) and an accompanying artery. In reality there is no artery that truly accompanies the external jugular vein – the only candidate is the thyrocervical trunk and its branches – but Leonardo believed that every vein was accompanied by a similar calibre artery. The arterial channel from subclavian to axillary to brachial is shown, along with the corresponding veins.

The note at upper left states:

> If you close the four vessels at *m* on each side of the throat, he who has them closed will fall to the ground immediately in sleep as if dead, and he will never wake up on his own. And if he is left for one-hundredth of an hour in such a condition he will never wake again, neither on his own nor with the help of others.

This describes the long-known phenomenon (described, for example, by Mondino) that pressure in this area can lead to unconsciousness. Rather than pressure on the vessels themselves, this is due to pressure on the baroreceptors of the carotid sinus, as had in effect been noted in antiquity: the Greek physician Rufus of Ephesus (*c.* AD 100) wrote in his treatise *On the names of parts of the human body* that 'the ancients called the arteries of the neck carotid [Greek *κάρωτιδες,* 'stupefying vessels'], because they believed that when they were pressed hard, the animal became sleepy and lost its voice; but in our age it has been discovered that this accident does not proceed from pressing upon these arteries, but upon the nerves contiguous to them' (as noted by Keele in K&P).

a
b
c
d
e

27 The vessels of the pelvic region

*c.*1508
Pen and ink over black chalk
19.2 × 14.0 cm
RL 19026r; MS B.9r; O'M&S 134; K&P 68r

These studies seem primarily concerned with demonstrating the symmetry and paired arrangement of the veins and arteries, in an area where bilateral symmetry is not the norm. In the upper drawing the abdominal aorta *a* and inferior vena cava *b* are shown in the correct relationship, and branching into the common iliac vessels; from these descend the internal iliac vessels, while lumbar vessels ascend on either side of the great vessels. The ascending lumbar veins are wonderfully drawn, but the accompanying arteries are imaginary. The deep circumflex iliac artery and vein are prominent in both studies, passing around the right side of the hip and labelled 'inguinal vessels to the flanks'.

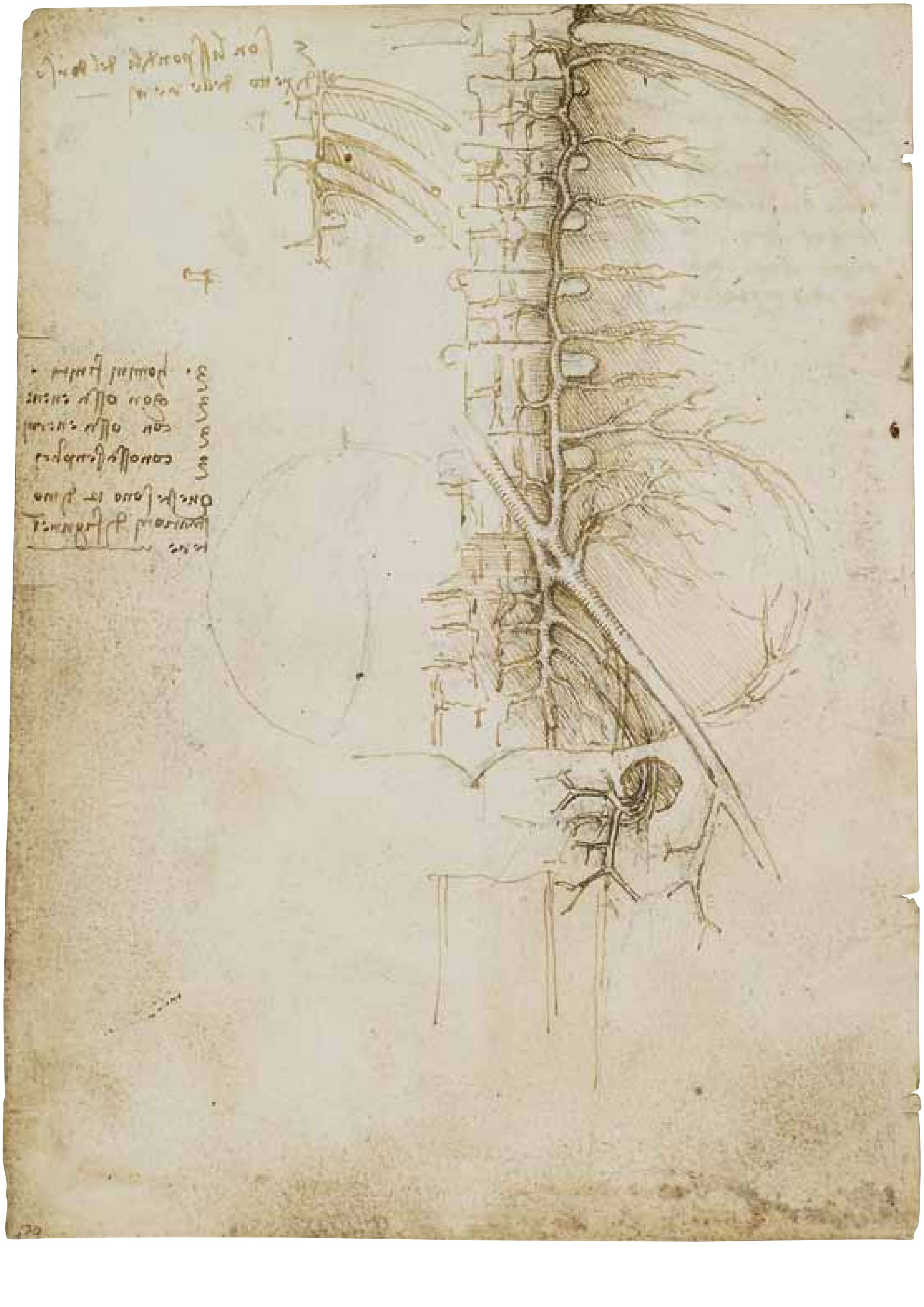
B. 9
P
V
P
V

28 The veins of the pelvic and lumbar region

*c.*1508
Pen and ink over black chalk
19.0 × 14.1 cm
RL 19023v; MS B.6v; O'M&S 135; K&P 65v

The principal drawing shows the lumbar region of the vertebral column from the front, with the sacrum and pelvic girdle lightly indicated and the last thoracic vertebra with ribs attached. Leonardo has drawn six lumbar vertebrae; though the note at top left gives the correct number in humans (five), six are usually present in horses, oxen and pigs, all of which were dissected by Leonardo. The obturator foramen (one of the pair of holes towards the front of the pelvis) is relatively small and round, which may also indicate an animal subject. The drawing, as usual, should probably be read as a synthesis of several dissections, both human and animal.

The focus of attention is an excellent depiction of the venous system. The left common iliac vein passes obliquely across the last lumbar vertebra and is shown splitting into three. The ascending lumbar vein passes alongside the spine to enter the thorax, where it is continuous with the hemiazygos vein and takes in the three lower posterior intercostal veins, as Leonardo has indicated in the detail at upper left. Tributaries from the external venous plexus are also shown on the anterior surface of the vertebrae. The internal iliac vein travels downwards in front of the sacrum, with many small tributary veins indicated, including what appears to be a double obturator vein passing through the obturator foramen (alternatively Leonardo may have mistaken the obturator artery for a second vein). The external iliac vein passes diagonally towards the leg, leaving the pelvis to split into the femoral vein and great saphenous vein at the lower right of the drawing.



29a The heart compared to a seed

*c.*1508
Pen and ink over black chalk
19.2 × 14.0 cm
RL 19028r; MS B.11r; O'M&S 119; K&P 70r

Here Leonardo attempted to resolve the ancient debate about the origin of the venous system (see no. 1) by appeal to the analogy of a plant:

> All the veins and arteries arise from the heart. And the reason is that the largest veins and arteries are found at their conjunction with the heart, and the further they are removed from the heart, the finer they become, dividing into very small branches. And if you say that the veins have their origins in the gibbosity of the liver because they have their ramifications there, just as the roots of plants have in the earth, the reply to this comparison is that plants do not have their origin in their roots, but the roots and other ramifications have their origin from that lower part of the plant which is situated between the air and the earth. And all the lower and upper parts of the plant are always less than this part which adjoins the earth … and in consequence, the veins take their origin from the heart, where they are biggest.

Accordingly at upper left Leonardo has drawn, on the left, the heart (labelled '*core*') with the vena cava and the hepatic and renal veins, and on the right a peach stone ('*noccolo*') with its branching stem and roots. The hepatic veins were analogous to the roots of the plant as the liver was believed to be the source of nourishment, which was carried by the venous system throughout the body (and indeed everything in the gastro-intestinal tract absorbed by the veins must travel through the liver). But Leonardo did not accord the heart undue importance: in a contemporary note on no. 35 he stated: 'The heart in itself is not the origin of life, but [simply] a vessel made of dense muscle vivified and nourished by an artery and a vein, as are other muscles.'

The principal drawing shows networks of veins entering the vena cava at two points: this may be intended as a double trunk to the hepatic vein (cf. the drawing at lower right on no. 30), but as the upper junction is opposite the right atrium it is more likely that Leonardo had confused the position of the right pulmonary vein, which actually returns to the left atrium. What appears to be a third 'great vessel' between the vena cava and aorta is the azygos vein (whose prominent arch is well depicted), shown as receiving intercostal venous drainage symmetrically and draining into the superior vena cava. A straight vein entering the vena cava at the junction of the brachiocephalic veins might be the thyroidea ima, present in a minority of human subjects. But the formation of the superior vena cava is too symmetrical (in humans the left brachiocephalic vein is long and oblique, and the right brachiocephalic vein shorter and almost vertical), and the aortic arch with its single branch is configured as in ungulates such as the cow.

B. 11

29b The vessels of the liver, spleen and kidneys

*c.*1508
Pen and ink over black chalk
19.2 × 14.0 cm
RL 19028v; MS B.11v; O'M&S 129; K&P 70v

Unusually, the drawings show Leonardo struggling to make sense of his dissection notes. The connections between the vessels are repeatedly drawn (both in chalk and in ink) and are thus rather confused in the upper two studies, and only in the third drawing does Leonardo arrive at a clear, if only partially correct, arrangement. The liver, on the left of that drawing, is small and the spleen enlarged, indicative of cirrhosis of the liver and associated portal hypertension.

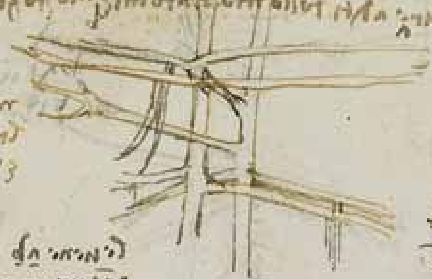
In the third drawing the aorta (on the right as we look at the drawing) gives off first the celiac axis, from which the common hepatic and splenic arteries arise (the left gastric is absent), then the superior mesenteric artery and lastly the renal arteries. The inferior vena cava receives the hepatic veins from the upper portion of the liver. The right gonadal vein is drawn as a long curve beginning by the right ureter and meeting the vena cava just below the hepatic vein. The left gonadal vein appears to overshoot its junction with the left renal vein, petering out around the splenic vein; but what Leonardo has actually shown there is a network of vessels in front of the spleen also draining into the left renal vein, and again possibly indicative of portal hypertension. The gonadal arteries are not shown.

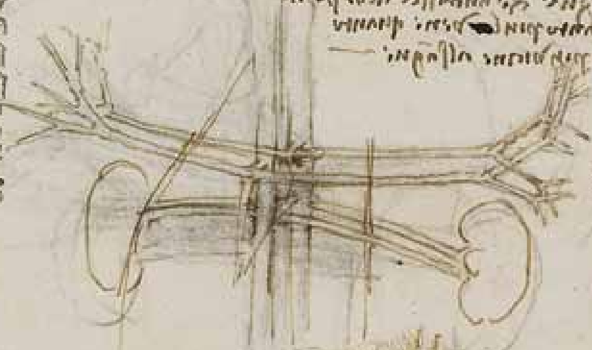
In the central sketch there appears to be an erroneous connection from the hepatic portal vein directly into the inferior vena cava – perhaps Leonardo was trying to find a venous analogue to the celiac axis. But the superior mesenteric vein is correctly shown uniting with the splenic vein to form the portal vein, as described in the note at lower left:

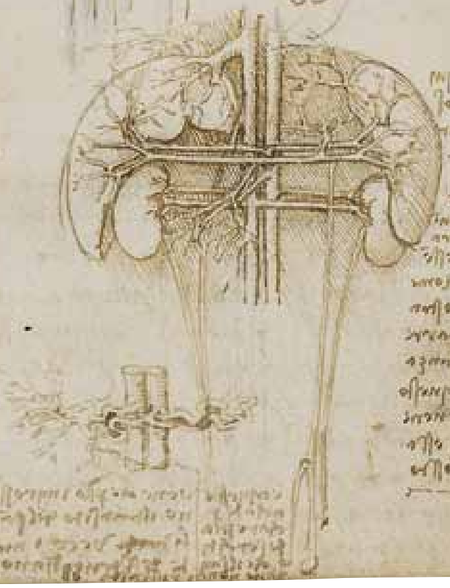
> The vein which extends between the gate of the liver and the gate of the spleen has its roots in five branches which ramify in the five lobes of the liver. In the middle of its trunk a branch arises [superior mesenteric vein] which ramifies in the nutriment at the base of the omentum extending to all its parts. And a little further along a branch rises upwards and is joined to the left lower part of the stomach [probably the short gastric veins]; and then it ends in two branches at its conjunction with the spleen, and goes ramifying through its substance.

Many of the other notes are concerned with the increasing tortuosity and constriction of the vessels in the elderly, as shown in the small detail at the bottom of the page. For instance, the passage at upper right asks:

> Why the veins in the aged should acquire great length, and those which used to be straight become so flexuous, and the coat thickens so much that it closes up and prevents movement of the blood. From this arises the death of the elderly without disease.







30 The vessels of the liver

*c.*1508
Pen and ink
19.1 × 13.5 cm
RL 19051v; MS B.34v; O'M&S 130; K&P 60v

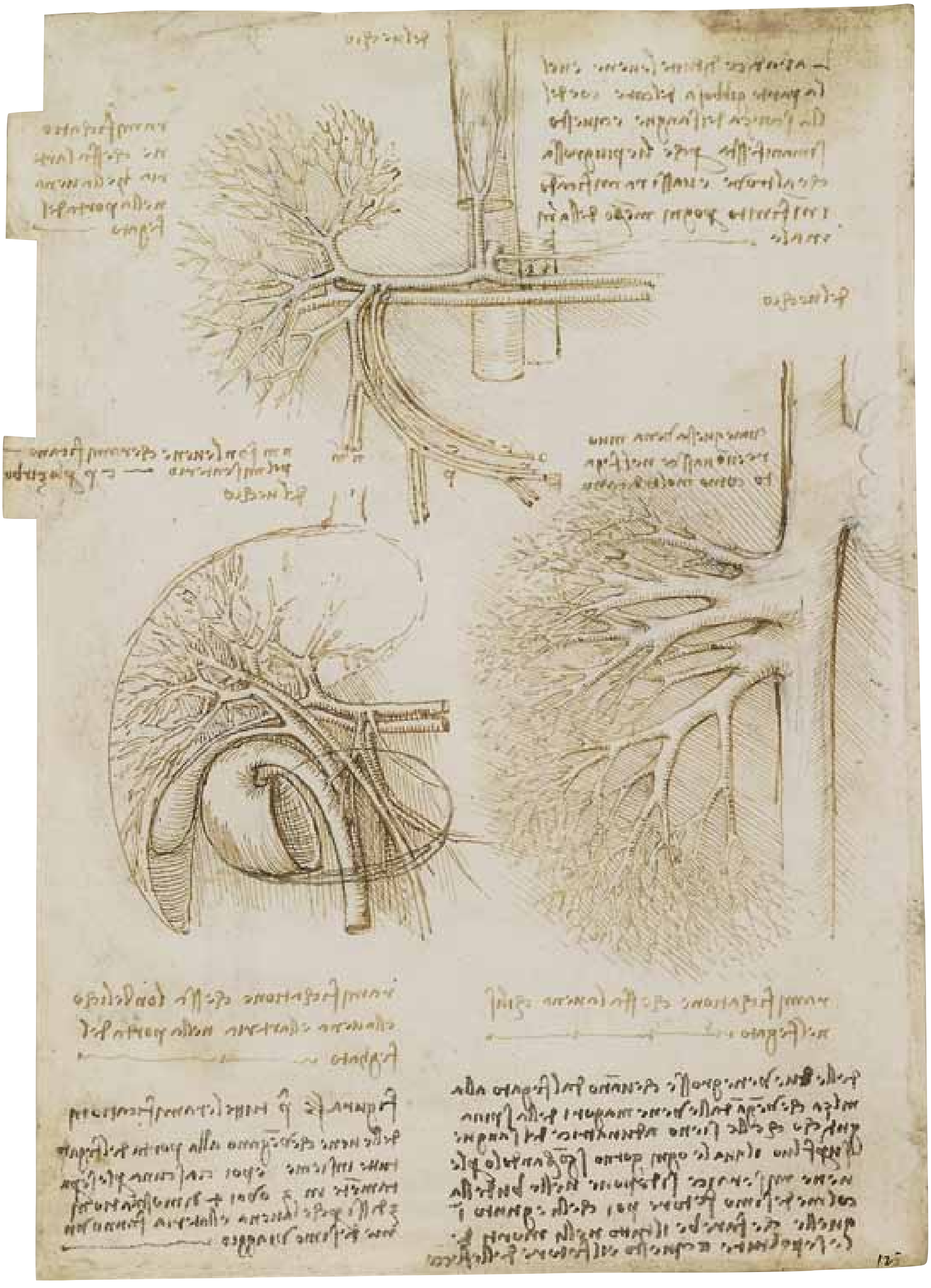
All three drawings are labelled *'del vechio'*, and thus continue the series of dissections of the 'centenarian' (no. 25). In the drawing at centre left, an enlarged umbilical vein is seen curving diagonally from the liver to lower right: although the umbilical vein closes after birth (remaining vestigially as the round ligament of the liver), portal hypertension in the cirrhotic subject appears to have forced the vein open again.

In the upper drawing the celiac axis is seen coming off the aorta (drawn incorrectly on the anatomical right of the torso) and splitting into the splenic and common hepatic arteries, drawn almost in a straight line; above their bifurcation is another branch, probably the left gastric artery. A smaller vessel branching off to the left (proper) from the celiac axis, almost at its junction with the aorta, could be the left phrenic artery or even an artery of the adrenal (suprarenal) gland. But the surrounding fascia of the aorta (tunica externa) is so thick in this area, and contains so many autonomic nerve fibres, that Leonardo's dissection would have been severely hindered unless he had completely removed it to expose the tunica media of the artery.

Branching downwards from the common hepatic artery are the right gastric artery (labelled *o* at its cut end) and the gastroduodenal artery, which in turn branches into the superior pancreaticoduodenal (*m*) and right gastric-epiploic (*p*) arteries, all with venous corollaries. Directly below the splenic and common hepatic arteries, the hepatic portal vein is shown as continuous with the splenic vein, with no contribution from the superior mesenteric vein. The convolutions of the duodenum and the intertwining of the mesenteric and hepatic portal vessels continue to provide today's anatomy students with difficulty, and faced with an extremely aged subject where atrophy or pathology could have complicated the anatomy, it is not surprising that Leonardo did not correctly illustrate this system.

In the drawing at centre left Leonardo has added the duodenum and outline of the stomach, and the gall bladder with its cystic duct merging with the hepatic duct to form the common bile duct. The bile duct is shown merging with the duodenum, but neither the pancreas nor the prominent junction of the pancreatic duct with the descending duodenum is indicated.

The drawing to the right shows the formation of the hepatic veins, an upper and a lower group, draining separately into the upper end of the inferior vena cava, just below its termination in the right atrium of the heart (indicated in the margin of the sheet).

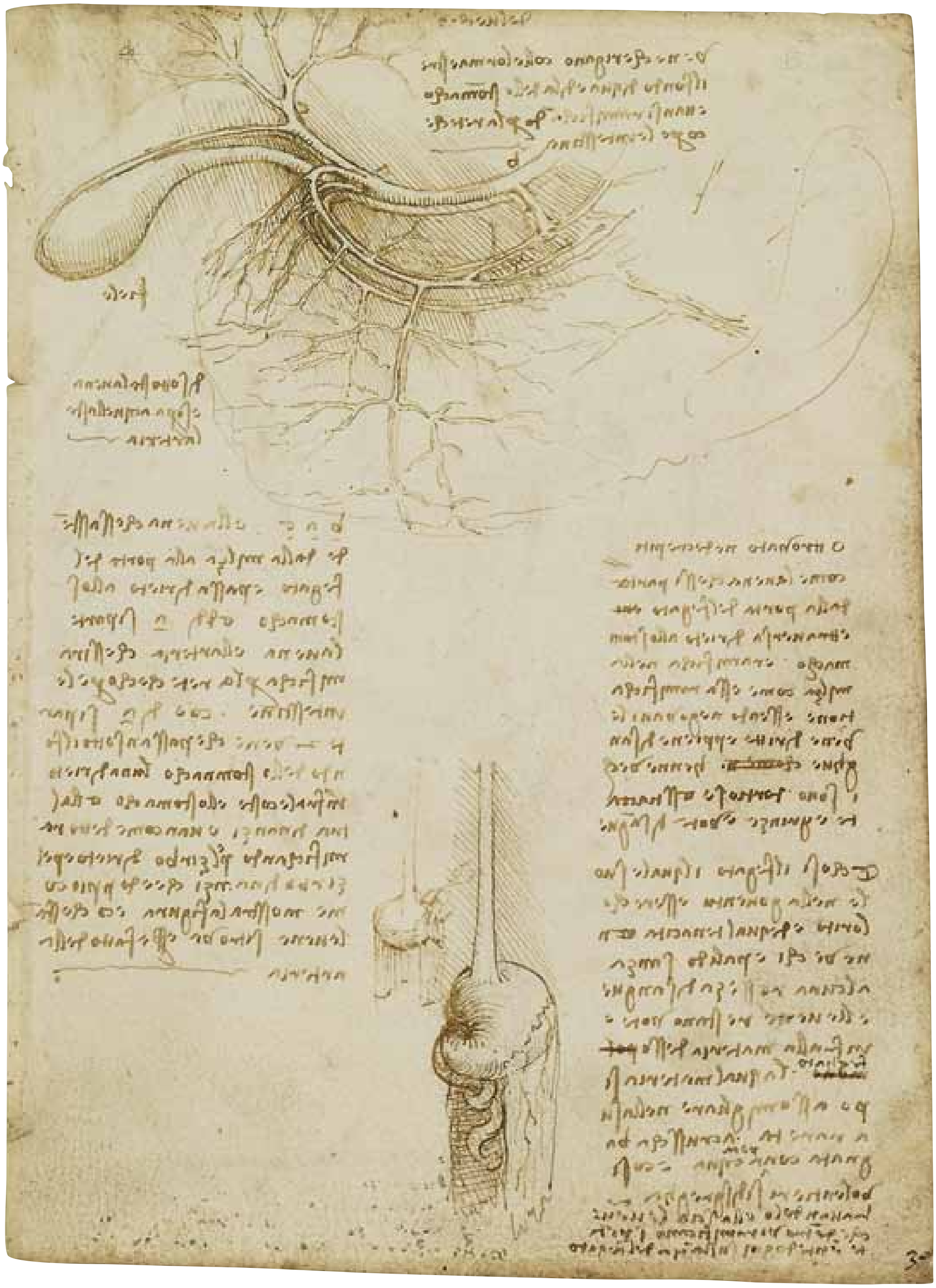


31a The stomach and related structures

*c.*1508
Pen and ink over traces of black chalk
19.2 × 14.1 cm
RL 19039r; MS B.22r; O'M&S 188; K&P 61r

The principal drawing (again labelled *'del vechio'*; see no. 25) shows details of the anatomy adjacent to the stomach and liver. The stomach is lightly outlined below and to the right of the drawing, and the liver is lifted away so that we are looking into the region between the two organs. The area of diagonal shading at the centre of the drawing corresponds with the lesser omentum, a clear membrane between the liver and the stomach and first duodenal segment. The gall bladder is to the left, with its duct and the cystic artery. The splenic and common hepatic arteries are drawn as if they were one continuous artery (labelled *c a b*), with the splenic and hepatic portal vein immediately below and partially obscured. The left and right gastric arteries branch off from the common hepatic artery at *b* and *a* respectively, their ramifications meeting on the lesser curvature of the stomach, with further branches spreading out over the surface of the stomach. The gastroduodenal artery should also begin around *a,* travelling behind the duodenum; possibly Leonardo has attempted to show the common hepatic artery trifurcating at that point, but the details are impossible to resolve.

Leonardo appears to have been confused by the various elements of the peritoneum, the membrane that forms the lining of the abdomino-pelvic cavity. In the larger drawing below, showing the stomach from the right, he correctly depicts the greater omentum attached to the stomach. The membrane apparently shown hanging down (shaded) behind the duodenum and first portion of small intestine is, however, incorrect – unless in the process of dissection a part of the peritoneum came loose from the posterior body wall. In the smallest, sketchiest drawing Leonardo seems to have illustrated the transverse mesocolon (the supporting mesentery of the transverse colon and part of the stomach) attached to the greater omentum, though lifted up; in its normal position it lies just below the stomach.



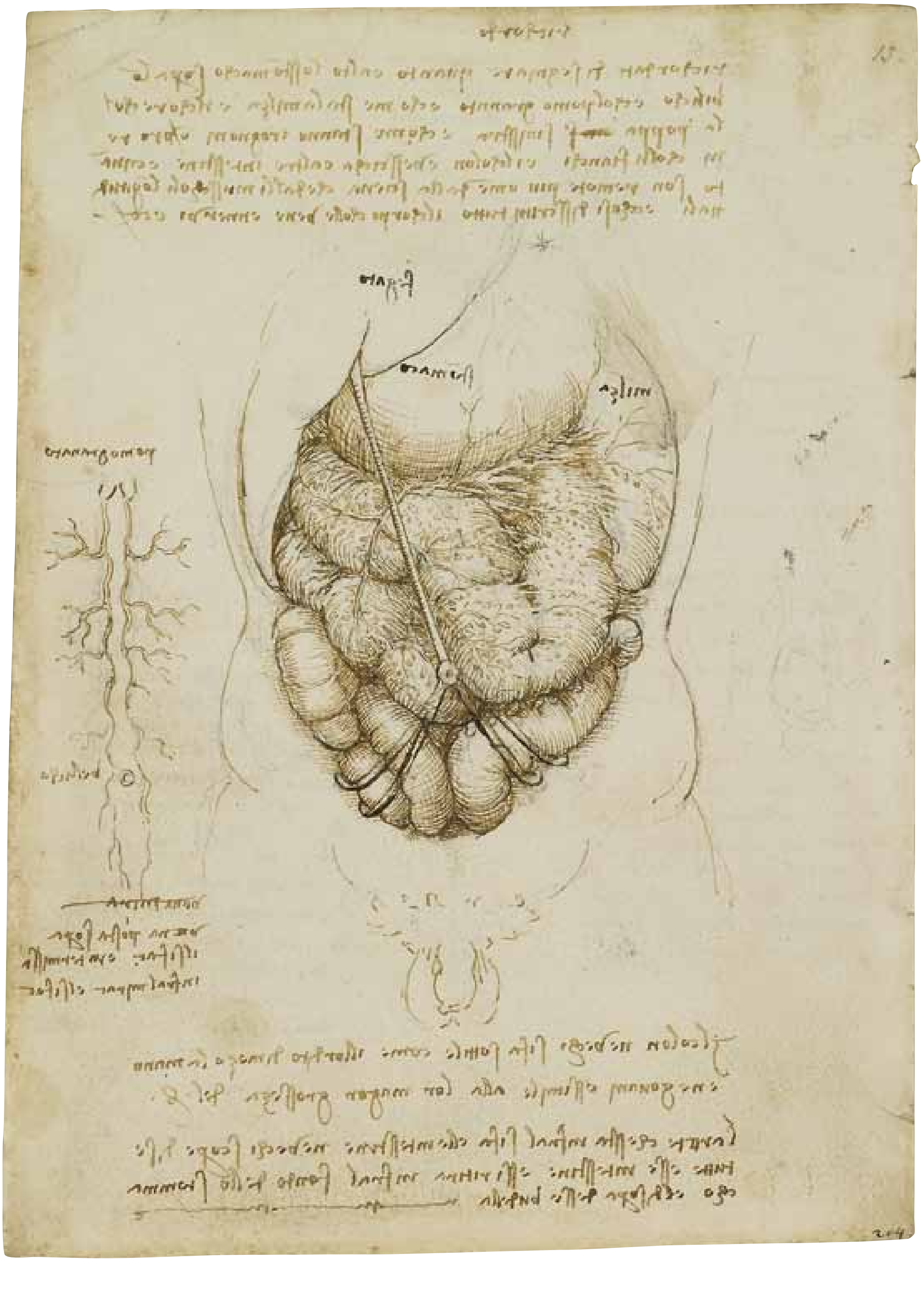
31b The abdomen

*c.*1508
Pen and ink over black chalk
19.2 × 14.1 cm
RL 19039v; MS B.22v; O'M&S 183; K&P 61v

The main drawing shows the abdomen from the front with the abdominal wall and peritoneum removed – Leonardo called these structures *'mirach'* and *'sifac'* respectively, the terms used by his principal source, Mondino, and derived from the Arabic of Avicenna and his peers. We see the liver *('fegato'),* stomach *('stomaco')* and spleen *('milza')* labelled above, with the membrane of the greater omentum rendered almost transparent and covering the small intestine. A note reads: 'the net [omentum] which lies between the *sifac* [parietal peritoneum] and the intestines in the old covers all the intestines and is drawn back between the bottom of the stomach and the upper part of the bowel [transverse colon]'.

Although Leonardo does not state that this depiction resulted from the dissection of the 'centenarian', the enlarged spleen and the presence of the umbilical vein indicate that it was based on that cirrhotic subject (see nos 28b and 30). Leonardo has also illustrated, below the umbilicus, two paired remnants of the umbilical arteries (the medial umbilical ligaments) wrapping around the colon – actually there is only one such structure on each side. Just to the anatomical left of the umbilicus is a large loop of what appears to be transverse colon. Below, Leonardo wrote 'the colon in the old becomes as slender as the middle finger of the hand, and in the young it is like the greatest thickness of the arm', but the intestines appear to be inflated with gas, as would happen as part of the putrefaction process.

In the drawing to the left, superior and inferior epigastric vessels (whether arteries or veins is unclear) are shown joining or anastomosing around the umbilicus. At the top of that drawing is the xiphoid process, at the end of the sternum, with a bifurcated form (a natural variation) and labelled with the picturesque term *'pomogranato'*.



32a The gastrointestinal tract

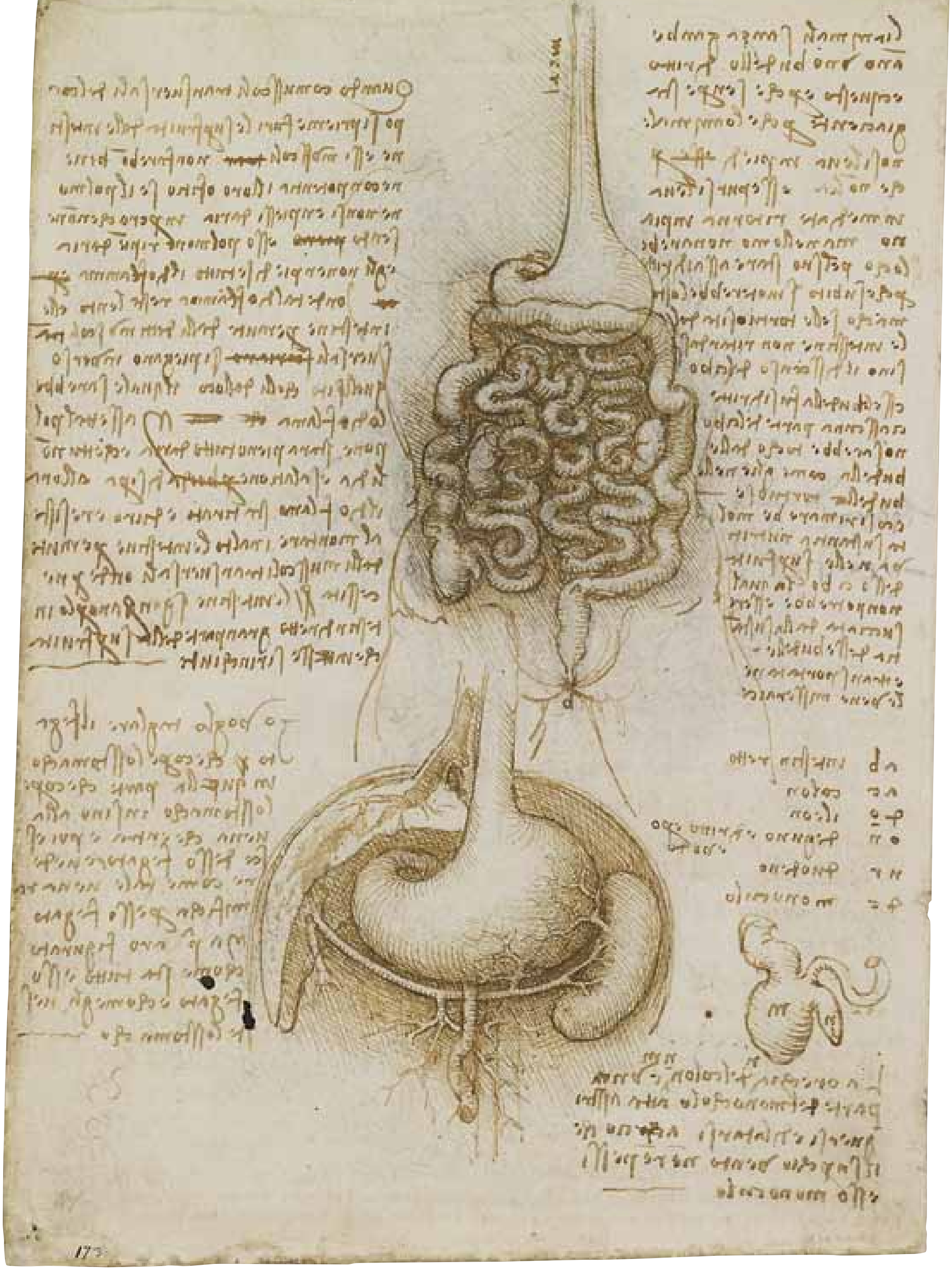
*c.*1508
Pen and ink over black chalk
19.2 × 13.8 cm
RL 19031v; MS B.14v; O'M&S 185; K&P 73v

The principal drawing depicts the stomach, the duodenum somewhat out of position, the jejunum, and the ileum in a somewhat schematised manner. The course of the large intestine is correct, though the epiploic appendices are not indicated. Attached to the cecum is the appendix, shown again in the detail at lower right – apparently the first depiction or description of this structure in Western medicine. Leonardo suggests that the function of the appendix is 'contracting and dilating so that superfluous wind does not rupture the cecum'.

In the note to the right Leonardo posits that the length and tortuosity of the alimentary tract is necessary to slow the passage of food, turning it around as it travels so that all of the food can make contact with the walls of the intestine; if the intestine were straight, gravity would cause the food to pass quickly through the body, and in the note to the right he states that the jejunum 'is upright and therefore empty'. But in the passage to the left he does go some way towards describing the process by which food is propelled along the tract, through peristalsis (the sequential contraction of smooth muscles) and the variations in pressure caused by the movement of the diaphragm in breathing:

> When with the transverse muscles the superfluities of the intestine are squeezed out of the body, these muscles would not perform this function well nor with power unless the lung were filled with air. If the lung were not filled with air, it would not itself fill up the whole diagram; the diaphragm would remain relaxed, and the intestines pressed on by the transverse muscles would move towards the side which gives way to them, which would be the diaphragm. But if the lung should stay completely full of air and you do not exhale it, then the diaphragm will stay taut and hard and resist the ascent of the intestines compressed by the transverse muscles, whence of necessity the intestines will rid themselves through the rectum of a great part of the superfluities contained within them.

The drawing at lower centre depicts the stomach, liver and spleen, with the splenic and superior mesenteric veins joining to form the hepatic portal vein. The short gastric veins drain from the left side of the stomach to the spleen, and what may be a gastro-epiploic vein drains from the middle lower part of the stomach into the splenic vein.



32b The gastrointestinal tract, and the bladder

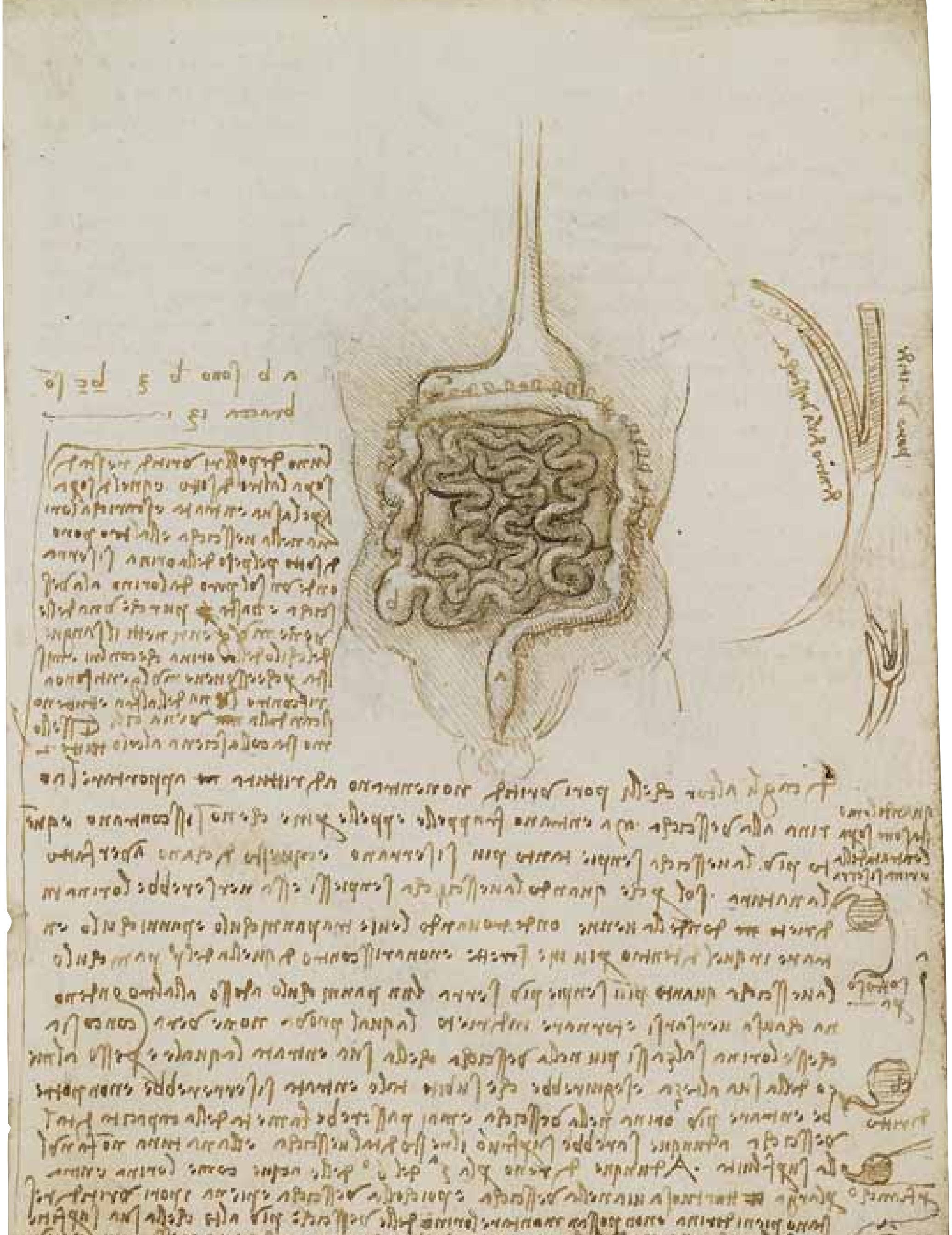
*c.*1508
Pen and ink over traces of black chalk
19.2 × 13.8 cm
RL 19031r; MS B.14r; O'M&S 192; K&P 73r

The principal drawing is a fine representation of the lower gastrointestinal tract. The stomach is attached (at *c*) to the duodenum in a human configuration, and thence connected to a somewhat schematised jejunum and ileum, with the kidneys visible behind. The cecum is at *b,* and the epiploic appendices of the colon are prominent. In the note to the left Leonardo gives the length of the small intestine as 13 *braccia* (about 7.5 m) and of the colon as 3 *braccia* (about 1.8 m), only a little in excess of the usual human dimensions.

The remainder of the page is concerned with the flow of urine from the ureters into the bladder. The diagrams at centre right are cross-sections of the ureterovesical valve, which prevents the passage of urine from the bladder back into the ureters; the ureteral lumen does travel obliquely through the bladder wall, but does not double back as sharply as drawn. Leonardo denied the traditional view that as the bladder filled, pressure on the lumen closed the valve, believing instead that gravity was solely responsible for the flow of urine from the kidneys to the bladder; unsurprisingly, he was unaware of the peristaltic contractions that propel urine along the ureters.

The marginal figures at lower right thus show the bladder with the body in various positions (upside down, upright, lying on one side, and lying on the front), and the long note reads:

> The authorities say that the passages of the ureter do not, in carrying the urine into the bladder, enter straight into it, but enter between one skin and another skin by ways that do not meet each other, and that the more the bladder fills the more they are closed. . . . This contention is not true, because if the urine were to rise in the bladder higher than its entrance, which is about the middle of its height, it would follow that this entrance would close and no more urine could enter the bladder, and it would never exceed half the capacity of the bladder. Therefore the rest of the bladder would be superfluous, and Nature makes nothing superfluous. Therefore we shall tell by the 5th [chapter] of the 6th [book] On Waters how urine enters the bladder through a wide and tortuous passage and how when the bladder is full the ureters remain full of urine . . . If a man lies down it can turn back through the ureters, and even more so should he be upside down . . . Where a man lies on his side one of the ureters rests above, the other below, and that which is above opens its entrance and discharges urine into the bladder, and the other duct below is closed by the weight of the urine, whence one single duct gives urine to the bladder, for it is sufficient that one of the renal veins should purify the blood of the vena cava of urine.



33a The bladder

*c.*1508
Pen and ink over black chalk
19.4 × 14.2 cm
RL 19054r; MS B.37r; O'M&S 190; K&P 53r

The page is headed 'Demonstration of the bladder of man'. It is one of the more formal and complete of Leonardo's anatomical sheets, and hints at how a page of his projected treatise might have appeared. The drawings are considered from left to right:

First demonstration

Of these three demonstrations of the bladder, in the first is drawn the ureters and how they leave the kidneys *L h,* and are joined to the bladder two fingers higher than the beginning of the neck of the bladder; and a little inside this junction these ureters pour urine into the bladder from *p b* into *n f* in the way drawn alongside, in the channel *s,* whence it is then poured through the pipe off the penis. It remains for me to draw and describe the situation of the muscles which open and close the passage of the urine into the mouth of the neck of the bladder.

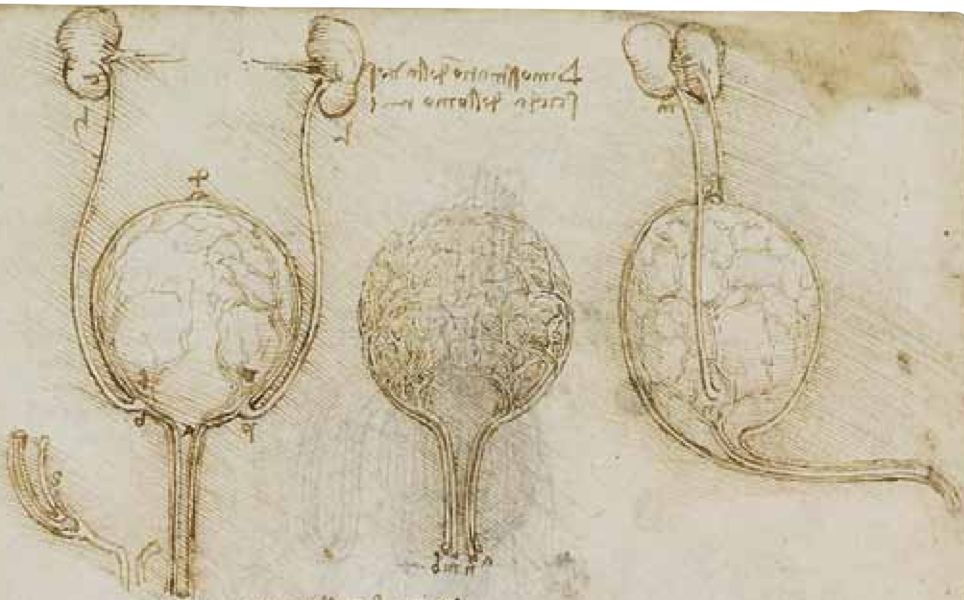
Second demonstration

In the second demonstration are drawn the four ramifications, that is the veins, right and left, which nourish the bladder, and the arteries, right and left, which give it life, that is, spirit; and the vein always lies above the artery.

Third demonstration

In the third demonstration is described the way the vein and artery go round the origin of the ureter *m n* at the position *n*.

The central drawing makes clear that Leonardo understood the blood supply as rising to the bladder wall along the line of the urethra. He presumably began the dissection from the exterior along the penis, and he may have found a minor connection from the testicular artery which would appear to course up and onto the bladder as he depicted – his dissection technique was good enough to observe fine vessels around the entrance of the ureters into the bladder. Somehow Leonardo missed the principal blood supply to the bladder, the superior and inferior vesical arteries, though in no. 44b a vessel is shown leading from what appears to be the common iliac artery to ramify on the upper part of the bladder.



33b The lungs

*c.*1508
Pen and ink over traces of black chalk
19.4 × 14.2 cm
RL 19054v; MS B.37v; O'M&S 171; K&P 53v

These schematic images attempt to convey the branching of the bronchi within the lungs. This branching is not visible on the surface of the lungs, and the drawings must be understood as an attempt to portray the system rather than the appearance of the lung.

It is not easy to comprehend the structure of the unfixed lung. The trachea divides into the two main bronchi much lower down than Leonardo has shown, between the lungs at the level of the sternal angle. These main bronchi then split into a number of secondary bronchi – in the human, three on the right and two on the left – which in turn split into tertiary bronchi, each of which supplies a bronchopulmonary segment. The drawings demonstrate that Leonardo appreciated the lobed structure of the lungs, but the relationship between these lobes and the branching of the bronchi is not even hinted at.

The study on the left shows the area from the front. To either side of the trachea are vessels standing for the common carotid arteries and their branching in the neck. The lungs are rendered semi-transparent to show the heart, oesophagus, aorta and vena cava, with hepatic veins travelling to the vena cava. In the drawing on the right, which shows the area from the right side of the body, Leonardo has labelled the structures – *'polmone'* (lung), *'feghato'* (liver), *'stomaccho'*, *'milza'* (spleen), *'diaflamma'* (diaphragm) and *'spina'* – with a key to the the structures of the neck – *'trachea'*, *'meri'* (oesophagus), *'ipopletiche'* (carotids), *'spina'* again, and *'spondili'* (vertebral processes). The length of these processes and the multiple lobes of the liver suggest that the subject of Leonardo's dissection was a pig, a favoured animal for anatomical investigation throughout the ages. He does not mention the animal in his notes on this page, but on another page in the manuscript (RL 19034r) he states that 'the enlargement of the lung when it is filled with air is latitudinal and not in its length, as can be seen by inflating the lung of a pig'.

Polmone destro
Polmone sinistro
Cuore

34 The nervous system

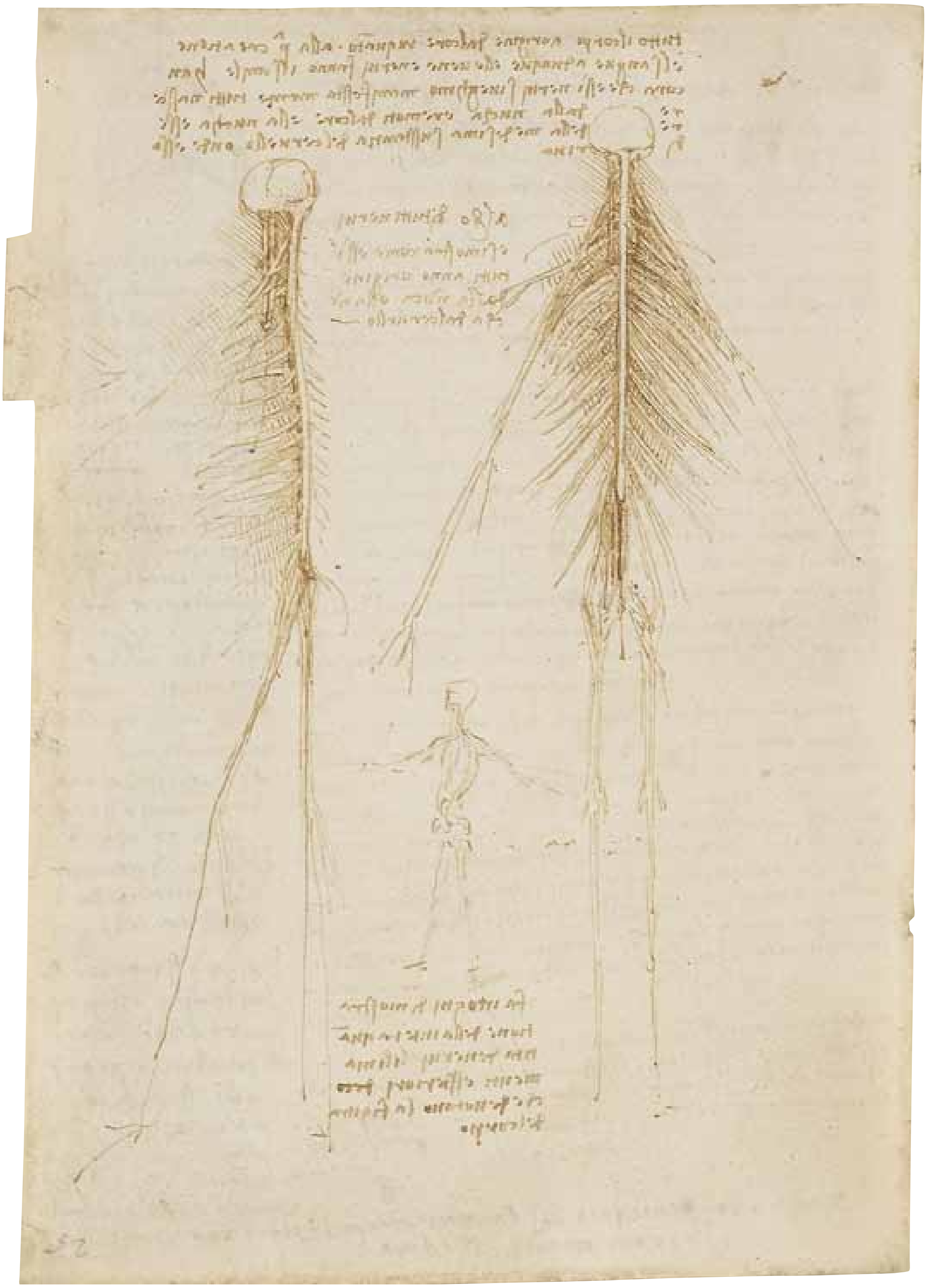
*c.*1508
Pen and ink
19.3 × 13.4 cm
RL 19034v; MS B.17v; O'M&S 144; K&P 76v

These drawings of the brain, spinal cord and spinal nerves, and a pair of cranial nerves are suggestive rather than detailed, but Leonardo has nonetheless managed to convey the complexity of the brachial plexus (nos 37–39b) and the lumbosacral plexus (no. 40a). At the lower end of the spinal cord he has indicated the filum terminale, a delicate fibrous strand that extends beyond the conus medullaris as far as the coccyx. Leonardo labelled the drawings: 'Tree of all the nerves: and it is shown how they all have their origin from the spinal cord, and the spinal cord from the brain'; nonetheless, both main drawings also show what are presumably the left and right vagus nerves descending directly from the base of the brain (seen in more detail on no. 35).

The drawings go some way to fulfilling a memorandum on no. 38a, to 'draw a man with arms open and with all his nerves and their uses. You should employ the most detailed diligence, especially for the reversive [recurrent laryngeal] nerves in all their ramifications'. Similarly, the sketch of the body at lower centre is annotated: 'In every demonstration of the whole extent of the nerves, draw the external outlines of the body which denote the shape of the body.' This sort of memorandum, in which Leonardo reminds himself about further illustrations, was to become one of the main themes of his anatomical notes in later years.

Fig. 18. Giovanni Leoni d'Este *John Evelyn's 'Anatomical table no. 1': the nerves*, *c.*1645–6
Human tissue mounted on pine board, 189 × 77 cm
Hunterian Museum, Royal College of Surgeons, London

The image bears a remarkable resemblance to John Evelyn's anatomical table of the nerves, now in the Hunterian Museum of the Royal College of Surgeons, London (fig. 18). The table is one of a set of four prepared by Giovanni Leoni d'Este, dissector to Johann Vesling, Professor of Anatomy at the University of Padua, and consists of the spinal cord and nerves of the trunk and limbs, dissected out, glued to a wooden panel and varnished. Evelyn attended Vesling's lectures in Padua and purchased the tables from Leoni in 1646; they appear to be the earliest surviving anatomical preparations in Europe, and hint at the sort of didactic material that the new wave of investigative anatomists might have prepared – with Leonardo, Marcantonio della Torre (p. 21) and, later, Andreas Vesalius in the vanguard.



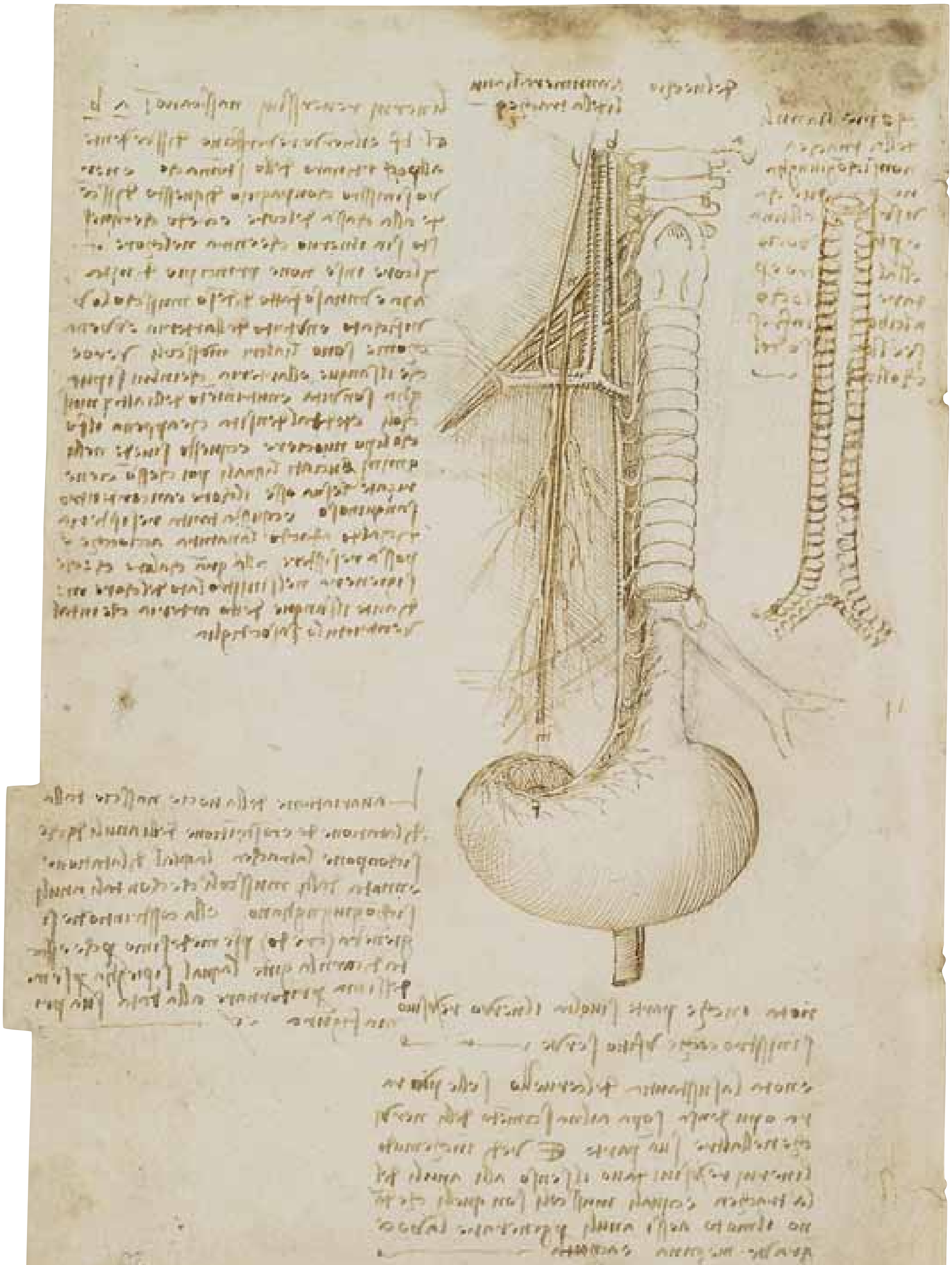
35 The distribution of the right vagus and right phrenic nerves

*c.*1508
Pen and ink over black chalk
19.3 × 13.3 cm
RL 19050v; MS B.33v; O'M&S 149; K&P 59v

The principal drawing (labelled *'del vechio'*; see no. 25) shows the trachea down to its bifurcation into the primary bronchi, below which the oesophagus is visible, leading to the stomach. Leonardo accurately follows the course of the right vagus nerve down the right side of the trachea, then along the oesophagus and finally around the lesser curvature of the stomach. Immediately to the left of the upper part of the nerve are the internal jugular vein and carotid artery, running vertically down to join the subclavian vein and artery and form the right brachiocephalic vein and artery respectively. Further to the left is the gently curving external jugular vein, with no accompanying artery.

Behind these vessels can be seen the brachial plexus (nos 37–39b), with the right phrenic nerve (the motor supply of the diaphragm) running from *n* to *m,* and accompanied by the pericardiacophrenic vessels, exaggerated in size. At about the mid-point of the trachea, the right recurrent laryngeal nerve can be seen branching off from the right vagus nerve and looping around the brachiocephalic vessels to travel upwards and innervate the trachea and larynx. Leonardo has confused the topography of this area: in reality the brachiocephalic artery and its branches lie *behind* their venous corollaries; the vagus nerve passes in front of the arterial branches, and the recurrent laryngeal nerve loops backwards underneath them.

The note below reminds Leonardo to 'observe in what way the reversive [recurrent laryngeal] nerves give sensation to the rings of the trachea, and which muscles give movement to these rings in order to produce a deep, medium or high-pitched voice' (cf. no. 51). The diagram to the right shows a longitudinal section of the trachea and proximal bronchi, with the cartilaginous structures commonly referred to as tracheal rings. These are in fact 'C' shaped and incomplete towards the spine; Leonardo suggests that this is 'to give room for the food [in the oesophagus] between themselves and the bone of the neck'.



36 The cranial nerves

*c.*1508
Pen and ink over traces of black chalk, with scratching out
19.0 × 13.6 cm
RL 19052r; MS B.35r; O'M&S 148; K&P 55r

Here Leonardo describes his method for dissecting the brain:

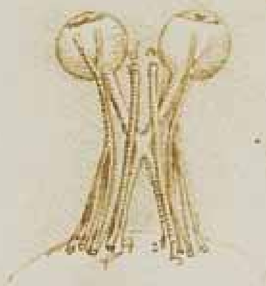
> Ease away the brain substance from the borders of the dura mater which lies between the basilar bone and the brain substance. Then note all the places where the dura mater penetrates the basilar bone with nerves ensheathed in it together with the pia mater … diligently raise the pia mater, commencing from the edges and noting bit by bit the situation of the aforesaid perforations, commencing first from the right or left side, and drawing this in its entirety; then the opposite side, which will give you knowledge of whether the first was correctly situated or not; furthermore, you will come to understand whether the right side is the same as the left. And if you find differences, review the other dissections to see whether such a variation is universal in all men and women.

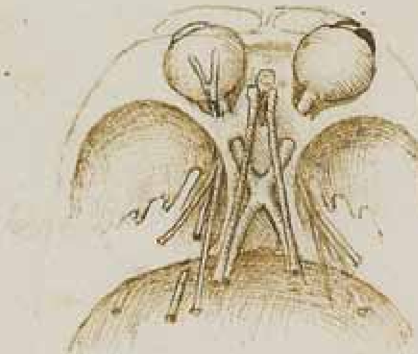
This meticulous technique allowed Leonardo to attain a surprisingly sophisticated understanding of the cranial nerves, despite the difficulties of dealing with soft, unfixed brain tissue. As in no. 14, by 'pia mater' Leonardo means the membrane that we now term the arachnoid.

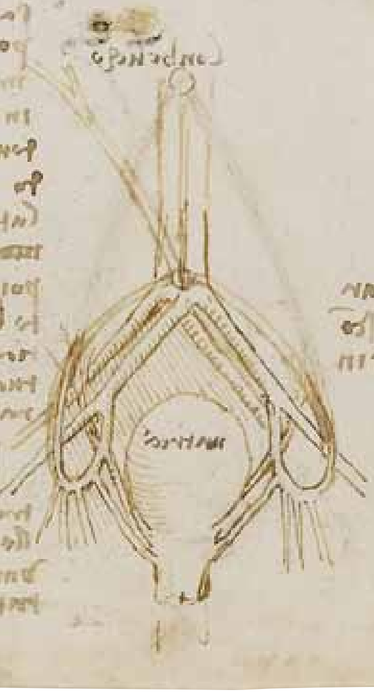
In the principal drawing Leonardo has opened the structure known as the cavernous sinus to show the nerves approaching the orbit, and both the anterior and middle cranial fossae. Beginning between the eyes are the olfactory nerves (cranial nerve I or CNI), with the olfactory bulb present. Emanating from the rear of the eyes are the optic nerves (CNII), crossing at the optic chiasm and continuing as the optic tract. Passing over the top of the left eye is the bifurcation of the frontal nerve (a derivative of the ophthalmic division of the trigeminal nerve, CNV) into the supraobital and supratrochlear nerves. Below can be seen the oculomotor nerve (CNIII), the root of the trigeminal nerve in the posterior fossa, then the ophthalmic, maxillary and mandibular divisions of the trigeminal nerve.

In the diagram at upper left the bone is omitted in an attempt to clarify the relationship between the nerves. While retaining the distinct identities of the olfactory and optic nerves, Leonardo has simply joined most of the other nerves together into a single structure.

The lower drawing purports to show the vessels of the abdominal area in a woman, with the umbilicus scratched out and correctly repositioned over the bifurcation of the great vessels, and the umbilical vein and arteries shown as normal vessels (as on no. 31b and elsewhere).







37 The brachial plexus

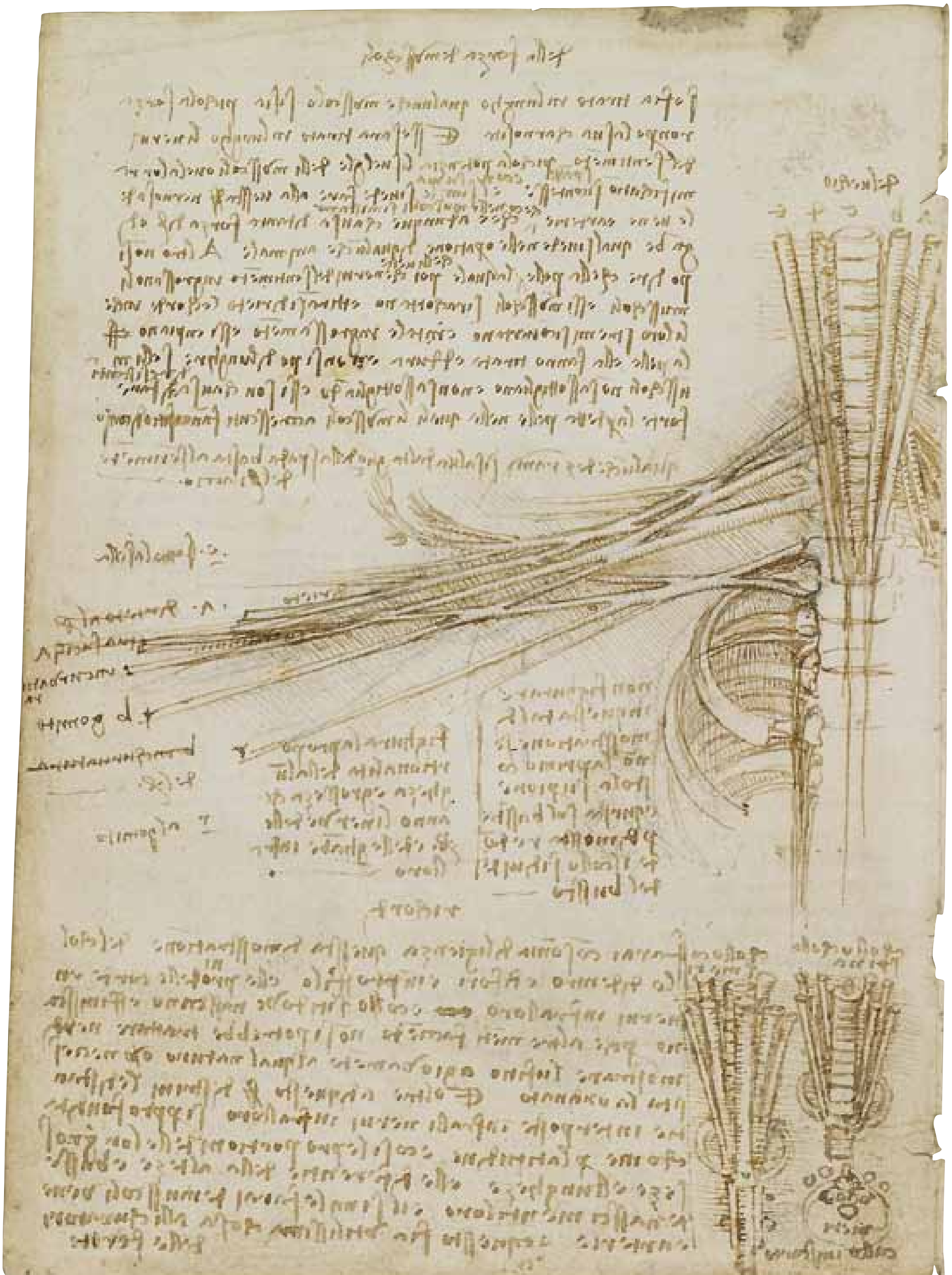
*c.*1508
Pen and ink over black chalk
19.3 × 14.3 cm
RL 19020v; MS B.3v; O'M&S 156; K&P 57v

The principal drawing is labelled '*del vechio*', 'of the old man', and is a fine example of the advances in Leonardo's detailed anatomical knowledge resulting from the dissection of the centenarian described in no. 25.

The brachial plexus is the network of nerves that runs from the spine to the arm. Its origin from five root nerves (ventral primary rami of cervical spinal nerves 5–8 and the first thoracic spinal nerve) is correctly shown. These five roots unite to form three trunks – upper or superior, middle, and lower or inferior, just as Leonardo has pictured them. From that point their separation into anterior and posterior divisions, then cords and terminal branches becomes harder to follow in the drawing: some cutaneous nerves and terminal branches such as the median nerve and ulnar nerve can be discerned, but the untidiness and numerous crossings-out in Leonardo's notes at centre left hint at his struggle to identify the destination of each nerve. The complexity of this area would have been compounded by the difficulty of working with unembalmed material – in this state the nerve trunks and their membranes are easily dissociated from one another and can be spread apart.

Leonardo has shown twelve stylised cervical vertebrae, rather than the correct seven, and the manner in which the spinal nerves issue from the vertebrae is very indistinct. Alongside the cervical vertebrae are vessels such as the internal jugular vein and common carotid artery, shown again in the subsidiary diagrams at lower right – two perspective views with the elements teased apart, and a cross-section. Along the right (proper) side of the thoracic vertebrae, and appearing to pass downwards from the spinal and intercostal nerves, are components of the sympathetic trunk and thoracic splanchnic nerves, which contribute to the nervous system of the internal organs.

The long note at the top of the sheet discusses the functioning of muscles in general. In the bottom half is a reminder to depict the systems of nerves, muscles, vessels and so on independently from each other, which 'will be most useful to those who treat wounds'; and alongside the main drawing Leonardo writes 'any one of the five branches saved from a sword-cut is enough for sensation in the arm'. This is an echo of one of the bases of anatomical knowledge in the millennia before Leonardo – his great predecessor Galen had derived much information from four years' work as a gladiatorial physician in the second century AD.



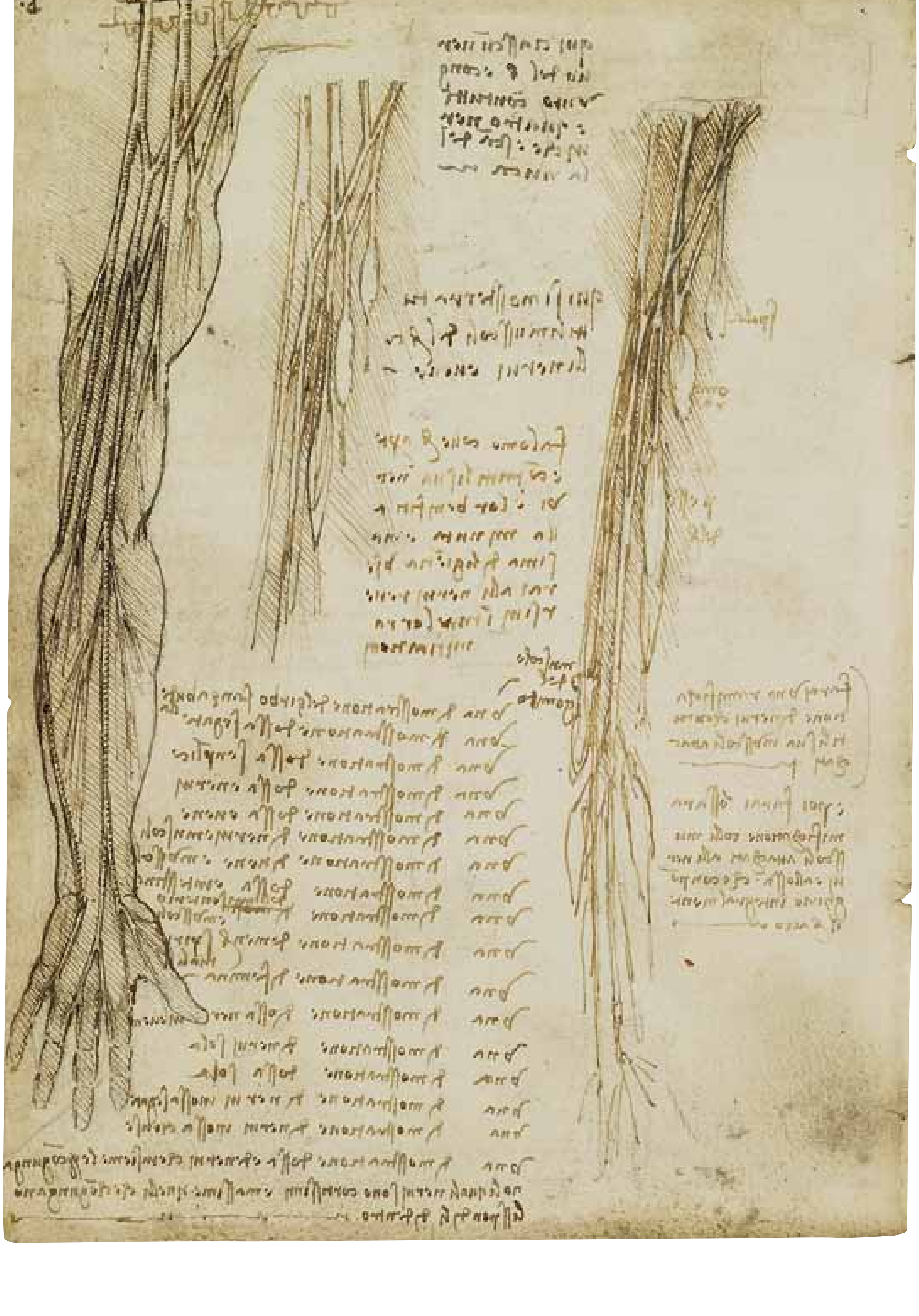
38a The brachial plexus and nerves of the arm

*c.*1508
Pen and ink over black chalk
19.1 × 13.7 cm
RL 19040v; MS B.23v; O'M&S 157; K&P 63v

The drawings again illustrate the nerves of the brachial plexus and right arm, here seen from the back with the arm held out, and can best be understood by turning the sheet anticlockwise. They attempt to show the innervations of the muscles by specific nerves; that on the right labels four of the muscle masses as 'shoulder' (deltoid), 'humerus' (probably brachialis), 'fish of the arm' (biceps) and 'muscle of the elbow' (triceps). Leonardo believed that nerves ramified within the body of the muscle, ensheathing each muscle fibre individually and causing it to contract when stimulated (see the passage quoted on the other side of this sheet, no. 38b). The brachial plexus is shown with only four roots, as in the earlier no. 3, and not the correct five, as seen in no. 37. In the drawing to the left the distribution of ulnar and radial nerves on the hand is reliable – this represents quite a feat of dissection, a couple of years before no. 64a.

The lower part of the sheet is filled with one of Leonardo's programmes for his intended treatise. Compared with earlier programmes (e.g. no. 11b), is it notable that the emphasis is here entirely anatomical, with no overt concern for the phenomena of life. His word *'dimosstratione'* emphasises the didactic nature of the treatise. The list is a little confused by Leonardo's indiscriminate use of *'nervi'* to mean nerves, tendons or ligaments; it is left untranslated below unless the meaning is clear from the context.

A demonstration of the omentum without the intestines
A demonstration of the bones, sawn
A demonstration of the bones, whole
A demonstration of the bones and *nervi*
A demonstration of the bones and veins
A demonstration of the *nervi* and muscles
A demonstration of the veins and muscles
A demonstration of the bones and intestines
A demonstration of the mesentery and muscles
A demonstration of the spiritual parts [thoracic organs]
A demonstration of the female
A demonstration of the bones, nerves and veins
A demonstration of the nerves alone [cf. no. 34]
A demonstration of the bones alone
A demonstration of the tendons on bones, sawn
A demonstration of the tendons on bones, whole
A demonstration of the bones and ligaments which join each other together, which ligaments are very short, particularly those that join the vertebrae.



38b The brachial plexus

*c.*1508
Pen and ink over black chalk
19.1 × 13.7 cm
RL 19040r; MS B.23r; O'M&S 155; K&P 63r

39a The brachial plexus

*c.*1508
Pen and ink over traces of black chalk
19.3 × 13.8 cm
RL 19021v; MS B.4v; O'M&S 154; K&P 62v

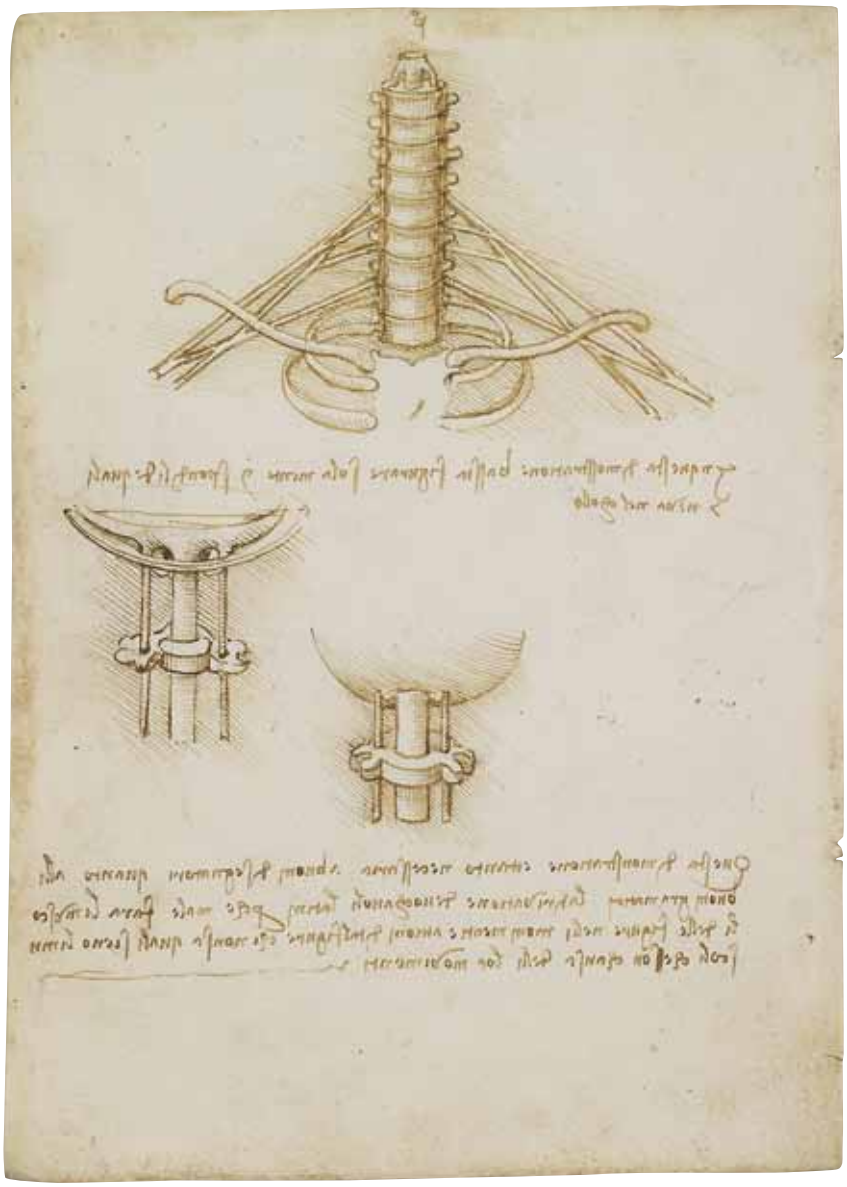
39b The brachial plexus, and the umbilical vessels

*c.*1508
Pen and ink over traces of black chalk
19.3 × 13.8 cm
RL 19021r; MS B.4r; O'M&S 131; K&P 62r

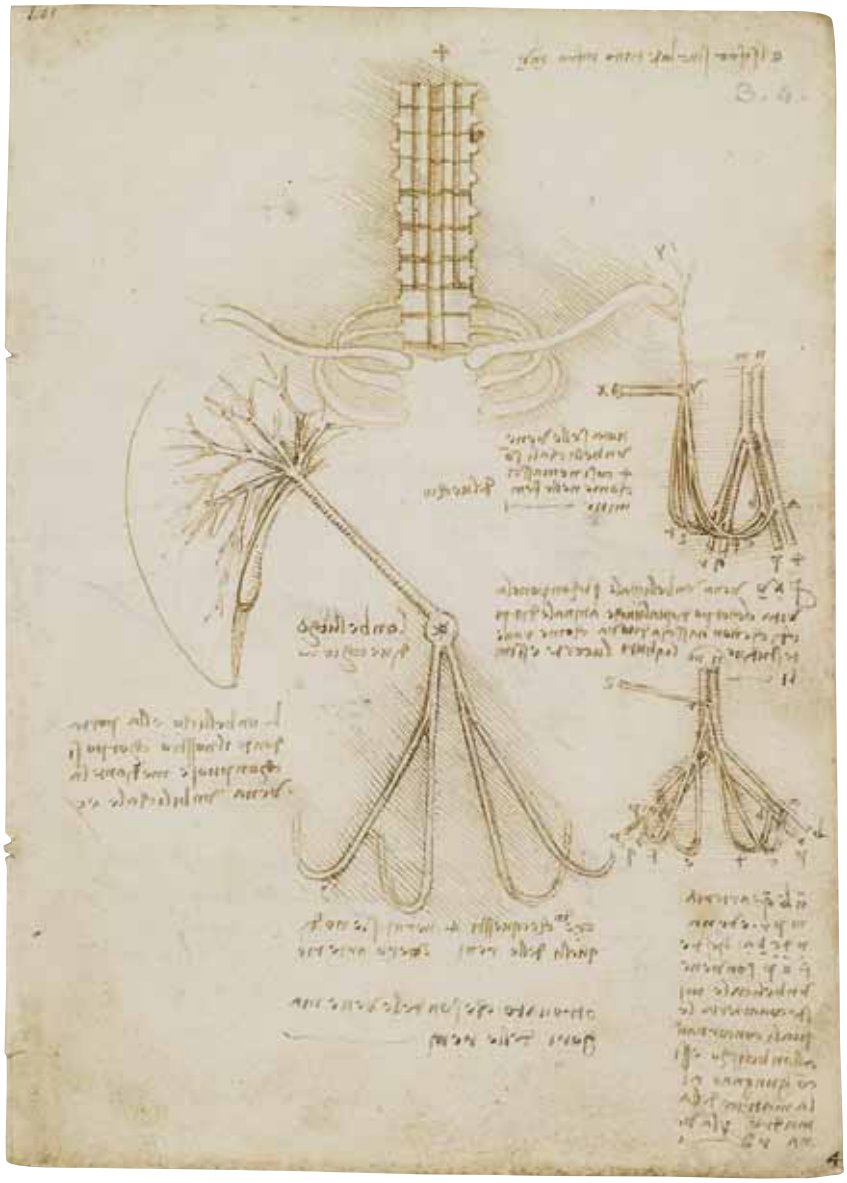
The four principal drawings on nos 38b–39b constitute a sequence of schematic diagrams of the brachial plexus (see no. 37). In the first, on no. 39a, the seven cervical and first two thoracic vertebrae are shown together with the clavicles and first two pairs of ribs, a gap where the sternum would be, and the brachial plexus on either side of the vertebrae formed from spinal nerves. In the second diagram, on no. 38b, the vertebrae are sectioned longitudinally to reveal the spinal cord with two parallel ancillary structures within the body of the vertebrae. The third diagram, immediately below, depicts this arrangement of nerves in isolation, with the base of the brain included; and the fourth diagram, on 39b, shows the bones alone, with the cavities supposed to house these nerves. On no. 39a Leonardo also gives two details of the spinal cord and ancillary structures entering the brain, and at upper right on 38b, a diagram of the membranous nature of the spinal cord.

Though the schematic nature of these diagrams might suggest that they are final expressions of Leonardo's understanding of the brachial plexus, they are in fact less accurate than the more loosely drawn no. 37. Four spinal nerve roots are shown rather than the correct five, and the pattern of branching in the plexus is excessively simplified. The structures on either side of the spinal cord are presumably intended to be the sympathetic trunks, a pair of bundles of nerve fibres and ganglia that run parallel to the spinal cord, from which nerves issue that pass both into the spinal nerves and through the foramina (holes) of the transverse processes of the cervical vertebrae. From the superior ganglion of the trunk, nerves arise and pass into the cranium via the carotid canal, accompanying the internal carotid arteries, but the sympathetic trunks themselves do

sternum



not enter the cranium. The sympathetic trunks lie anterior to the transverse processes and do not play a significant role in the formation of the brachial plexus; the structures which present in this manner, passing through the body of the cervical vertebrae, are in fact the vertebral veins and arteries. The appearance of the sympathetic trunk changes greatly as it goes from the thorax into the neck: in the thorax it is quite regular, with ganglia and communicating rami at each level, but above the first rib it has only three or so ganglia



and can be of much smaller diameter. Leonardo may well have been confused by this transition: even with modern dissection methods, and knowing what to expect, this can be a very difficult area.

The drawings in the lower half of no. 39b constitute another examination of the umbilical vein and arteries of the 'centenarian', as studied on nos 31b and 36 and elsewhere.

40a The muscles and nerves of the leg

*c.*1508
Pen and ink over black chalk
19.2 × 14.0 cm
RL 19035r; MS B.18r; O'M&S 161; K&P 77r

On the left is a rather bizarre drawing of the sacral plexus, the complex of spinal nerves from which the sciatic nerve originates (cf. the schematic drawings of the brachial plexus, nos 38b–39b). The spinal column kinks through almost 90 degrees between the last lumbar vertebrae and the sacrum (which is shown with distinct elements), and the nerves of the sacral plexus appear to come directly off the bone of the sacrum rather than the spinal cord. The lower part of the drawing shows the tibial and common fibular components of the sciatic nerve, which Leonardo follows down to the foot:

> At *f g h* [sacral plexus] arise the nerves which with their branches wrap around the muscles of the calf at the back of the leg below the knee at *a b*. And lower down they surround the second group of muscles at *c d;* and lastly they are bent behind the ankle-bones at *e f* and then pass beneath to the foot.

In the drawing on the right, the sartorius muscle has been cut at both ends (labelled *a* and *b* to accord with the studies on the other side of the sheet, no. 40b) to show neuro-vascular elements in the adductor (Hunter's) canal – probably the superficial femoral artery (with the deep femoral artery branching off towards the top) and the saphenous branch of the femoral nerve. Some components of the quadriceps femoris complex may be distinguished, and the insertions of the semimembranosus and semitendinosus at the inside of the knee. The study is very similar to that on no. 5, executed some twenty years earlier and perhaps the first evidence of Leonardo's dissection of human tissue.

The note to the right, with two small diagrams below, is a succinct expression of one of Leonardo's favoured illustrative techniques:

> Remember never to change the outlines of any limb because of some muscle which you have lifted off in order to expose another. And if indeed you remove muscles, the borders of which form the contour of a limb from which you have detached it, then you must mark with dots the boundary of that limb … And do this so that the shape of that limb which you are describing may not be left a monstrous thing through having its parts taken away. Besides this, one gets a greater knowledge of the whole because having lifted off the part you can see the true shape of the whole from which the part was removed.

40b The muscles of the leg

*c.*1508
Pen and ink over black chalk
19.2 × 14.0 cm
RL 19035v; MS B.18v; O'M&S 68; K&P 77v

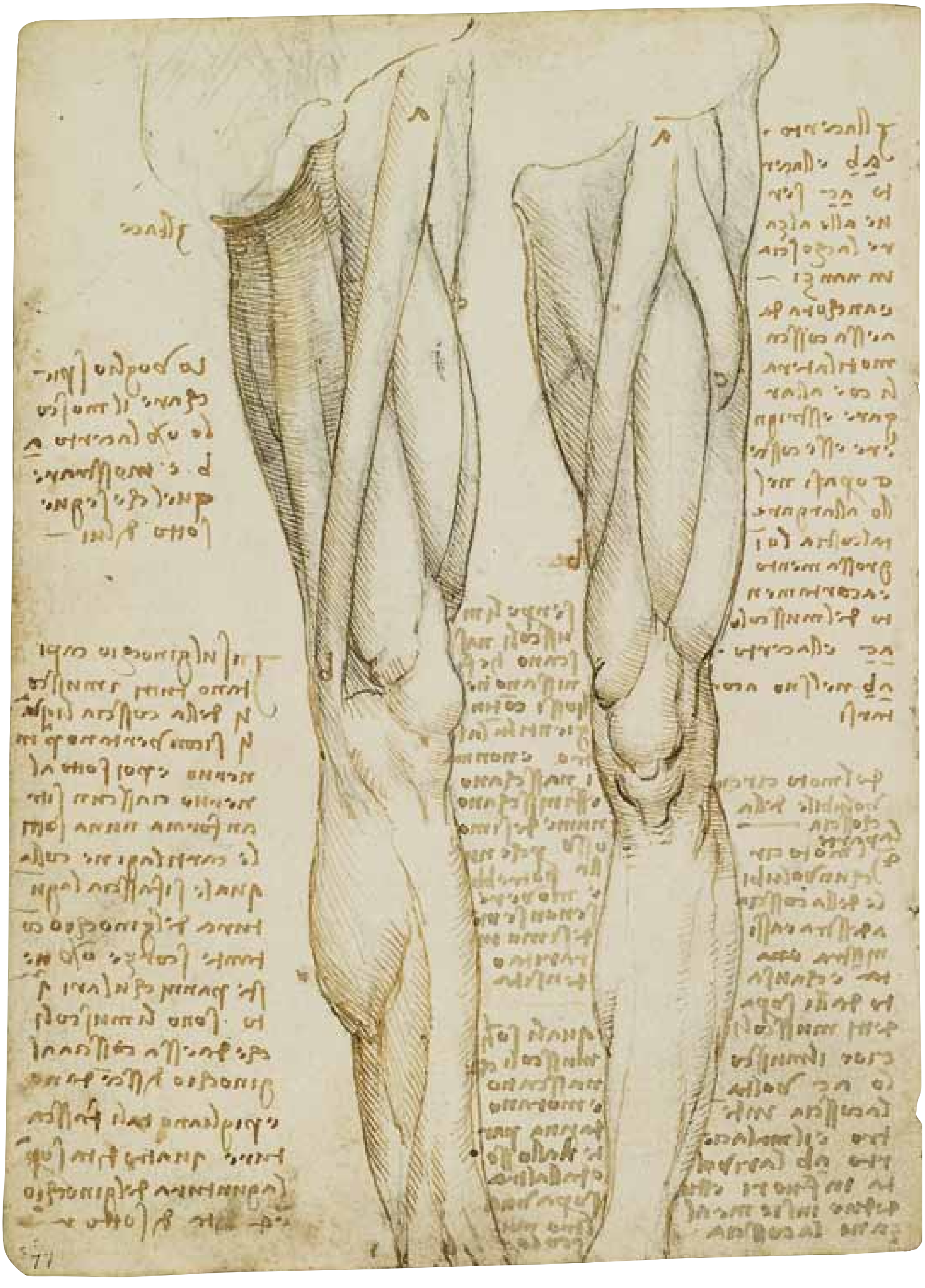
These are masterful studies of the muscles of the left leg. The long sartorius muscle is prominent and labelled *a b* in both studies; tensor fasciae latae is labelled *c,* though Leonardo has not indicated the iliotibial tract (the aponeurotic insertion of tensor fasciae latae and gluteus maximus). Across the front of the thigh rectus femoris, vastus medialis and vastus lateralis, components of the quadriceps femoris complex of muscles, are clearly distinguished.

In the drawing on the left the leg is turned a little to show the muscles of the calf, including gastrocnemius and soleus. The muscles on the inside of the thigh (including gracilis and adductor magnus and longus) are not differentiated, and all are labelled '*il lace*[*rto*]', literally 'lizard' – Leonardo's usual name for long, relatively narrow muscles, as distinct from '*musculo*' (from Latin 'small mouse') which referred to muscles generally and to short, rounded muscles specifically.

In the notes down the right of the sheet Leonardo attempts to analyse the action of these muscles:

> The *lacerto a b* [sartorius] and the *lacerto a c* [tensor fasciae latae] serve to lift the thigh forwards. Furthermore, they give the thigh lateral movements, that is to say, spread out [abduct] and narrow [adduct] the thighs. In producing widening [abduction] of the thigh there is enlargement and shortening of the muscle *a c*. The *lacerto a b* works by shortening.
>
> On the rotatory movement of the thigh. Part of the rotatory movement of the thigh to right and left is caused by the aforesaid muscles, that is, the muscle *a c* revolves the thigh inwards and the *lacerto a b* revolves it outwards; and the two together lift up the thigh.

In the note at upper left Leonardo writes 'I want to detach the muscle or *lacerto a b* [sartorius] and show what passes under it', and on the other side of the sheet (no. 40a) he does just that.



41 The muscles of the leg

*c.*1489 and *c.*1508
Pen and ink over black chalk
19.0 × 13.8 cm
RL 19037r; MS B.20r; O'M&S 71; K&P 81r

Leonardo has removed most of the muscles of the right thigh, in particular the quadriceps femoris complex, to reveal the femur and display the position and action of sartorius (running diagonally across the front of the thigh; see nos 40a–b), semitendinosus (behind and to the right of sartorius as we look at the drawings) and tensor fasciae latae (on the left edge of each drawing). The muscles of the calf, gastrocnemius and soleus, are depicted in the study to the left; these are removed in the second drawing to show the tibia and fibula, and the thigh muscles are reduced in thickness to demonstrate their origins and insertions even more clearly.

The sartorius muscle is partly responsible for rotating the leg medially (moving the knee outwards and the foot inwards) when the knee is flexed – it cannot do that when the knee is extended and locked into full stance – but none of the notes explores this action explicitly. Instead, rather puzzlingly, Leonardo seems to suggest that he has here depicted all the muscles responsible for upward movement of the thigh and flexion of the knee:

> In this demonstration made from different aspects, account is taken of all the muscles which move the leg; which muscles are attached to the lip of the pelvis [iliac crest] from which also arise the muscles which move the thigh from the knee upwards; and also of those which bend the knee when one kneels.

The five lines at the head of the page were in fact written during the earlier period of compilation of the notebook, *c.*1489, and list possible subjects to be investigated in Leonardo's proposed treatise (cf. no. 11b):

> The ramification of the veins of the shoulders upwards, and from the spleen to the lung.
>
> The ramification of the nerves and of the reversive nerves to the heart.
>
> Of the shape and position of the intestines.
>
> Where the umbilicus is attached.
>
> Of the muscles of the body and of the loins.

42 The muscles of the back and arm

*c.*1508
Pen and ink over black chalk
18.9 × 13.7 cm
RL 19044r; MS B.27r; O'M&S 15; K&P 47r

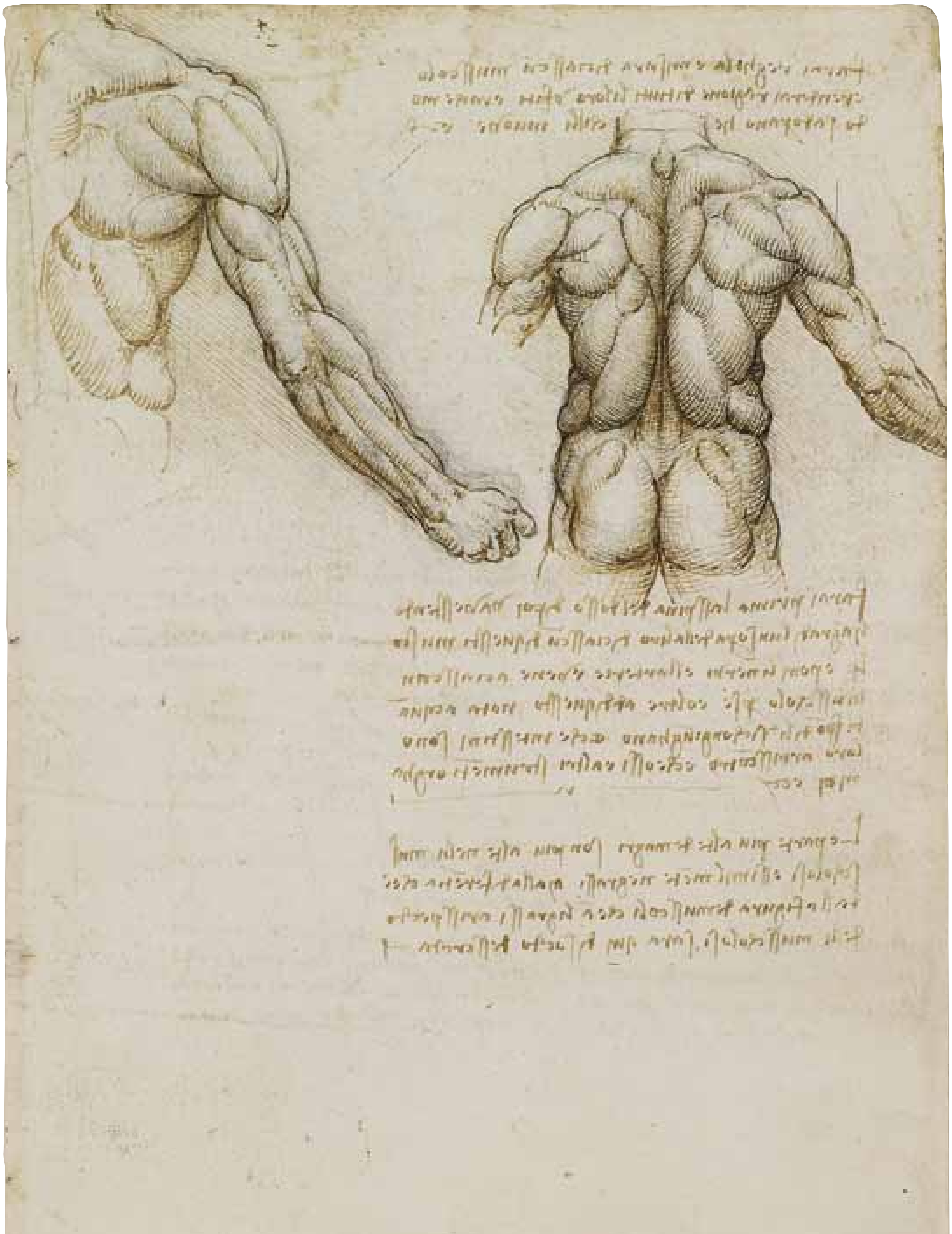
In these rather grotesque drawings Leonardo deliberately exaggerated the muscles of the back and arm – not just by using pen and ink alone (with no wash) to model the muscles, but also by drawing lines around some of the muscles in a darker ink. Most of the major muscle groups of the back and posterior surface of the arm are identifiable, though the shapes of many are unusual, suggesting that while Leonardo was generally familiar with the arrangement of the muscles, from a combination of surface observation and dissection, he remained uncertain about their form and function.

Trapezius is shown as at least two distinct muscles, either side of and below the vertebra prominens at the base of the neck. Latissimus dorsi, in the mid-region of the back, is rendered as a succession of bulges that do not correspond with the direction of action of that muscle; deltoid is likewise divided into so many bulges that it is impossible to tell where it ends and where infraspinatus starts. In the study to the left, biceps, brachialis and the long extensors of the wrist and hand are clearly defined, and an outcropping muscle of the thumb is indicated on the upper border of the forearm, by the wrist.

The three blocks of notes are programmatic: Leonardo states his intention to analyse every muscle of the body, starting with the spine and gradually 'clothing' it with the muscles before adding the nerves, vessels and viscera. He also planned to analyse differences in muscle shape for different body types:

> The most prominent parts of thin people are [also] more prominent in muscular people, and likewise in fat people. But the difference which exists between the shape of the muscles in fat people in comparison with those who are muscular will be described below.

There is no evidence that Leonardo ever compiled such a survey, nor fulfilled the similar intention recorded on no. 64b to determine 'what are the parts of man where the flesh never increases no matter how fat he is, and what are those places where the flesh grows more than any other' – that is, the fat distribution of the body. This concern with different physical types was potentially of great use to the artist and was to be one of the dominant, even overwhelming themes of Albrecht Dürer's treatise *On human proportion,* published in 1528.



43 The muscles of the torso

*c.*1508
Pen and ink over black chalk
19.3 × 14.0 cm
RL 19032v; MS B.15v; O'M&S 19; K&P 74v

The principal drawing is again an amalgam of information obtained from both dissection and surface observation. Though only the bodies of the muscles are shown, without their origins or insertions, they are represented in a more distinct manner than may be seen in even the most heavily muscled individual. The arm has been cut away to display the muscles on the side of the torso: serratus anterior is shown as five bodies (lettered *n m o p q*) interdigitating with the external abdominal oblique muscle (*a*) to create the 'serrated' appearance which gives the muscle its name. The external abdominal oblique muscle is inserted into an aponeurosis (a sheet-like tendon) which covers the rectus abdominis muscle, across the front of the abdomen. The deltoid (shoulder), pectoralis major (chest) and latissimus dorsi (labelled *'superiore'*, 'upper') muscles are also prominent.

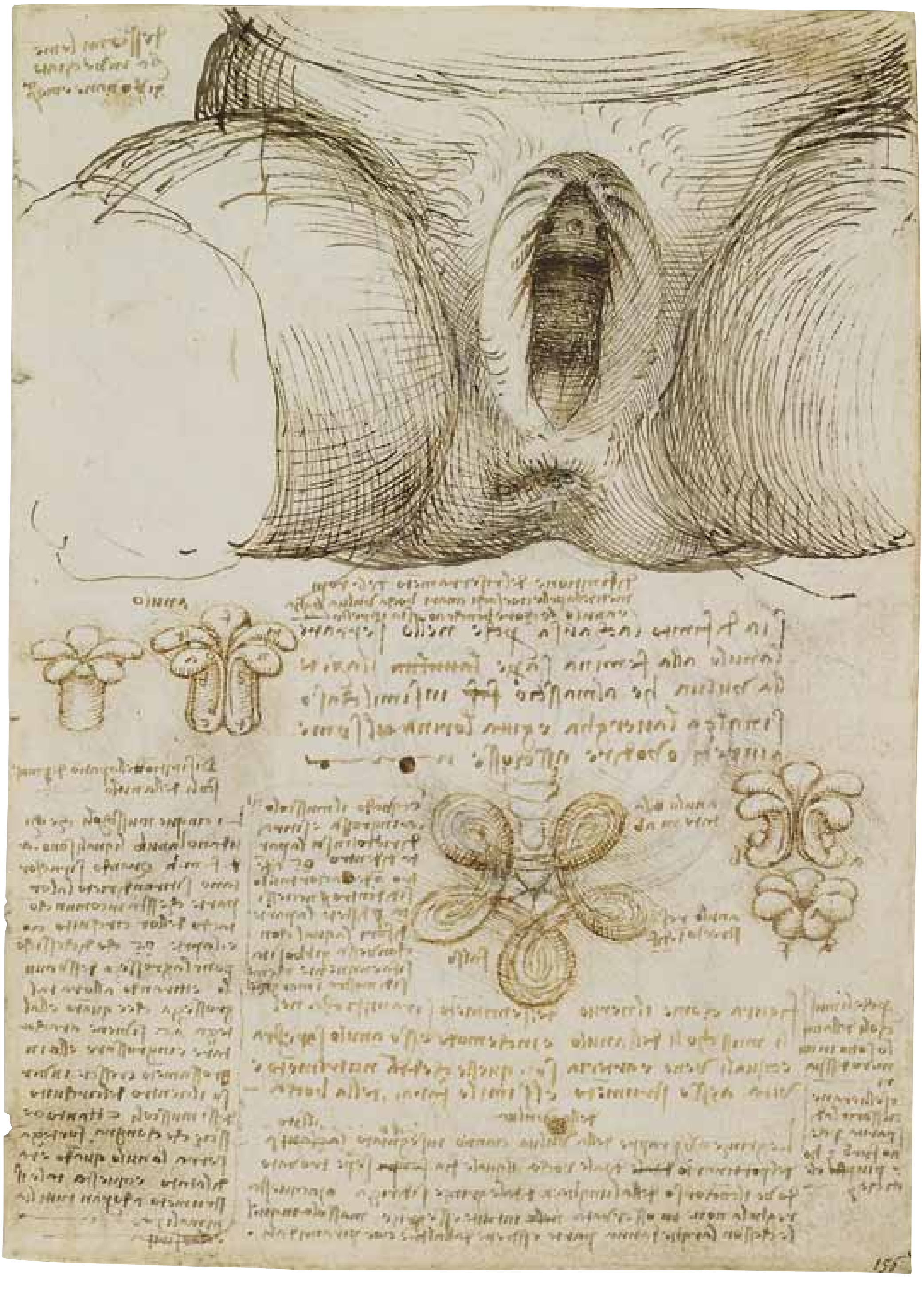
In the lower drawing latissimus dorsi has been removed to show more of serratus anterior, extending backwards towards the scapula, and a blood vessel, possibly the middle subscapular artery, travelling in the depths of the axilla. The two small sketches of curves at lower right are annotated *'a b c* [above] is the concavity of antique muscle; *c d f* [actually *e,* below] is modern'. Leonardo's use of the words '*antico*' and '*moderna*' (rather than *vecchio* and *giovane*) indicate that he was not discussing changes of muscle shape with ageing, but differing modes of representing muscular bodies in ancient and Renaissance sculpture: he clearly believed that the muscles in ancient statues were more sharply delineated than those in modern works.

44a The vulva and anus

*c.*1508
Pen and ink over black chalk
19.1 × 13.8 cm
RL 19095r; QA III.1r; O'M&S 200; K&P 54r

The principal drawing shows the vulva of a multiparous woman, with the labia majora separated to show the urethral orifice and the transverse rugae of the vagina; the labia minora are not evident. The urethral orifice is almost papilliform, and as this individual had given birth multiple times there may have been some prolapse, a weakness in the musculo-tendinous floor of the pelvis, which holds the bladder.

Leonardo was interested in how the 'six gaps in the skin' could open and close – 'the eyes, nostrils, mouth, vulva [or] penis and anus, and the heart though it is not in the skin'. He maintained, quite correctly, the principle that a muscle can only pull and not push, but it did not occur to him that a muscle could be ring-shaped rather than linear, so he failed to comprehend the nature of sphincter muscles. Here he posited that the anus consisted of a ring of five separate muscles, each of which in contraction would increase in thickness, so closing the anus. It was unclear even to Leonardo himself why there should be five such muscles: he asked 'why the muscles of the anus are odd in number; and if this disparity were necessary, why were three or seven not chosen rather than five?' Possibly he derived this figure from the number of 'pyramidal wrinkles' visible at the anus in his subject – on RL 19055v Leonardo states that 'the skin which forms the covering of muscles which pull always directs its wrinkles to the place where the cause of movement is'.



44b The male and female reproductive systems

*c.*1508
Pen and ink over black chalk
19.1 × 13.8 cm
RL 19095v; QA III.1v; O'M&S 201; K&P 54v

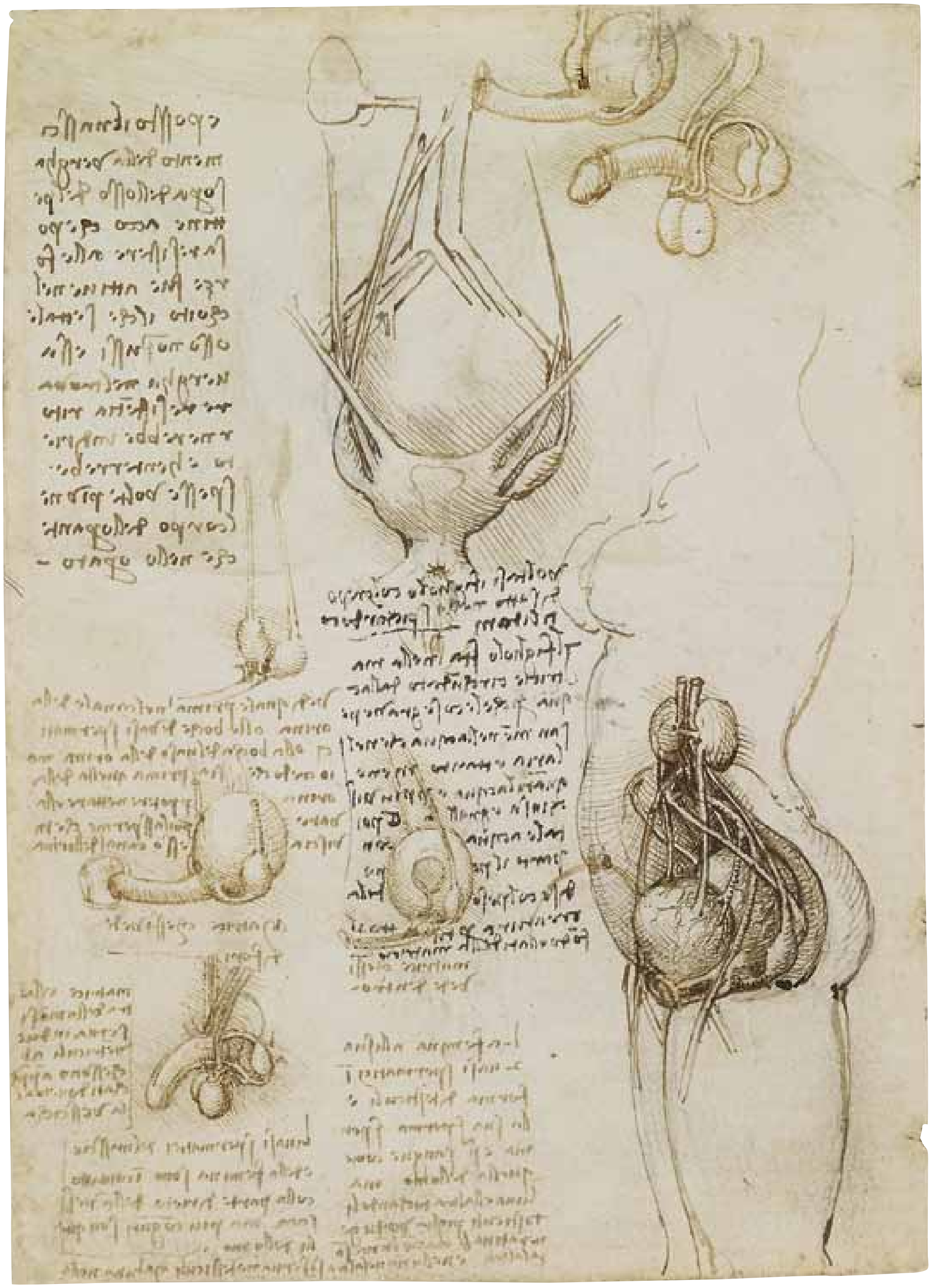
Here Leonardo attempts to analyse the similarities between the male and female generative organs:

> The female has her two spermatic vessels in the form of testicles, and her sperm is first blood, like that of the male. But in both one and the other [female and male], on reaching the testicles it takes on generative power … Neither in the one nor the other is it kept in the testicles, but in one in the uterus and in the other, that is the male, in the two ventricles [seminal vesicles] attached to the back of the bladder.

It is thus clear that Leonardo regarded both male and female as contributing equally to conception (cf. no. 2): he calls the ovaries 'testicles', and states that they also form sperm from blood and send it to the uterus. But he does not try to impose these homologies too strictly. Although in these drawings the seminal vesicles are of the same shape and in the same position as the ovaries, he is clear that it is the testicles that are the source of sperm, which is simply held in the vesicles. He has also now discovered that the urethra is the only channel in the penis, and that the ejaculatory ducts issue into the urethra.

The external view of the uterus at upper centre, however, shows that Leonardo still had a poor understanding of the region. Three structures are shown attached at either side; these may be (from top to bottom) a uterine ligament, seen in a variety of configurations in Leonardo's drawings of the period (cf. no. 47a); the mythical vessel thought to carry menstrual blood during pregnancy to the breast for conversion into milk (cf. no. 2); and the ovary, with the ovarian vein at its upper end and discharging 'female sperm' (alluded to in the passage quoted above) from its lower end into the uterus.

The drawing at lower right tries to make three-dimensional sense of these supposed structures. Most clearly visible is the bladder at the front of the body, with the ureters passing from the kidneys and what is presumably the superior vesical artery emanating from the internal iliac artery (cf. no. 68). Behind the bladder is the uterus, with the left ovary joined to a vessel that can be traced upwards to the region of the kidneys (the left ovarian vein does indeed connect to the left renal vein); the 'menstrual blood vessels' loop upwards from both sides of the uterus to peter out in front of the kidneys. A further blood vessel seems to pass down towards the front of the bladder, from where another passes back up to the umbilicus; the colon can be seen curving around behind the uterus, terminating in a dark patch of ink at the anus.



45 The uterus of a gravid cow

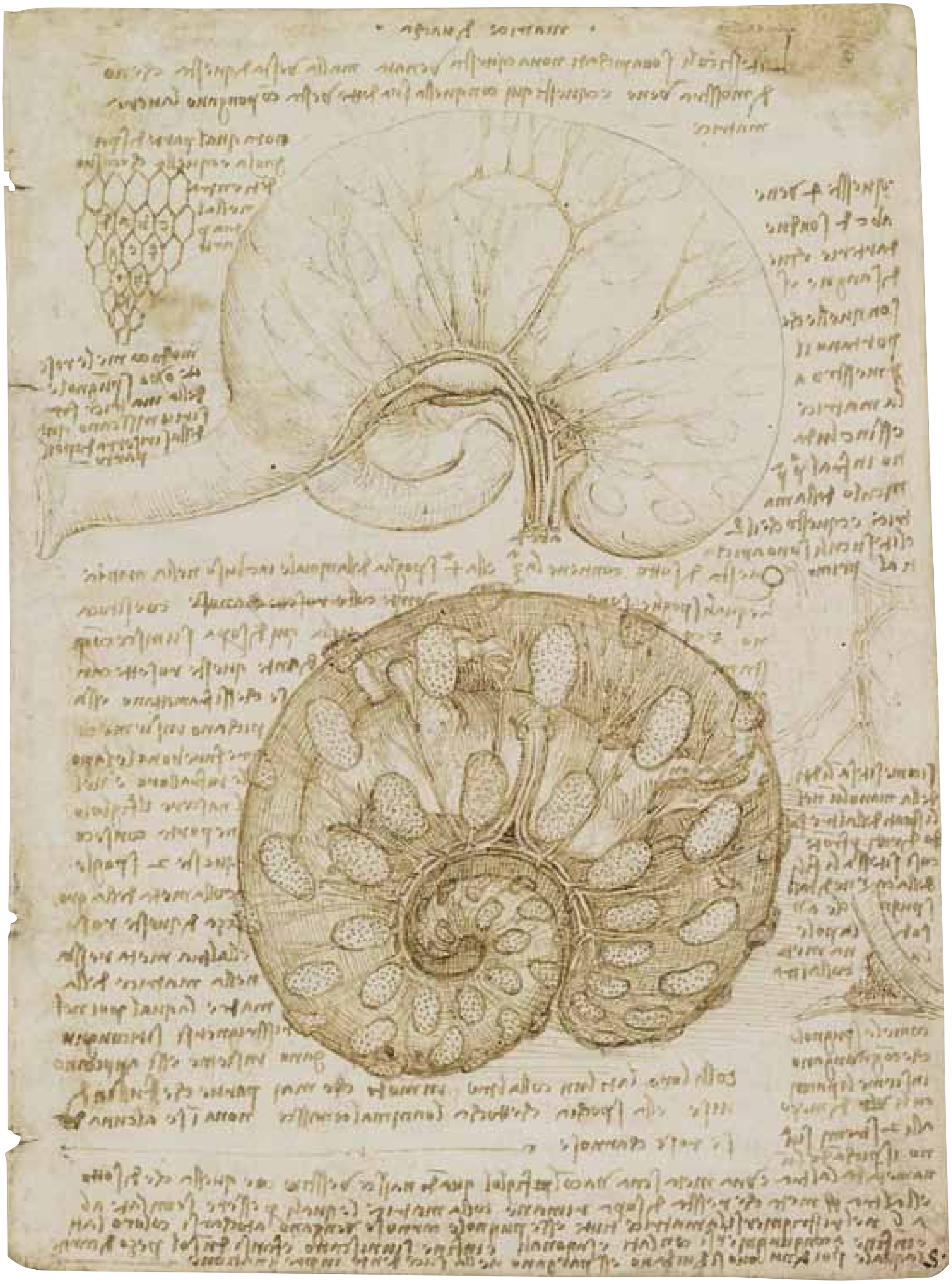
*c.*1508
Pen and ink over traces of black chalk
19.2 × 14.2 cm
RL 19055r; MS B.38r; O'M&S 211; K&P 52r

This is one of Leonardo's great studies of *in utero* development. The upper drawing is an external view of the bipartite uterus of a cow, with the vagina to the left, the ovaries and their suspensatory ligaments at the centre, and the blood supply from below. The upper section of the uterus is gravid (pregnant), and Leonardo has lightly indicated the individual portions of the multiple, cotyledonous placenta as a pattern of small ovals. In the lower study the uterine wall has been removed to show the chorionic membrane, with countless vessels arising in the chorion and uniting to form the foetal blood supply coursing to the umbilicus of the calf. The foetal calf is visible, on its back with its head to the left and its legs upwards. The lower, non-gravid portion of the uterus spirals away in an excessively stylised manner, and the individual cotyledons of the placenta are dotted to represent their supposedly digitated form.

Leonardo understood the placenta as a union of maternal and foetal tissues, and in the small sketch at lower right he shows them peeling apart to demonstrate their interdigitation (cf. nos 46, 71). On no. 44b he had noted that 'the child turns with its head downwards on the separation of the cotyledons', and indeed his later drawings of the child in the womb show that he believed that the child sat in breech position until shortly before birth (nos 69–71). Leonardo also knew that, despite the multiple, cotyledonous structure of the bovine placenta, the afterbirth was expelled as a single entity, and he explained this as a union of the foetal cotyledons when the uterus contracted after parturition – as illustrated in the sketch of hexagons at upper left. Around the lower drawing he wrote:

> This drawing below contains the third and fourth sloughed membranes [chorion and amnion] of the animal enclosed in the uterus. These membranes are united, that is, they are in contact with each other, and that which is more superficial is united with this [the uterus] through the fleshy rosettes [cotyledons] which interlock and stick together as burrs do with each other. And at birth the infant carries with it these two coats with half the thickness of these rosettes, and the other half remains within the uterus of the mother, which then in contracting joins them together … in such a way that they would never appear to have been separated. And the sloughed membrane in contact with the animal which is born has none of these fleshy rosettes.

Although the page is headed 'uterus of the cow', these notes refer not to cow and calf but simply to mother (or animal) and infant. Leonardo assumed that all mammals had essentially the same reproductive structures, and in his embryological studies of a few years later he applied to the human form the cotyledonous placental structure that he had observed in the cow.



46 The foetal blood supply of the cow

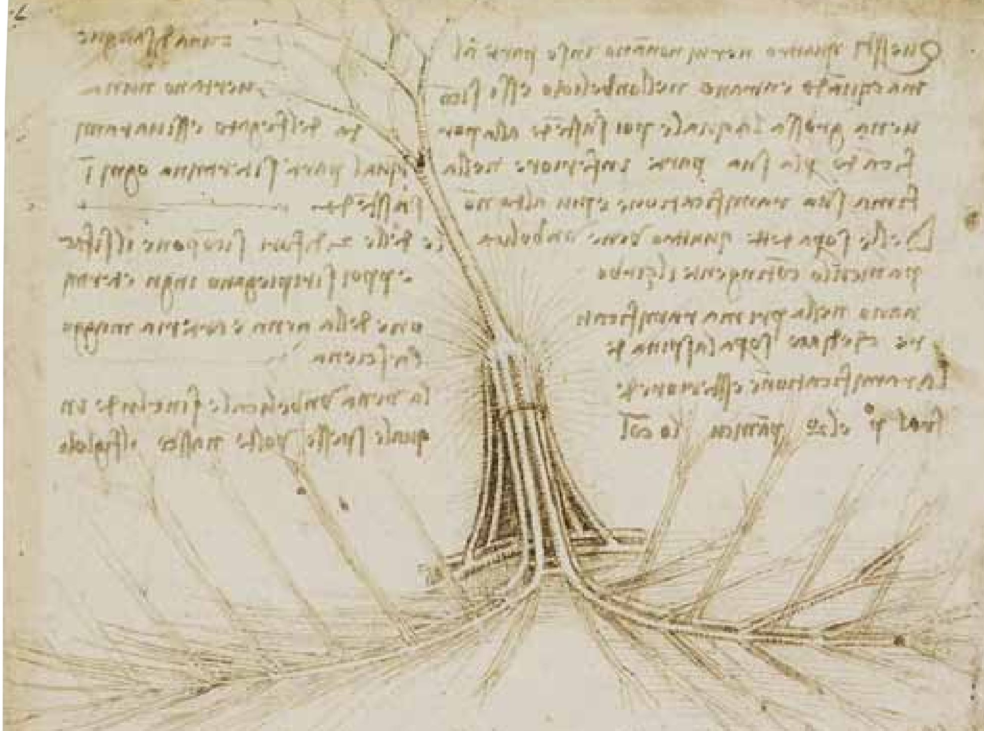
*c.*1508
Pen and ink
19.0 × 14.0 cm
RL 19046v; MS B.29v; O'M&S 208; K&P 51v

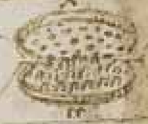
These studies were presumably based on the same dissection of a gravid cow recorded in no. 45, and can best be understood by comparison with that sheet. The main drawing centres on the umbilical cord, shown unnaturally short, but correctly with two arteries and two veins (in humans there are two arteries but only one vein). Above the umbilicus of the calf, the umbilical vein travels upwards to ramify within the liver; below, on either side of the cord, are two pairs of vessels, the umbilical arteries and (imaginary) accompanying veins, leading to the internal iliac arteries and veins on either side of the calf's body (the adult remnants of the umbilical arteries are shown on nos 31b and 39b). At the lower, maternal end of the umbilical cord, a short bridge (the Hyrtl anastomosis) can be seen between each pair of arteries and veins. These vessels then ramify within the foetal membranes, each branching pair of arteries and veins terminating at a cotyledonous placenta (not shown).

An individual cotyledon is shown in the detail at centre right, with the upper, maternal part represented as a disc with holes, peeling away from the lower, foetal part to reveal its 'digitation'.

In the long note below Leonardo analyses the ramification of the placental vessels and describes the phenomenon of the infant born in its amniotic sac:

> This umbilical vein is the origin of all the veins of the animal which is generated in the womb, and it does not take any origin from any vein of the gravid woman because each of these veins is entirely separated and divided from the veins of the gravid woman.... And of the [placental] ramifications drawn here, those which extend upwards are ordained for the nourishment of the third fine membrane of the uterus [decidua] and the lower vessels placed obliquely are those which nourish the outermost membrane which is in contact with the animal [foetal amnion], which is clothed by it. And both one and the other of these membranes often emerge together with the creature out of the womb of the mother. This happens when the animal cannot rupture them for then it emerges clothed in them. And this easily happens because these two very thin membranes are in no place united with the womb, which is itself composed of two further membranes which are very thick, fleshy and sinewy [decidua and muscular uterine wall].





47a/b The cardiovascular system and principal organs of a woman

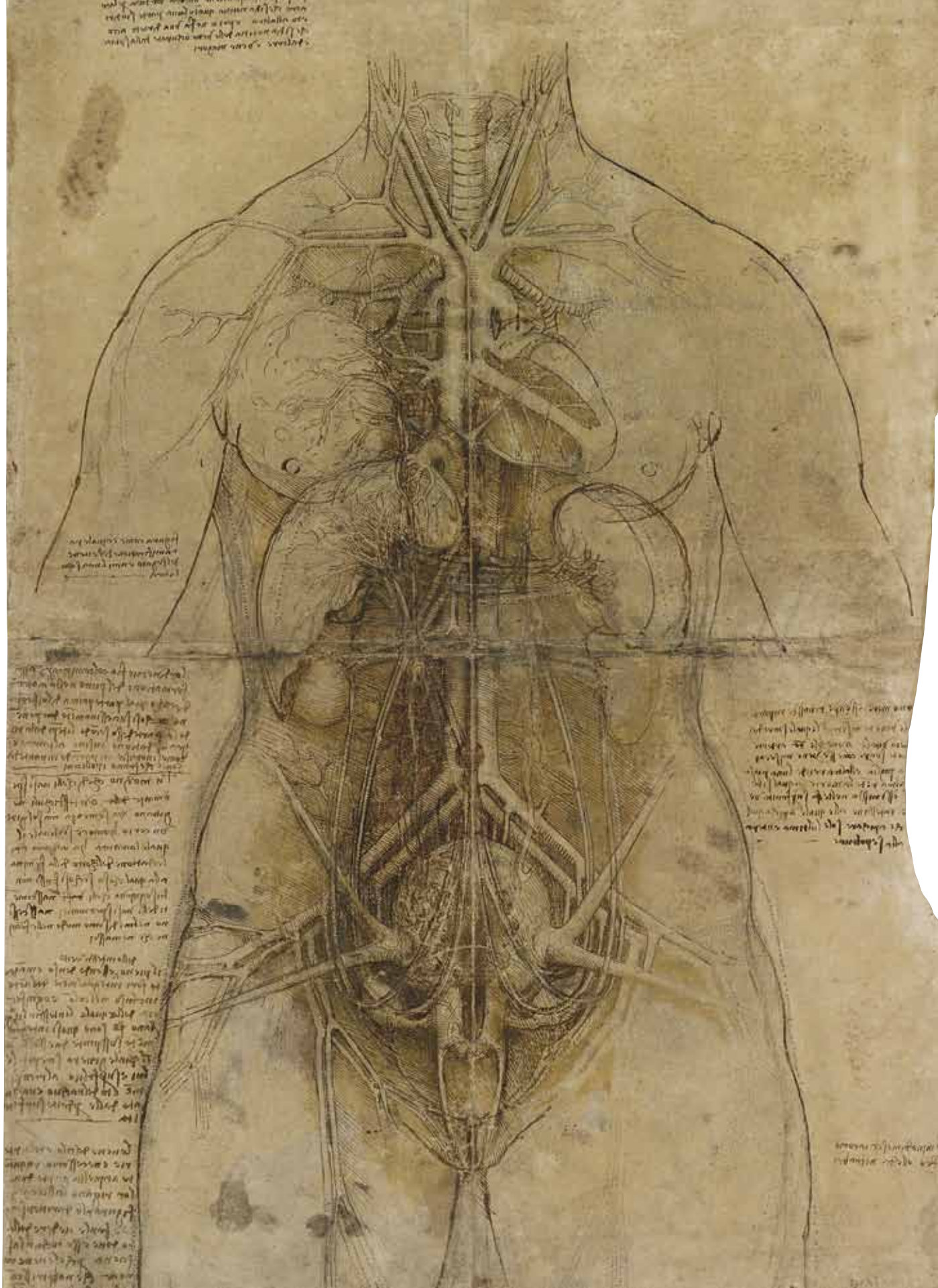
*c.*1509–10
Black and red chalk, ink, yellow wash, finely pricked through
47.6 × 33.2 cm
RL 12281r–v; QA I.12r; O'M&S 202; K&P 122r–v

This magnificent drawing is the culmination of Leonardo's researches into the viscera contained in his Manuscript B (nos 25–46). It contains many features transcribed from the studies in that notebook, though elements of the gastrointestinal tract and nervous system are not present.

The sheet was compiled in several stages. The outlines of the torso from the armpits downwards and the diaphragm were first sketched in red and then black chalk; the sheet was then folded in half and these outlines were pricked through the two thicknesses of paper to give a perfectly symmetrical framework for the addition of the internal features.

The trachea and bronchi were copied from the left-hand drawing on no. 33b. In front of the bifurcation of the trachea are the upper ends of the great vessels, as on no. 29a: the aortic arch is bovine, with both right and left brachiocephalic arteries, and the brachiocephalic veins are similarly symmetrical. The venous return from the right lung is to the superior vena cava rather than to the left atrium of the heart, and the arch of the azygos vein correctly connects with the superior vena cava. The heart consists only of the ventricles, with no atria. The lower aortic bifurcation and vena cava formation are shown correctly at the level of the umbilicus, though the subsequent vessels extend too far laterally in the thigh/gluteal region, as in no. 27. The ascending lumbar veins can be discerned on either side of the inferior vena cava and thoracic aorta, as in nos 27 and 28.

The liver, spleen (drawn twice) and kidneys are in approximately the correct locations, as in no. 29b, though this is such a heavily worked part of the sheet that the blood vessels are hard to follow. Passing diagonally from the umbilicus to the liver is the umbilical vein, and looping downwards from the umbilicus are two pairs of vessels, the umbilical arteries and their imaginary venous companions, as in nos 31b and 39b. At first glance these seem to be continuous with the ureters and ovarian vessels, but closer inspection reveals that they connect to the common iliac vessels. The ureters pass from the kidneys to the bladder, drawn as a circular outline over the vagina, with no urethra visible and a papilliform urethral orifice (as in no. 44a), in an uncertain relationship to the sectioned vagina. The right ovarian vein and artery travel from the suspensatory ligament of the ovary to the vena cava and aorta, and the left ovarian vein is correctly shown terminating at the left renal vein; but the left ovarian artery is similarly shown originating at the left renal artery, whereas it should also spring from the aorta.



The perfectly spherical (and rather large) uterus is 'scalloped' within, forming the traditional seven chambers, and its greatly exaggerated ligaments extend like horns to the flanks of the pelvis. Vessels can be traced meandering upwards from the upper surface of the uterus, alongside the ascending lumbar veins; these are possibly the vessels thought to carry the retained menses of pregnancy to the breasts, first seen in no. 2. Though the nipples are correctly positioned, the breasts themselves appear oddly masculine.

Having added all this detail, Leonardo attempted to clarify the spatial relationships of the organs and vessels by shading with pen hatching and yellow wash. The outlines of the torso and the diaphragm were adjusted and inked in; it was then that the inky-fingered Leonardo picked up the sheet, for his thumbprint is plainly visible at the left edge of the sheet, smudging the wet outline a little just above the central fold, with a corresponding partial fingerprint on the verso of the sheet.

Leonardo then folded the sheet down the central axis again, and pricked all the supposedly symmetrical elements through both sides of the sheet. Finally, the sheet was unfolded and the non-symmetrical elements, such as the liver and heart, pricked through. The resulting dense array of prick-holes can be seen on the verso of the sheet. Leonardo could then use this sheet as a template, pouncing chalk dust through the holes to make a pattern of dots to be joined with pen and ink, thus creating an unlimited number of 'clean copies' for further elaboration. No. 80 includes the note 'make a pounce of the rings [of the trachea] and then add the veins and arteries and substance of the lungs', which may well refer to an elaborated replica of the upper part of the present sheet. And on RL 12280v is an extensive partial replica of the image, with several organs not inked in, but the arrangement of the vessels in the abdomen much clearer than here.

Despite the complexity of the present image, it is still plainly a working study, with the marginal notes only loosely relevant. And at the top of the sheet is a memorandum to make equivalent studies from the side and from behind:

> Draw this demonstration seen also from the side in order that knowledge may be given as to how much one part is behind another; and then draw one from behind in order that knowledge of the vessels located near the spine and heart and great blood vessels may be given.

48 The brain

*c.*1508–9
Pen and ink over black chalk
20.0 × 26.2 cm
RL 19127*r*; QA V.7*r*; O'M&S 147; K&P 104r

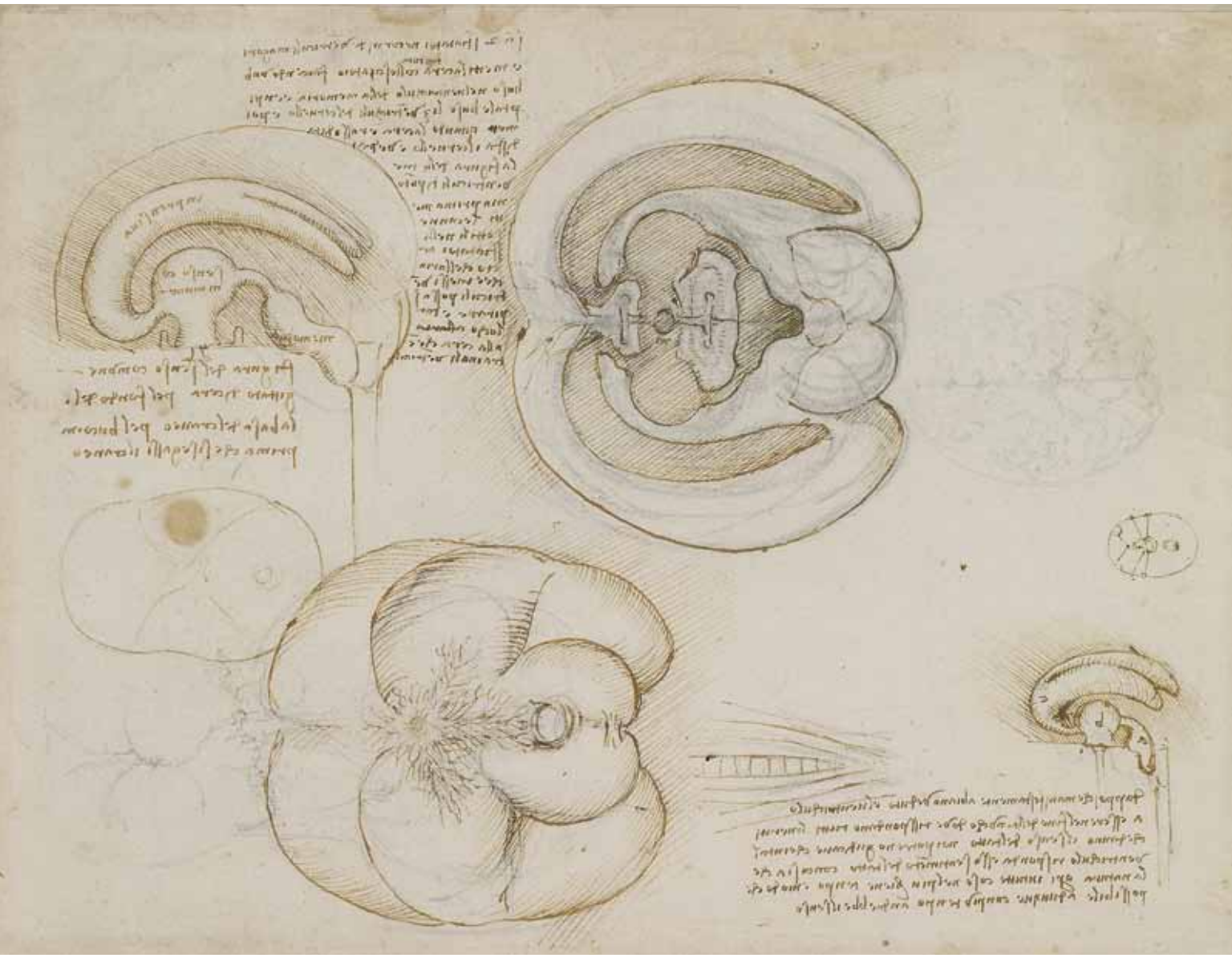
Leonardo's earlier studies of the nerve pathways in the head (nos 5, 14) adopted the traditional belief that the brain contained three bulbous ventricles arranged in a straight line backwards behind the eyes. Even a rudimentary dissection of the brain would have shown him that the brain does indeed contain cavities, but not of this form. However, the soft consistency of the unfixed brain and the difficulty of determining the shape of a cavity must have frustrated Leonardo's attempts to determine the correct form of the ventricles, so he performed the procedure described here:

> Make two vent-holes in the horns of the greater ventricles and insert melted wax with a syringe, making a hole in the ventricle of memory [the fourth ventricle, at lower right in each drawing]; and through this hole fill the three ventricles of the brain. Then when the wax has set, dissect off the brain and you will see the shape of the ventricles exactly. But first put fine tubes into the vent-holes so that the air which is in these ventricles is blown out and makes room for the wax which enters into the ventricles.

This simple but brilliant technique, adapted from Leonardo's knowledge of casting bronze sculpture, is the first recorded instance in medical science of injecting a setting medium into a body cavity.

Leonardo probably used a cow's brain, easier to obtain than a human brain and with the foramen magnum (from which the spinal cord issues) more conveniently positioned at the back of the skull. But, as usual, he adjusted the proportions and contours to accord with the shape of a human brain, and the largest drawings thus appear essentially human in form: in the drawing at upper left, the spinal cord is indicated vertically below, rather than horizontally to the rear as it does in most quadrupeds; the cerebellum (the lobes at centre right of the largest two drawings) is human in position and relative size.

Fig. 19. A human brain injected with wax and dissected



The drawing at upper right shows the brain cut in half through the mid-line and opened out, such that the structures mirror one another. Comparison with a human brain sectioned using modern instruments (fig. 19) demonstrates the success of Leonardo's procedure: the only major flaw in his images is the size of the third (middle) ventricle, enlarged and distorted by the pressure of injection; also, the wax did not penetrate to the superior and inferior horns of the curved lateral ventricles, but the results are nevertheless spectacular. The feathery structure spreading out from the centre of the lower drawing, showing the brain from below, is the vascular structure known as the rete mirabile, found in a number of animals (including the cow) but not in humans.

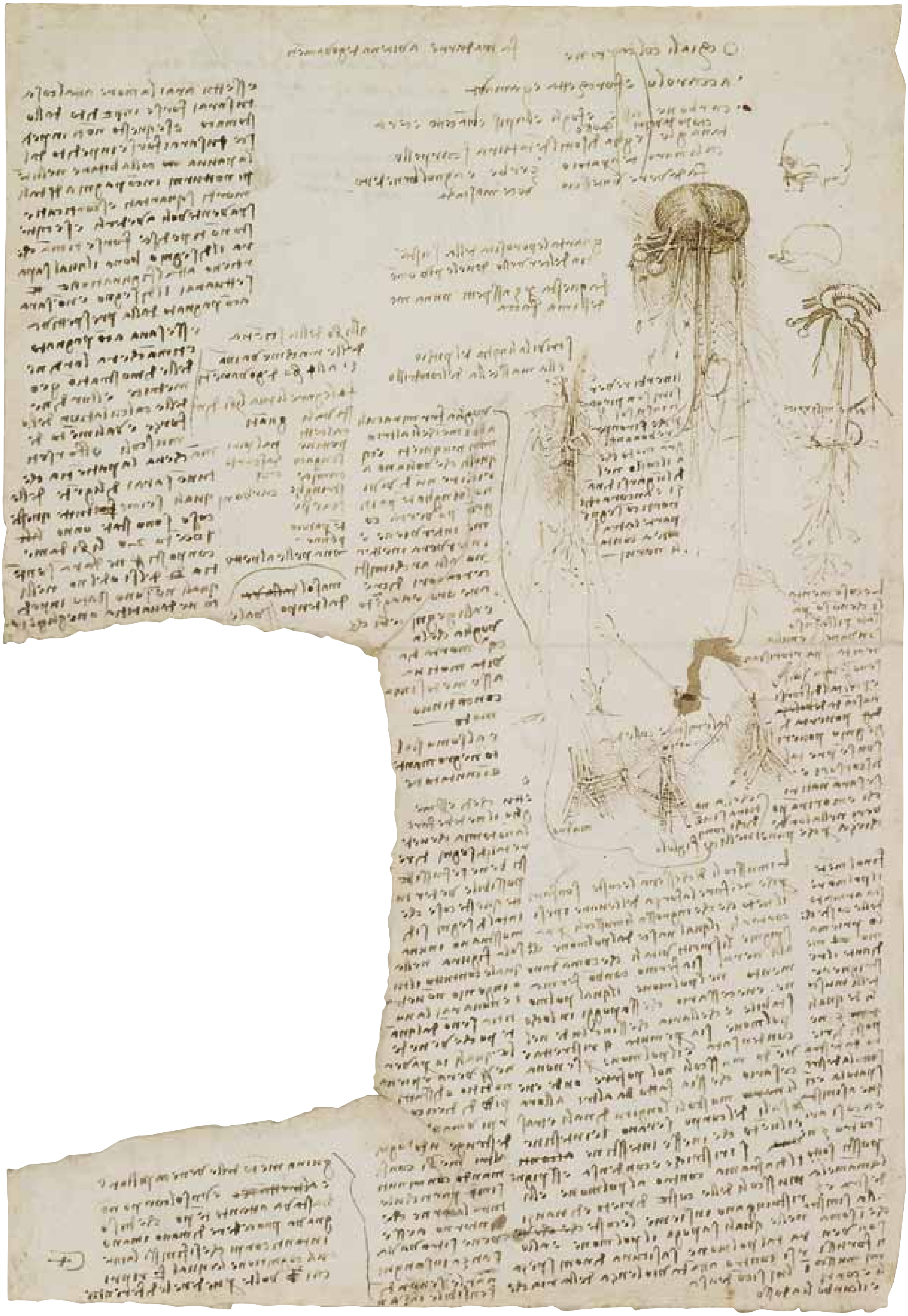
49 Miscellaneous notes and anatomical sketches

*c.*1508–10
Pen and ink
32.0 × 22.1 cm
RL 19070v; QA I.13v; O'M&S 146; K&P 113r

The sketchy drawings deal with the cardiovascular system (including a detail of the supposed connections between the pelvic and umbilical vessels in mother and child, cf. no. 46), and with the nervous system. The densest drawing shows the brain with the spinal cord down to the lumbosacral plexus, and several pairs of cranial nerves including the vagus nerves down to the recurrent laryngeal nerves. The other neurological sketch, to the right, is odd in that it shows the nerves connected to the cavities of the ventricles as if they were all composed of one substance. This may be Leonardo's last attempt to relate the nervous system directly to the form of the ventricles; in no. 50 they are independent structures.

But it is the miscellany of notes that is the most remarkable aspect of the sheet, and only a sample can be given here. Leonardo's description of the difficulties of dissection is quoted on p. 29; the lists of items suggest that he was gathering possessions ready for a journey:

> Have Avicenna translated. 'On the Utilities'.
>
> Spectacles with case, firestick, fork, bistoury, charcoal, boards, sheets of paper, chalk, white, wax, forceps, pane of glass, fine-tooth bone saw, scalpel, inkhorn, pen-knife. Zerbi, and Agnolo [*sic*] Benedetti [see p. 16]. Get hold of a skull. Nutmeg.
>
> Observe the holes in the substance of the brain, where there are more or less of them.
>
> Describe the tongue of the woodpecker and the jaw of the crocodile.
>
> Give the measurement of the dead using his finger [as a unit].
>
> The book 'On Mechanical Science' precedes that 'On the Utilities'. Get your books on anatomy bound. Boots, stockings, comb, towel, shirts, shoe-laces, shoes, pen-knife, pens, a skin for the chest, gloves, wrapping paper, charcoal.
>
> Mental matters that have not passed through the *senso comune* are vain and they beget nothing but the prejudiced truth. And because such discourses arise from poverty of wit, such reasoners are always poor, and if they are born rich they will die poor in old age because it seems that Nature revenges herself on those who want to work miracles, so that they have less than quieter men. And those who want to grow rich in a day live for a long time in great poverty, as happens, and will happen to eternity – the alchemists, searchers after the creation of gold and silver, and those engineers who want dead water to give itself moving life with perpetual motion, and the supreme fool, the necromancer and enchanter.



50 The nerve pathways to the brain

*c.*1509–10
Pen and ink over traces of black chalk
29.0 × 21.4 cm
RL 12602r; QA V.8r; O'M&S 145; K&P 103r

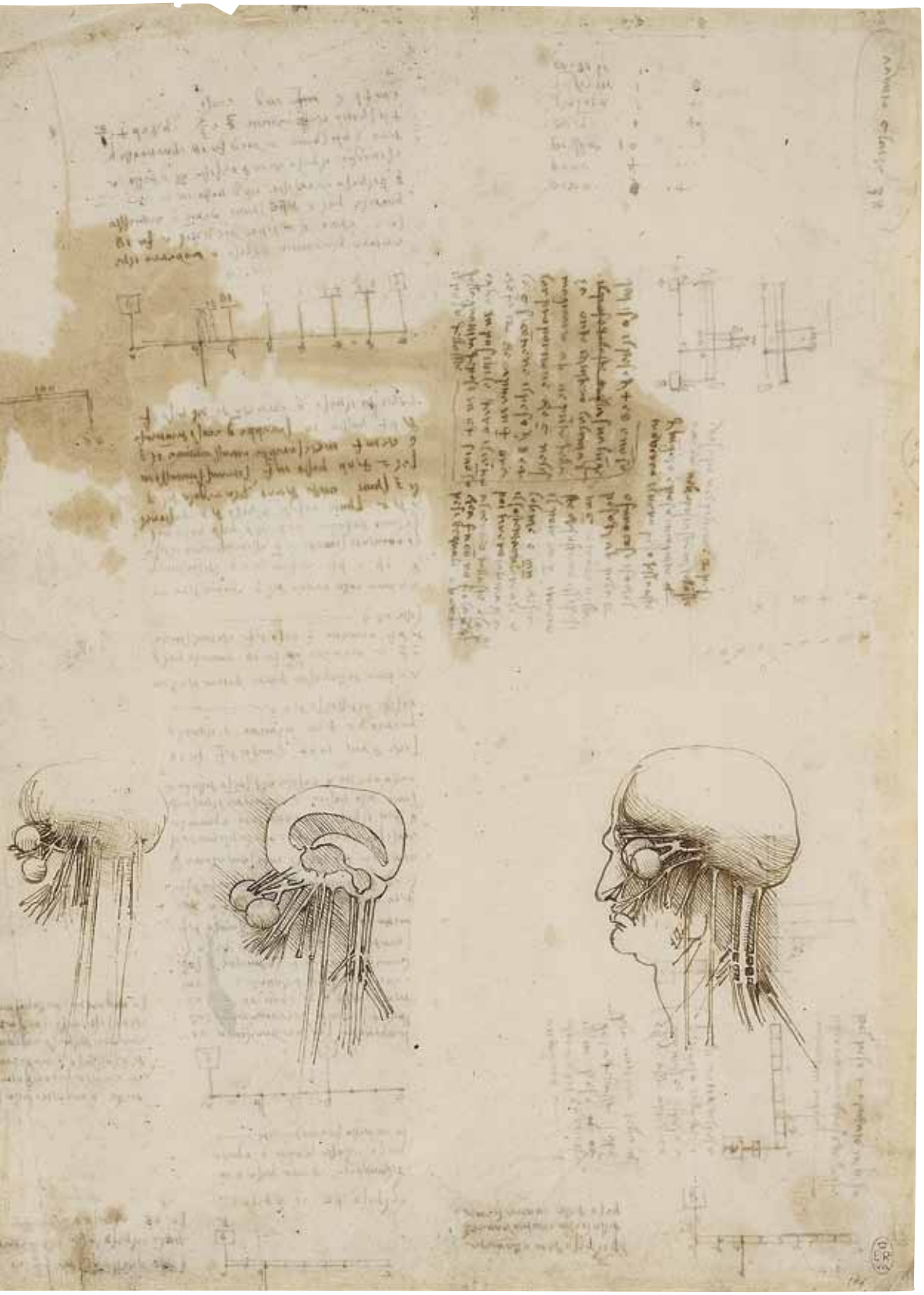
Leonardo's injection of wax into the ventricles of the brain, recorded in no. 48, revealed that their form was much more complex than the traditional three bulbs. He still labelled the lateral ventricles '*imprensiva*', the third ventricle '*senso comune*' and the fourth ventricle '*memoria*', wishing to locate the mental faculties within the ventricles, but on the same sheet he wrote:

> Since we have clearly seen that the [fourth] ventricle *a* is at the end of the spinal cord where all the nerves which give the sense of touch come together, we can judge that the sense of touch passes into this ventricle, since Nature operates in all things in the shortest time and way possible.

In other words, he believed that the spinal cord passed into the fourth ventricle, but he still labelled that ventricle '*memoria*'. We can sense the tension between theory and observation, and observation was starting to prevail. On a stray sheet from Manuscript B, now in Weimar (fig. 20), the ventricles are again labelled with the faculties but the cranial nerves and spinal cord stream to the base of the brain with no apparent connection to the ventricles/faculties. And on the present sheet Leonardo has finally abandoned any attempt to connect the nerves with the ventricles or to locate the mental faculties.

Fig. 20. Leonardo da Vinci
*The brain, cerebral ventricles and cranial nerves, c.*1508
Pen and ink, 19.2 × 13.5 cm
Schlossmuseum, Weimar

The same basic pattern of cranial nerves is indicated in all three drawings. To the front of the brain are the olfactory tracts (associated with cranial nerve I or CNI) and the eyes, optic nerves, optic chiasm and optic tracts (CNII – cf. no. 36). Below are the maxillary and mandibular nerves, shown with separate points of origin on the brain though they are in fact divisions of the trigeminal nerve (CNV); its third division, the ophthalmic nerve, is not shown. The vagus nerves (CNX) are seen travelling from the mid-point of the brain vertically downwards (cf. no. 35). Either side of the spinal cord are the pair of ancillary nerves, which Leonardo had erroneously shown travelling within the cervical vertebrae in nos 38b–39b, together with a portion of the brachial plexus.



51 The tongue, and the production of the voice

*c.*1508–10
Pen and ink over traces of black chalk
32.1 × 22.7 cm
RL 19115r; QA IV.10r; O'M&S 39; K&P 114v

The theme of this page is the physiology of the human voice – a remarkably novel field of study – but Leonardo constantly finds himself bogged down by excessive detail or sidetracked into irrelevant issues. Above centre is a depiction of the tongue, which Leonardo states has 24 muscles, 'which correspond to the six muscles of which the mass of the tongue … is composed'; we now identify eight tongue muscles on either side (four extrinsic, with an origin outside the tongue, and four intrinsic, beginning and ending within the tongue), and thus 16 in total. Above this is a cross-section of the tongue and hard and soft palates to show the cavities of mouth and nose, all of which Leonardo recognised as involved in sound production. Immediately to the left are three rough sketches and a note on the position of the lips in the production of the vowel sounds 'a', 'o' and 'u'.

Leonardo goes on to consider the function of the trachea in sound production:

> Describe and draw in what way the function of varying, modulating and articulating the voice in singing is a simple function of the rings of the trachea moved by the reversive [recurrent laryngeal] nerves, and in this case no part of the tongue is used. And this rests on what I have proved before, that the pipes of an organ are not made lower or higher pitched by the mutation of the fistula (that is, the place where the sound is generated) by making it wider or narrower, but only by the mutation of the pipe itself, into wide or narrow, or into long or short.

Leonardo thus believed that the shape of the 'pipe' of the trachea is responsible for the pitch of the note produced in the throat (cf. no. 35), and that the vocal cords are merely a sounding device. A more sophisticated analysis of the role of the vocal cords is to be found on no. 57a. Finally Leonardo states that 'the tongue is employed in the pronunciation and articulation of the syllables, components of all words', and at top right he starts a grid of simple syllables, each consonant with each vowel.

But within this relatively straightforward analysis of voice production, Leonardo continually digresses, culminating in the paean:

> Though human ingenuity by various inventions with different instruments yields the same end, it will never devise an invention more beautiful, simpler or more succinct than does Nature, because in her inventions nothing is lacking and nothing superfluous, and she does not involve counterweights when she makes organs suitable for motion in the bodies of animals, but puts there the soul, the composer of the body. … This discourse does not belong here but it is required in the composition of animal bodies. And the rest of the definition of the soul I leave to the minds of friars, fathers of the people, who by inspiration know all secrets.

52a The superficial anatomy of the shoulder and neck

*c.*1510–11
Pen and ink with wash over black chalk
29.2 × 19.8 cm
RL 19003r; MS A.4r; O'M&S 43; K&P 137r

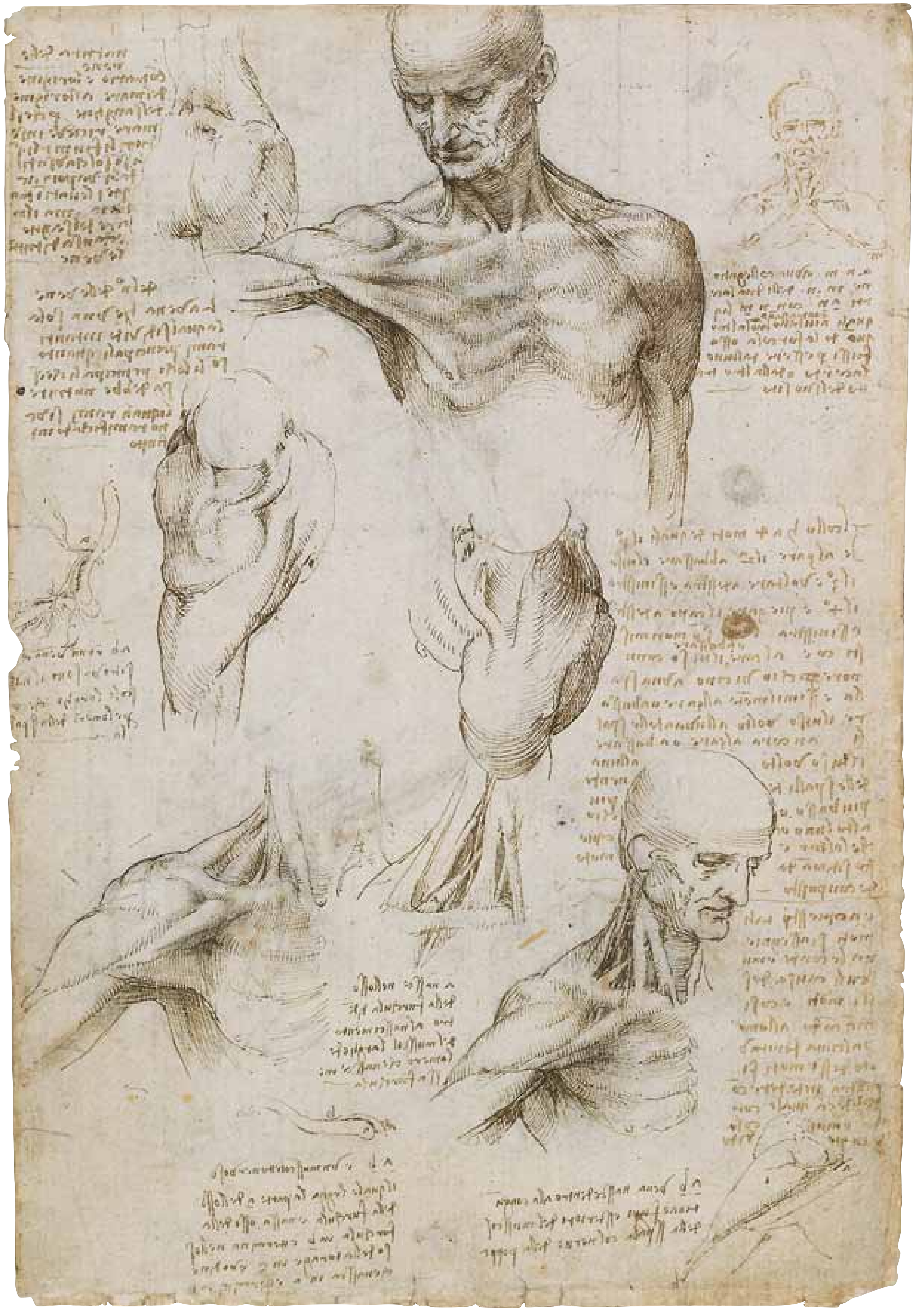
This and the following 15 sheets (to no. 67) come from the so-called 'Anatomical Manuscript A' (hereafter simply Manuscript A), compiled during the winter of 1510–11 when Leonardo was apparently working in collaboration with Marcantonio della Torre, Professor of Anatomy at the University of Pavia. As a result of this collaboration Leonardo had more access to human material than at any other period in his career, and the resulting drawings, concentrating on the muscles and bones, are in many respects the high point of his anatomical work.

Most of the drawings on the present sheet are based on study of a live subject, informed by a knowledge of the underlying structures obtained by dissection. They display perplexing anatomical features seen on many other sheets of the period – a wide gap between the two heads of the sternocleidomastoid muscle on the sternum and clavicle, and a fascicular appearance to the muscles pectoralis major (from the chest to the arm) and deltoid (shoulder). For example, in the study at lower left we see a strongly contracted clavicular portion of pectoralis major and a virtually flaccid sternocostal portion, and deltoid appears divided almost in half.

The drawing at the centre of the page shows the left shoulder from above with the subject facing to the left, whereas the drawing at centre left, which at first glance depicts the same region, shows the right shoulder from above with the subject facing to the right. The two images should thus mirror one another, but the musculature is very asymmetric: in the latter drawing, deltoid is again divided and appears to receive a major contribution from the clavicular portion of pectoralis major.

The drawings to lower right show the structures underlying the superficial views. The omohyoid muscle is seen underneath and almost perpendicular to sternocleidomastoid, though it seems to attach to the clavicle rather than to the scapula. The cephalic vein within the deltopectoral groove is well shown in all three drawings.

In a note Leonardo discusses his understanding of movement as composed of separable elements. He distinguished between 'simple' movements caused by one muscle or muscle group only; 'mixed' movements (elsewhere called compound or composite movements), caused by two independently operating muscles; and 'decomposite' or doubly compound movements, caused by three independently operating muscles. This is an expression of Leonardo's understandable urge to resolve complex physical scenarios into simpler elements. His work as an anatomist led him to see that the apparently infinite movements of the body were the result of a finite number of muscle actions.



52b The muscles of the shoulder

*c.*1510–11
Pen and ink with wash, over black chalk
29.2 × 19.8 cm
RL 19003v; MS A.4v; O'M&S 48; K&P 137v

All the drawings on this page deal with the muscles of the right shoulder. At upper centre and lower right Leonardo divided pectoralis major into four fascicles, and pectoralis minor is thus visible beneath; in the neck one can see sternocleidomastoid, omohyoid, levator scapulae and trapezius (cf. key diagram to no. 57b). Trapezius perplexed Leonardo: it is composed of superior fibres that descend, middle fibres that are horizontal and inferior fibres that ascend, and he therefore sometimes rendered it as several distinct muscles.

The drawing at top left is very similar to that on no. 53b (cf. key diagram there), though here the deltoid is in place; that muscle is also composed of three distinct sets of fibres, and Leonardo thus rendered it in a number of different ways – here it is virtually split in two, with distinct heads on the acromion and spine of the scapula.

At centre left is the deep structure of the shoulder and scapula from the front, with the ribs lifted away (roughly sketched in a lighter ink to the right). The contribution of the broad sheet of subscapularis to the 'rotator cuff' of the shoulder is elegantly demonstrated. The long head of biceps is present in its entirety, and its short head and coracobrachialis are indicated by two of the 'tabs' on the coracoid process (the other two are pectoralis minor). Leonardo has correctly shown the long head of triceps attaching to the border of the scapula. A note records the function of teres major and latissimus dorsi in rotating the humerus, but their attachments should be adjacent anterior to posterior, not proximal to distal as illustrated.

The drawing below places the ribs over the scapula and adds another layer of muscle. A nerve, either the median or ulnar, runs adjacent to coracobrachialis and can be followed up into the neck; the coracoclavicular ligament is clearly depicted. Most of these structures are seen again in the drawing at lower right.

At top right is perhaps the most complex of Leonardo's 'thread diagrams', summarising the entire three-dimensional structure of the shoulder in a single depiction. All the major muscles, both anterior and posterior, are reduced to threads or cords along their lines of force. The clavicle and ribs are also reduced in thickness to improve the 'transparency' of the diagram, but as Leonardo acknowledges in the note tucked under the arm, the density of information in such a diagram hinders its intelligibility: he reminds himself to draw the diagram larger while maintaining the same thickness of ribs and muscle-threads.

53a The superficial anatomy of the shoulder and neck

*c.*1510–11
Pen and ink with wash over black chalk
28.9 × 19.8 cm
RL 19001v; MS A.2v; O'M&S 44; K&P 136v

These drawings run as a sequence from upper right, turning the body slowly in space to end with a frontal dissected view at the bottom of the sheet. While one must be wary of reading Leonardo's anatomical drawings as simple depictions of what he had in front of him, the sensitivity of surface modelling strongly suggests that they were made from the life – though the convincing manner in which Leonardo shows the skin stripped from the living muscles in the last drawing emphasises his powers of visualisation. Leonardo was aware that in death the muscles are fully relaxed, and that to obtain a true knowledge of their form he had to observe them in the living.

The final drawing shows pectoralis major (running from the chest across to the humerus), again divided into fascicles. While it is not unusual to see a difference in the clavicular, sternal and costal portions of that muscle, this degree of fasciculation is highly unnatural. Dissection of unfixed tissue may lead to the accidental separation of a muscle into strands, whereas fixation hardens the muscle fibres and accentuates the fascia that separates the individual muscles. Leonardo believed that, with enlargement, muscles could fuse, and with atrophy they could separate; and indeed, in the extremely lean individuals that Leonardo liked to draw, muscles can appear fasciculated due to loss of muscle mass. But here and elsewhere he divided the muscle primarily for didactic purposes, to emphasise its different portions and range of attachment, as a compromise between a 'realistic' depiction and the schematisation of his 'thread diagrams'. Thus Leonardo could show clearly, for example, that the clavicular portion of pectoralis major inserts further down the humerus than the sternal and costal portions. Between the fenestrations in pectoralis major one may also glimpse neurovascular components running from the brachial plexus, and pectoralis minor passing upwards from the third, fourth and fifth ribs to its attachment on the coracoid process of the scapula.

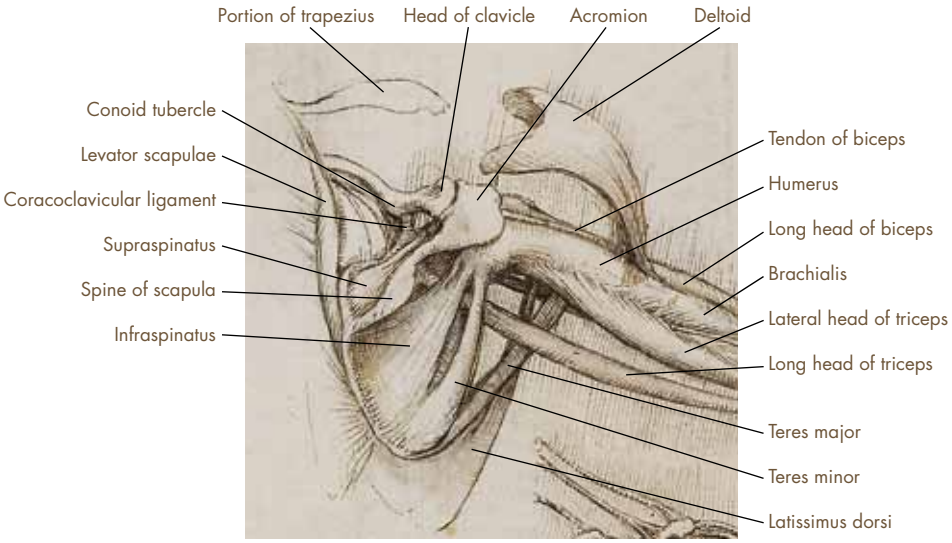
53b The bones and muscles of the shoulder

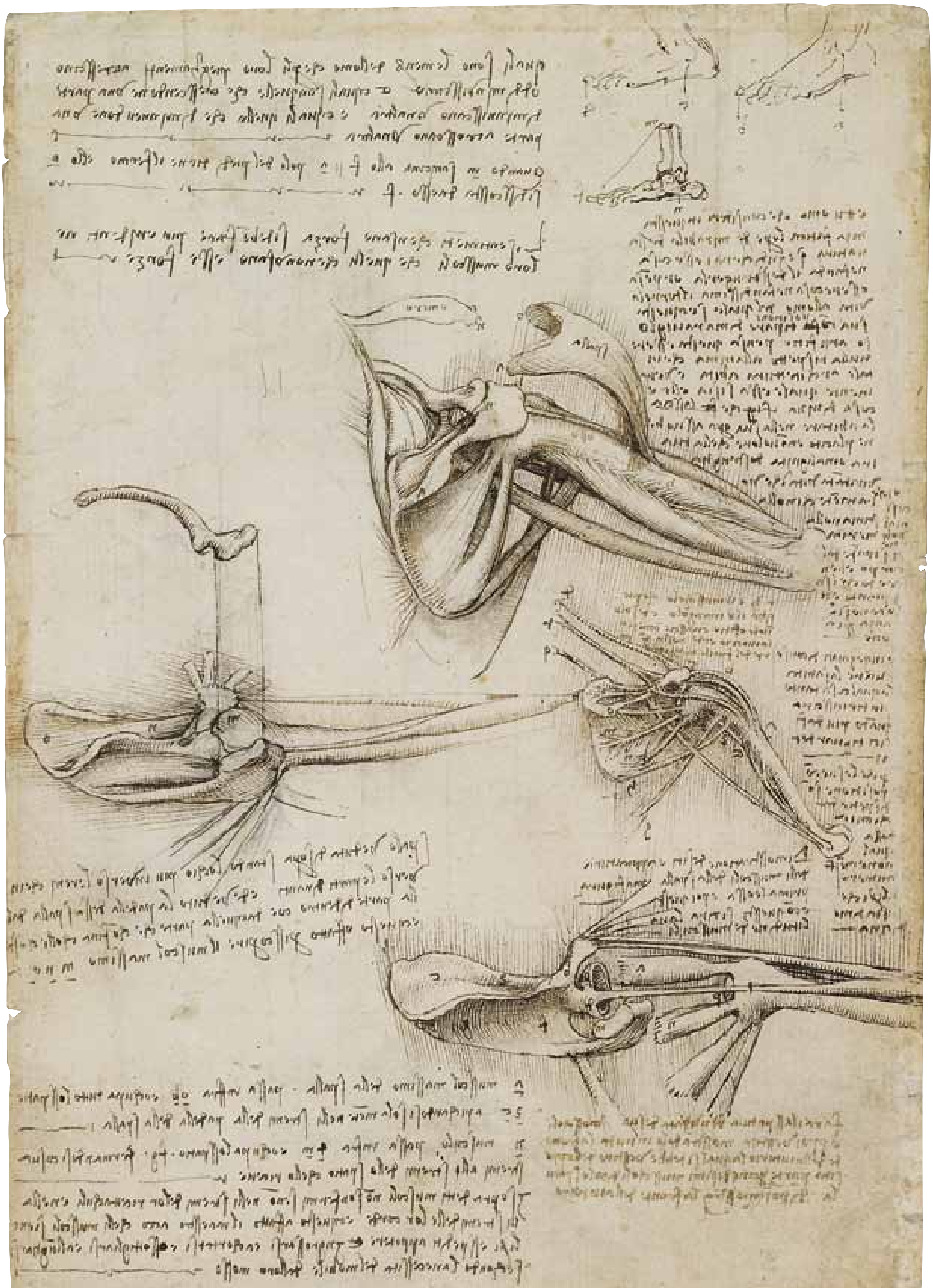
*c.*1510–11
Pen and ink with wash over black chalk
28.9 × 19.8 cm
RL 19001r; MS A.2r; O'M&S 50; K&P 136r

The drawings show the bones and muscles of the right shoulder from behind and above. In the largest drawing, at upper centre, deltoid and a portion of trapezius have been lifted away to show the 'ball' of the head of the humerus sitting in the 'socket' of the glenoid fossa (see key diagram below). Leonardo's anatomical acuity is demonstrated by his illustration of part of the coracoclavicular ligament, just next to the conoid tubercle of the clavicle; but (as throughout the manuscript) he shows a strange articulation between the clavicle and the acromion, with the entire curved end of the clavicle as a 'ball' fitting into an extensive shallow 'socket' on the acromion. The 'thread diagram' at centre right shows the same region, with deltoid and trapezius in place and all the muscles reduced to cords.

In the drawing at centre left Leonardo turns the scapula forward so that subscapularis can be seen (*o n m*). The tip of the coracoid process appears spatulate (flattened) with the short head of biceps and four tabs radiating from its anterior aspect: the tab to the right is probably coracobrachialis, the other three probably pectoralis minor. The two heads of biceps meet in a long 'V' with the apex towards the elbow.

The drawing at lower right shows the structure from the same angle, with the humerus now pulled from the glenoid fossa. The four tabs on the head of the humerus represent the muscles of the 'rotator cuff' – subscapularis, supraspinatus, infraspinatus and teres minor. The two heads of biceps are seen, on the superior aspect of the glenoid fossa and on the coracoid process.





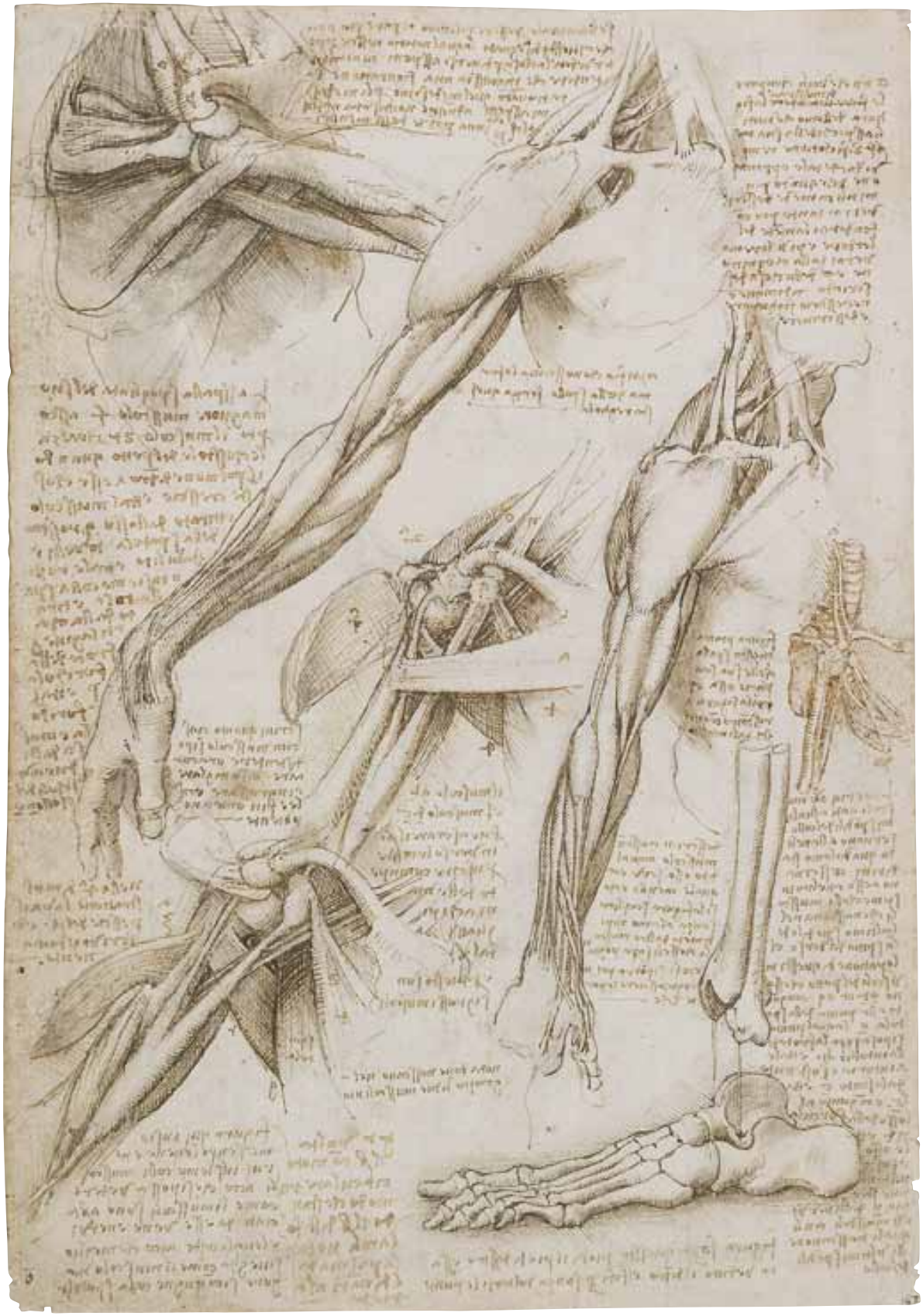
54 The muscles of the shoulder and arm, and the bones of the foot

*c.*1510–11
Pen and ink with wash, over black chalk
28.9 × 20.1 cm
RL 19013v; MS A.14v; O'M&S 49; K&P 144v

This is one of the densest and most majestic of Leonardo's anatomical sheets, and once again the focus is the structure of the shoulder and arm. The largest drawings at upper centre and centre right show the same stage of dissection from a slightly different aspect; the muscles and tendons of the forearm, especially those that act upon the thumb, are exquisitely drawn. In the drawing at the centre of the page, the deltoid is lifted away and the upper and lower portions of pectoralis major removed (the sternal portion remains) to reveal more of the shoulder joint, showing clearly the attachment on the coracoid process of pectoralis minor, coracobrachialis and the short head of biceps. These structures are represented (in a lateral view) in the 'thread diagram' at centre right, with a note that attempts to explain the mechanism by which the cavity of the chest expands, tracing a chain of muscular action from the first vertebra of the neck, through trapezius, the clavicle, the coracoid process and pectoralis minor to the ribs. There must have been great satisfaction for Leonardo in explaining how this structure worked as a unit – but in reality none of these structures significantly effects the expansion of the chest.

At lower left, the sternal portion of pectoralis major has been reflected to the side of the humerus, and the axillary nerve and posterior humeral circumflex vessels can now clearly be seen streaming into the region from the neck. Leonardo reminds himself: 'In the fourth diagram, lift off the fish of the arm [biceps] and describe what remains'; the continuation of this series of dissection views can be seen on no. 52b.

The drawing at upper left of this sheet is one of Leonardo's less successful depictions of the shoulder – the curvature of the clavicle is exaggerated and the acromion is shown as a separate bone (cf. no. 64b). The drawing of the bones of the foot at lower right is one of a series of similar studies scattered throughout Manuscript A.



55 The muscles of the upper spine

*c.*1510–11
Pen and ink with wash, over black chalk
28.9 × 20.5 cm
RL 19015r; MS A.16r; O'M&S 16; K&P 149r

Leonardo's primary concern here was the movement and stabilisation of the upper spine. This is a complex, layered region and extremely difficult to dissect with fresh material; while Leonardo's details are not perfect, the fact that he was able to arrive at a clear grasp of the area is highly impressive. As usual, the page should be read from upper right to lower left – the five main drawings are labelled '1st' to '5th', showing the order of dissection from superficial to deep.

In the first drawing the trapezius muscle is shown as a fused bundle of more or less distinct elements, with its origins running down the upper vertebrae (its upper point on the occipital bone is not seen) and its insertion on the spine of the scapula. Leonardo's drawing seems to show the lower portions attached to, or even disappearing under, the medial (inner) margin of the scapula, below the level of its spine. Next, trapezius is removed to reveal supraspinatus, and levator scapulae is seen running upwards from the scapula. What is probably serratus posterior superior is shown as three muscles running diagonally downwards from the spine.

In the third drawing levator scapulae is reduced to threads and rhomboid major and the posterior layer of the thoracolumbar fascia are removed to show the erector spinae muscles coursing upwards; some ribs are now glimpsed, with their external intercostal muscles. The inferior belly of the omohyoid muscle and components of the brachial plexus are indicated above the scapula, and the three muscles representing serratus posterior superior are seen again. That muscle is often so poorly developed that it can be missed by the novice dissector, but its insertion on the ribs led Leonardo to believe that it was important for breathing.

In the fourth drawing Leonardo removes serratus posterior superior and the view of the erector spinae muscles is now unimpeded, together with a splenius muscle, probably splenius capitis, coursing upwards. In the fifth drawing this has been removed and the spinalis muscles are seen coursing downwards, with what may be semispinalis capitis running more vertically.

At lower right is a 'thread diagram' that attempts to combine the previous five drawings into a single schematic depiction, with trapezius shown as at least 12 threads between the spinous processes and different parts of the scapula. And below centre is a schematic depiction of a vertebra pulled in different directions by the tendons of ten muscles: Leonardo saw that for almost every muscle acting on a vertebra, another acts in the opposite direction, the system thereby effecting movement while simultaneously stabilising the spinal column.

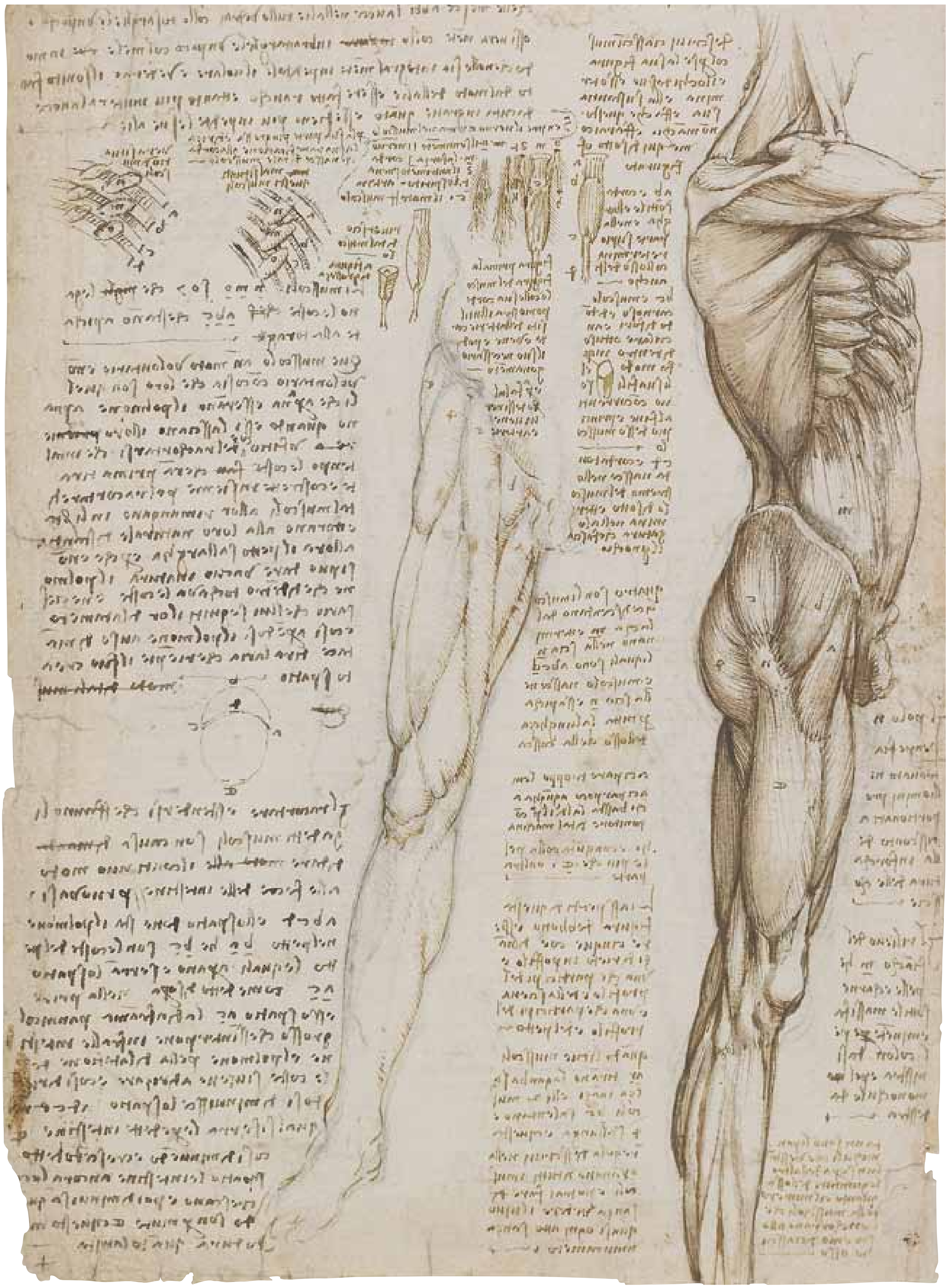
56 The muscles of the trunk and leg

*c.*1510–11
Pen and ink with wash, over black chalk
28.6 × 20.7 cm
RL 19014v; MS A.15v; 20; K&P 148v

The page is dominated by a boldly modelled study of the superficial muscles from the neck to the ankle. Trapezius has been removed from the neck and shoulder, and thus the spine of the scapula is prominent. Latissimus dorsi occupies the region under the arm; to its right is serratus anterior, interdigitating on the lower ribs with the external abdominal oblique muscle (cf. no. 43), the lower portion of which descends to its insertion on the iliac crest of the pelvis. Below the iliac crest are the muscles tensor fasciae latae and gluteus medius and maximus converging on the greater trochanter. Running down the side of the thigh from the greater trochanter is vastus lateralis; Leonardo distinguished an anterior portion of that muscle and stated that it is attached to the skin – as it appears to be continuous with tensor fasciae latae, this may in fact be a portion of the fascia lata, the tissue that connects many of the structures of the thigh. To the left is a front view of the leg with muscles such as sartorius, tensor fasciae latae and gluteus medius clearly shown.

The small diagrams and notes at upper centre constitute an astute analysis of the structure and function of muscles. In diagrammatic form Leonardo distinguishes between a broad, thin tendon of attachment, a muscle body and a narrower tendon of insertion, with connections to the nerves, arteries and veins. Each of these components is identified with a specific function – not just the mechanical function of the muscle and tendon, but also the sensation due to the nerve, and the traditional concepts of 'nourishment' provided by the venous system and 'spirit' by the arterial. In two further small diagrams Leonardo sketches a muscle cut through the middle to show that its section is not circular.

The two drawings at upper left represent intercostal or subcostal muscles (more likely the latter, as Leonardo counted only seven). The annotation 'true position of the muscles' by the left-hand diagram indicates Leonardo's knowledge of the oblique positioning of these muscles with respect to the ribs – the diagram alongside, labelled 'these muscles are poorly positioned', shows the schematic muscles passing perpendicularly from rib to rib. The notes and diagram below outline a system by which the act of breathing aids propulsion of the intestinal contents. Leonardo states that when the subcostals shorten, the ribs are pulled together, the chest is compressed and thus the lungs are squeezed in exhalation. When the subcostal muscles relax, the ribs dilate, the lungs inflate, and the diaphragm, attached to the bottom of the ribs, stretches and flattens, thus compressing and propelling the contents of the colon. While much of this is incorrect, Leonardo did realise that the lungs themselves are passive and inflate due to expansion of the chest.



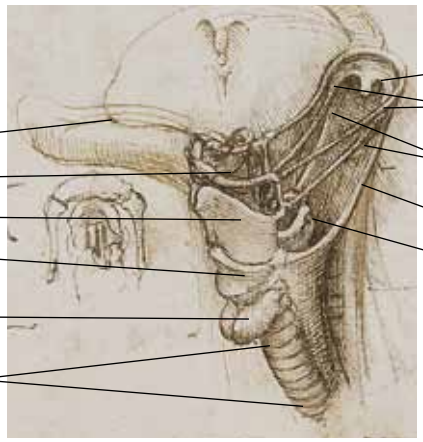
57a The throat, and the muscles of the leg

*c.*1510–11
Pen and ink with wash over black chalk
29.0 × 19.6 cm
RL 19002r; MS A.3r; O'M&S 169; K&P 134r

The leg was presumably the first study to be made here, but the remainder of the page is devoted to the throat, with studies of the pharynx, larynx and trachea and their functions in breathing, speaking and swallowing. The large drawing at upper left displays many of the features seen in the subsequent, less extensive studies (see key diagram below); the odd form of some of the structures may have been derived from animal dissection. Leonardo has shown the uvula, the wishbone-shaped hyoid bone, the thyroid gland, and the thyroid, cricoid and tracheal cartilages. But his understanding of the function of these structures was merely speculative: the thyroid gland, for instance, is 'made to fill in where the muscles are missing, and . . . hold the trachea apart from the bone of the clavicle'.

The three drawings at centre and centre left show the palatoglossus and palatopharyngeus muscles pulling the hyoid bone backwards in order to press the epiglottis over the opening of the larynx during swallowing, thus preventing food or drink entering the larynx, as shown in the sketch at centre right. This is the reason that 'one cannot swallow and breathe or speak at the same time'.

A similarly mechanical account of vocalisation is not easy (cf. no. 51). Leonardo noted correctly that 'the voice is generated at the head of the trachea', and the frontal section of the larynx at lower centre shows the vocal cords and arytenoid cartilages forming a space (the rima glottidis) referred to by Leonardo as a 'flute'. He had studied vortices in wind and water, and he believed that turbulence in the expired air passing through the narrowed area of the rima glottidis set up vibrations that produced the voice (cf. his analysis of blood flow through the similarly shaped aortic valve on nos 85–7). This is substantially correct, with fine muscle movements adjusting the length and tension on the vocal cords to vary the air flow. But Leonardo inferred no role for the uvula in speech, regarding it as 'the dripstone from which falls the humour that descends from above, and falls by way of the oesophagus to the stomach'. This ancient physiology, in which the systems of the body were controlled by the movement and balance of the 'humours', sits uncomfortably alongside the wealth of acute anatomical and physiological observations on the page.



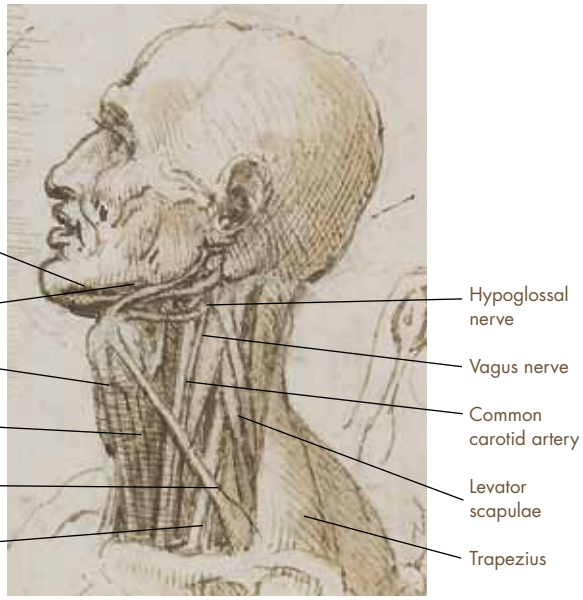
57b The bones of the foot, and the muscles of the neck

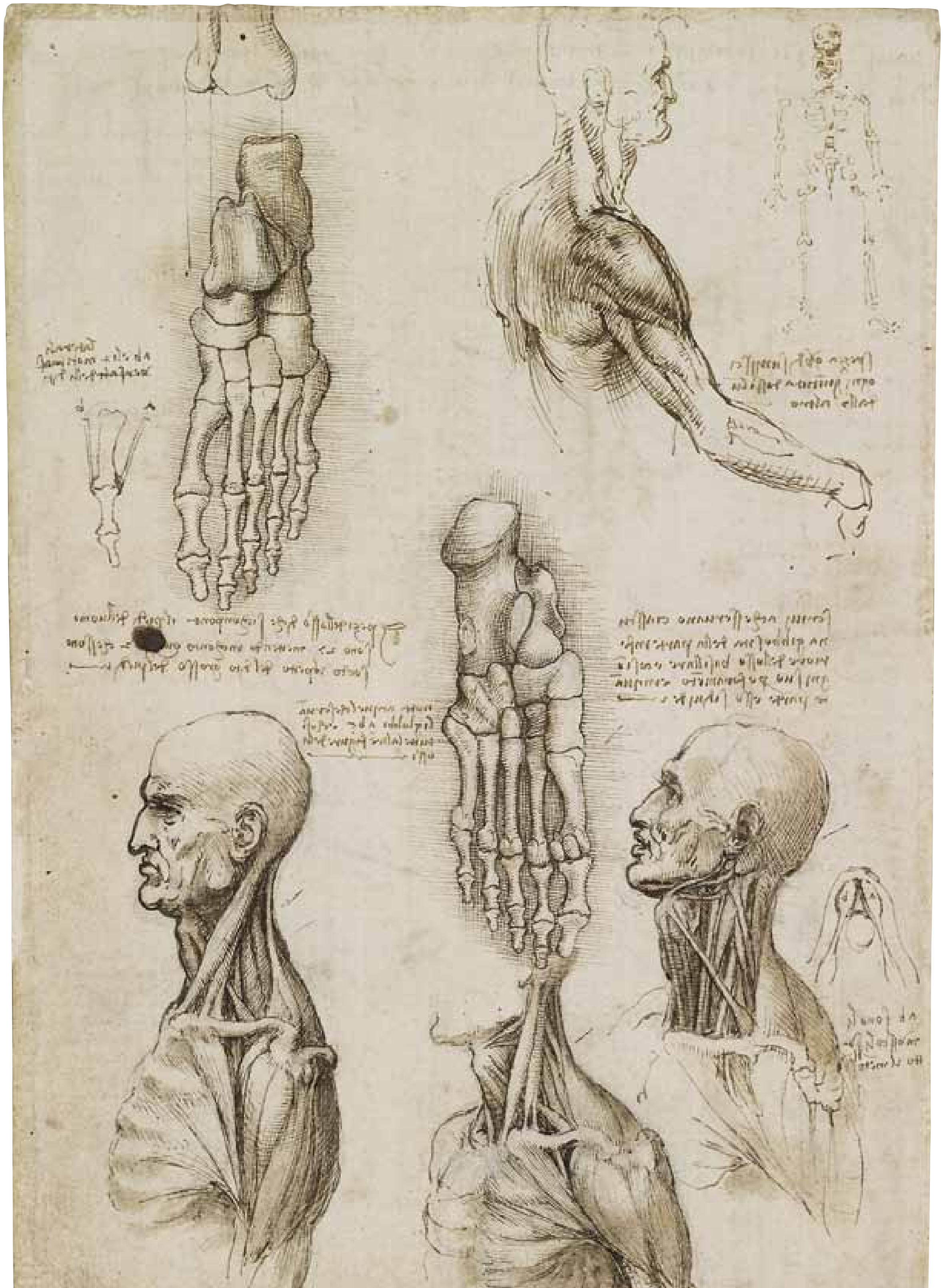
*c.*1510–11
Pen and ink with wash over black chalk
29.0 × 19.6 cm
RL 19002v; MS A.3v; O'M&S 36K&P 134v

The studies of the bones of the foot are mostly accurate, and the few inconsistencies may have resulted from Leonardo using fresh material, poorly cleaned dried material with fragments of ligament remaining, or dried material bound together too loosely. The drawing at the centre of the page shows the foot from below and concentrates on the topography of the cuboid bone, with features labelled *a, b* and *c*—the attachment site of the short plantar ligament, the cuboid tuberosity, and the groove for the tendon of fibularis longus respectively.

The drawing at upper left shows a left foot, though the tibia and fibula hovering above are in the configuration for a right leg; Leonardo may have realised his error, as the lines drawn downwards from the fibula do not end on any tarsal bone. The little toe is shown with two phalanges – three is now usually stated as normal, but in fact two or three phalanges for the little toe occur in roughly equal numbers. The small diagram alongside indicates the action of the abductor and adductor muscles of the toes, those responsible for 'lateral movement', to use Leonardo's term. Muscles analogous to those that move the fingers from side to side are found on the toes, but the ligaments and shape of the phalanges hinder the distinct actions, and usually the best we can do is spread the toes somewhat.

The four drawings along the bottom of the page concentrate on the muscles of the neck and shoulder, and bear some of the peculiarities found throughout Leonardo's depictions of this region. The neck muscles, however, are beautifully presented. The two drawings to the left show the same stage of dissection, with all the muscles intact; in the drawing to the right sternocleidomastoid has been removed to display more clearly the complex of underlying muscles, nerves and vessels, most of which can be identified (see key diagram). The two bellies of the digastric muscle are shown again in the detail of the jaw from below, alongside.

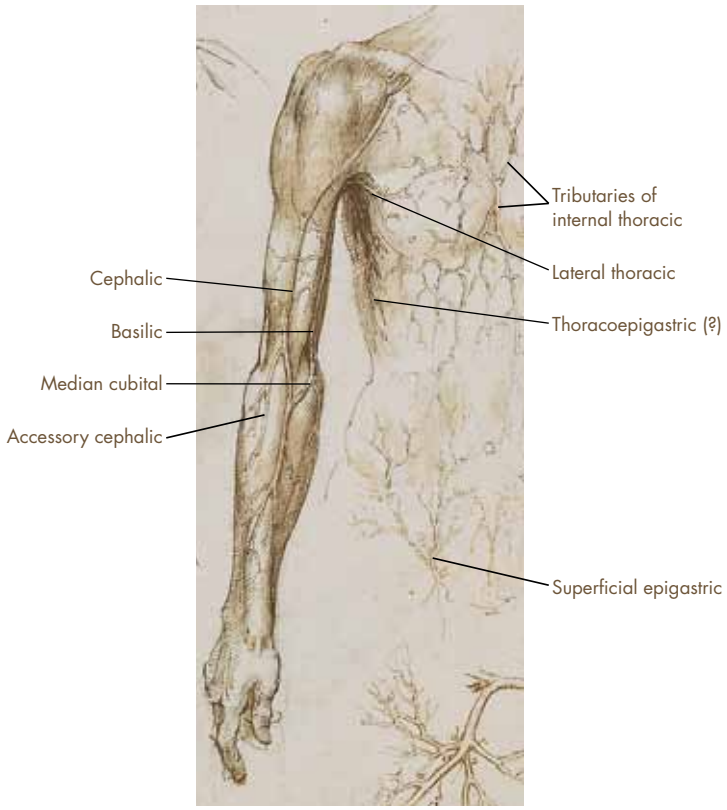




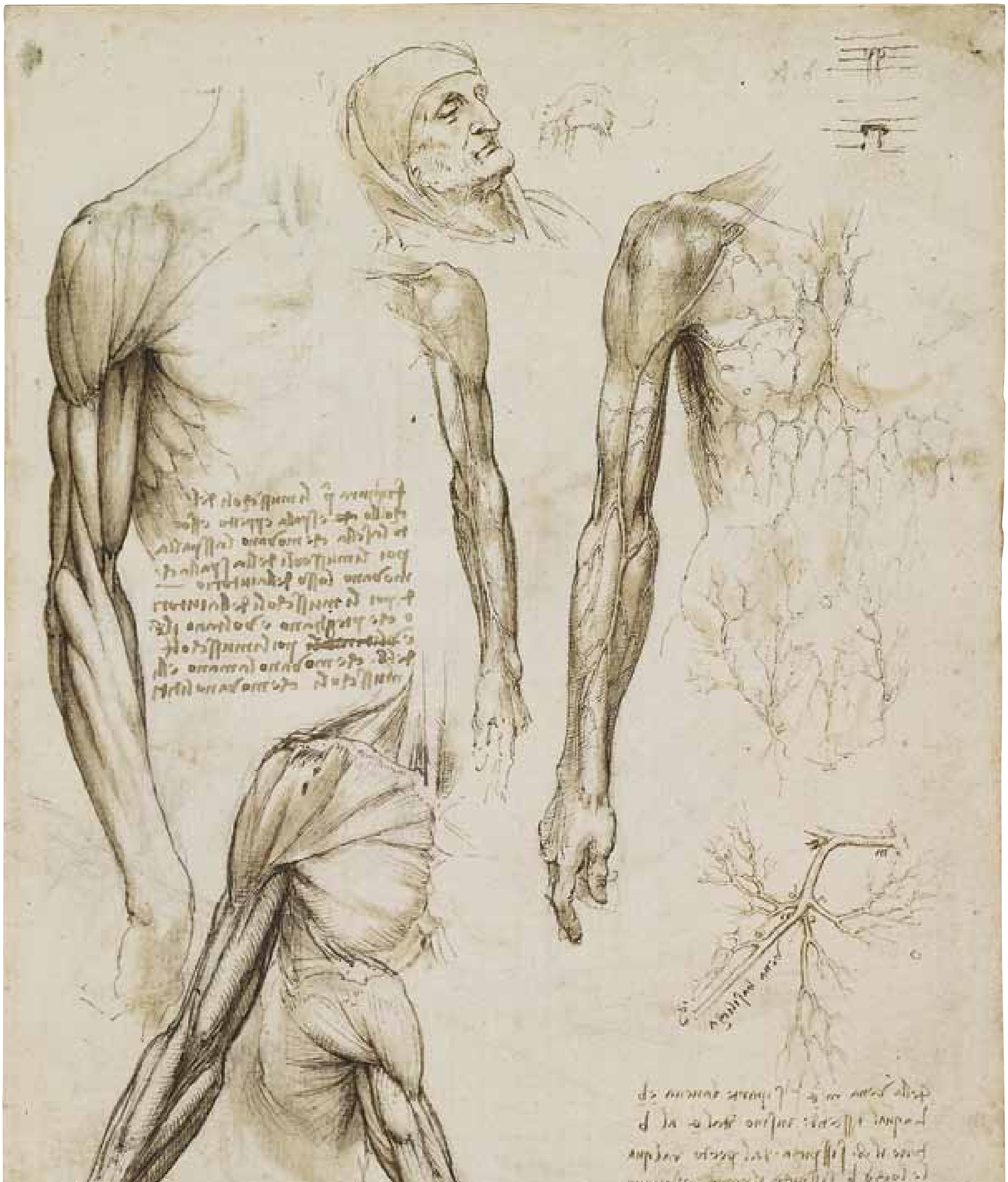
58a The muscles of the arm, and the veins of the arm and trunk

*c.*1510–11
Pen and ink with wash, over black chalk
28.9 × 19.9 cm
RL 19005r; MS A.6r; O'M&S 45; K&P 141r

The elderly and apparently dead man depicted at the top of the sheet was presumably the subject of some of the dissection studies here and elsewhere in Manuscript A. To the right of the head is a sketch of his jaw and neck, with the tongue and hyoid sunken in the flaccidity of recent death. The three consummately elegant studies of the upper limb down the left side of the page, however, give the old man the musculature of Apollo. With a few dabs of wash Leonardo has captured the shimmer of the deep fascia, the connective tissue surrounding and interpenetrating the muscles. As was usual throughout the Renaissance, the corpse is posed as if in action, the muscles imbued with the tension of life. Leonardo has not resorted to diagrammatic devices (such as fenestrating pectoralis major, as is seen repeatedly throughout the manuscript), and all the muscles are identifiable. It is Leonardo at his best.



The large drawing at upper right shows the trunk with only the skin removed (see key diagram). The cutaneous veins of the arm – cephalic, basilic and median cubital – are visible, and on the trunk can be seen the lateral thoracic vein, superficial epigastric veins, tributaries of the internal thoracic vein and possibly a thoracoepigastric vein. Below is a more detailed study of the basilic vein as it enters the axillary vein and then in turn the subclavian vein. The identities of the other veins in this detail are not certain, as there is a large amount of venous drainage in the axillary region, but the cephalic, subscapular, lateral thoracic, thoracoepigastric and thoracodorsal veins are probably all present.



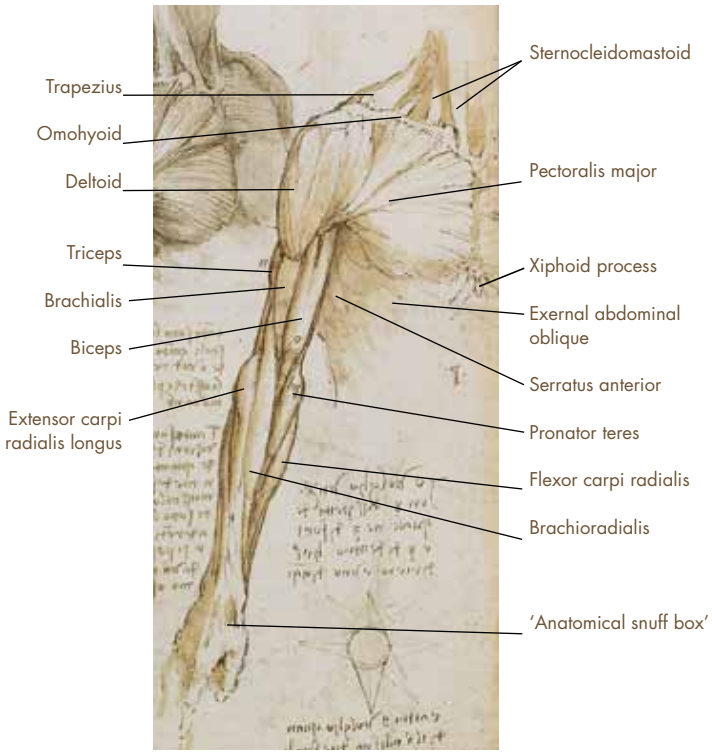
58b The muscles of the shoulder, arm and neck

c.1510–11
Pen and ink with wash over black chalk
28.9 × 19.9 cm
RL 19005v; MS A.6v; O'M&S 47; K&P 141v

59a The muscles of the shoulder, arm and neck

c.1510–11
Pen and ink with wash over black chalk
28.8 × 20.2 cm
RL 19008v; MS A.9v; O'M&S 46; K&P 140v

These two sheets comprise a sequence of eight drawings in which Leonardo turned the shoulder and arm from a fully anterior view (at far right) to a fully posterior view. The small star-shaped diagram and accompanying note at lower right explain Leonardo's intention of depicting the arm through 360 degrees from eight aspects, but the two pages together provide an even more finely divided set of depictions, eight aspects in 180 degrees. There are, as always, a few idiosyncrasies, but the drawings and notes reveal a profound understanding of the muscles of the shoulder and upper arm. Medical illustration has never produced images to surpass those on this sheet, and had Leonardo published his researches, as was clearly in the forefront of his mind at this time, the results would have been truly groundbreaking.



Most of the superficial muscles of the arm and shoulder can be identified (see key diagram). While pectoralis major is here shown as a single muscle (cf. nos 52b, 53a), the deltoid (f`orming the rounded upper contour of the shoulder) is as usual depicted as a compound structure comprising distinct sets of fibres (cf. nos 23, 52a). Likewise, the superior portions of trapezius, running upwards from the spine of the scapula, appear to be separate.

Towards the wrist, at centre right of no. 58b, Leonardo has labelled the tendons of the

abductor pollicis longus and extensor pollicis brevis muscles, both of which act on the thumb, reminding himself to remove the covering muscle (supinator) to find their origins. He goes on to note:

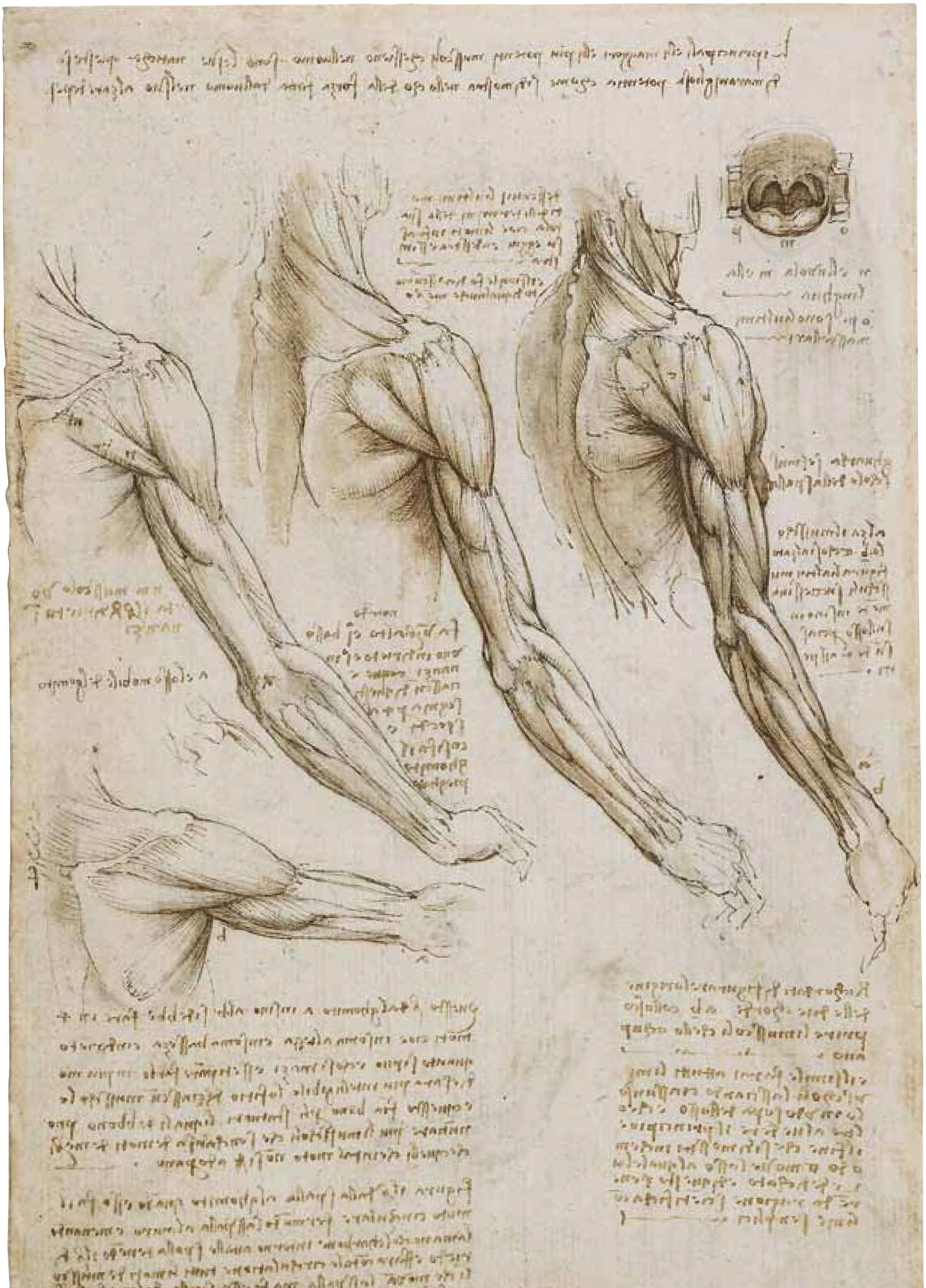
> Do the same for all the muscles, leaving each one on its own, naked on the bone, so that besides seeing its beginning and end, it is shown in what way it moves the bone to which it is dedicated; and of this, the scientific explanation ['*ragione scientificha*'] is to be provided with lines alone [i.e. in a 'thread diagram'].

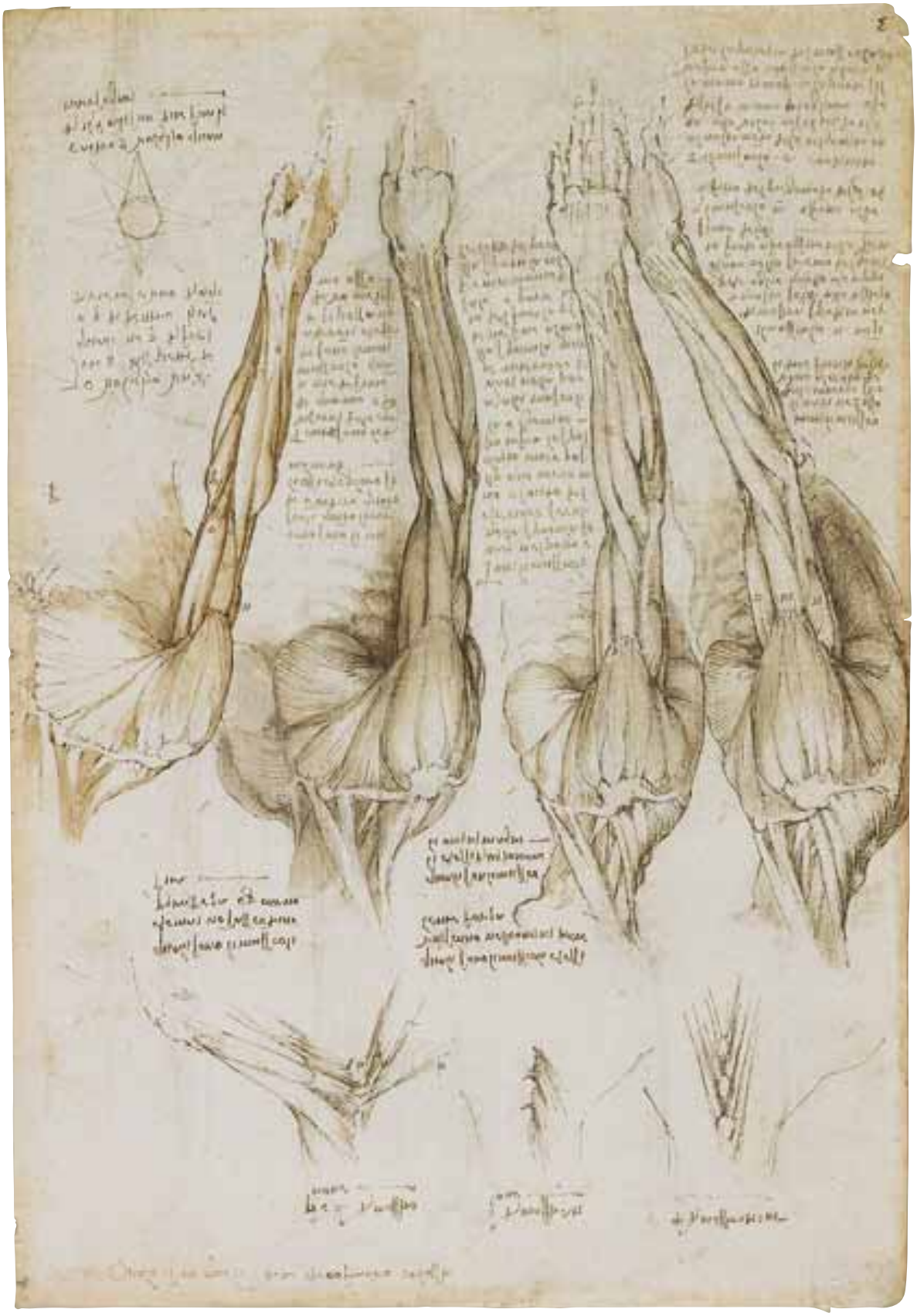
Leonardo explains the actions of the scapular muscles upon the humerus, acutely observing that serratus anterior stabilises the scapula against the chest wall in order for the limb to bear weight, and he notes that brachialis can flex the elbow regardless of the degree of supination of the forearm.

At lower left of no. 58b is a rare mention of the potential artistic usefulness of these anatomical drawings:

> This arm from the elbow [to the shoulder] must be drawn in four movements, that is, fully raised and fully lowered, and backwards as far as possible and likewise forwards; and if it occurs to you to draw it in more ways, the purpose of each muscle will be more intelligible. And this will be good for sculptors, who have to exaggerate the muscles that are the cause of the movements of the limbs more than those that are not used in such movements.

The drawing at the upper right of no. 58b is of the open mouth, showing the uvula, palatal arches, surface of the tongue and upper and lower molars, and should be studied alongside no. 57a. The three brief drawings at the top of no. 59a illustrate the layers of muscles attached to the spinous processes of the neck; this region is studied in much more detail on no. 55.





59b The bones and muscles of the leg

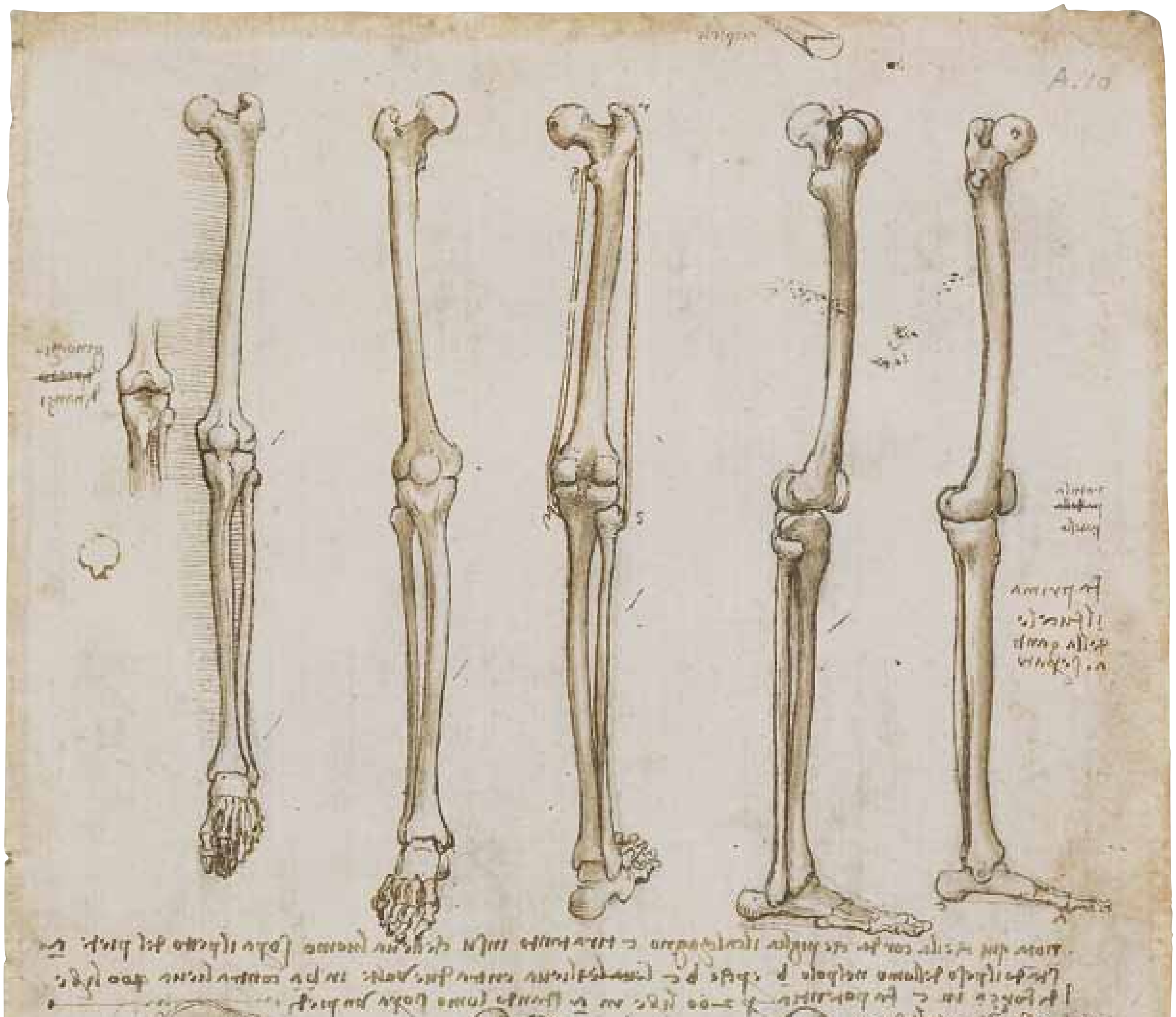
*c.*1510–11
Pen and ink with wash over black chalk
28.8 × 20.2 cm
RL 19008r; MS A.9r; O'M&S 11; K&P 140r

The notes on this page reveal that Leonardo was concerned with three of the mechanisms of the leg, though the shapes of the bones themselves are the most prominent topic of the drawings. The talocrural (ankle) joint is well shown, with the mortice formed by the lower heads of the tibia and fibula fitting onto the talus of the ankle (the tarsal bones of the foot are drawn as a single unit). The slightly enlarged upper head of the fibula and the blunted appearance of the styloid processes at the end of the tibia and fibula may have resulted from using freshly prepared bones with portions of ligaments and cartilage remaining, rather than dried bones.

The drawing at upper right, together with the note running through the centre of the sheet, examines the dynamics of the calcaneal (Achilles) tendon, through which the gastrocnemius and soleus muscles of the calf act on the calcaneus (heel-bone). By a simple proportional calculation Leonardo stated that the distance from the axis of the ankle to the ball of the foot is twice the distance to the end of the calcaneus, and thus to raise a man of 200 pounds on the ball of one foot requires a pull of 400 pounds – his appreciation of the large forces within the body required to perform a simple action is implicit. This action is studied again, though with the proportions of the 'lever' expressed differently, on no. 65a.

Leonardo considers the role of the patella as a sesamoid bone, observing that it connects the muscles rectus femoris, vastus lateralis and vastus medialis with the patellar tendon in the lower leg. A note discusses the lengthening of the surface of the leg in flexion, paralleling the observations on the arm on no. 61. Although there is no equivalent of the patella at the elbow, the fact that on no. 58b Leonardo calls the olecranon 'the moveable bone of the elbow' suggests that he was trying to find an equivalence between the knee and elbow.

The third action to be analysed is more problematic. In the drawings at upper and lower centre Leonardo drew threads to indicate the antagonistic action of muscles on either side of the leg. While the insertions indicated correspond to semimembranosus on the inside of the leg and biceps femoris on the outside, the origins of those muscles lie on the pelvis and not at the head of the femur. When the leg is semiflexed, as in the two drawings below, it is true that contraction of one of these muscles will cause some rotation of the tibia at the knee, but it is surprising that Leonardo chose to highlight this rather than the much more significant actions of flexion and extension.


A.10

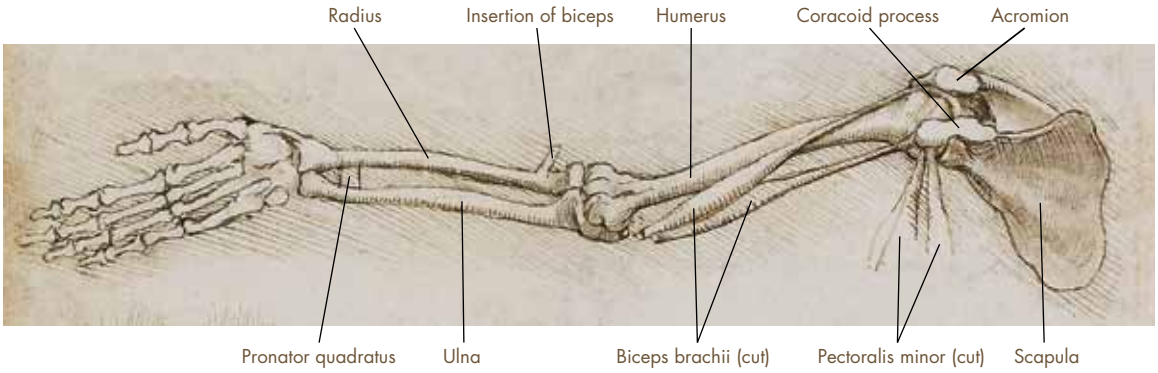
60 The bones and muscles of the arm

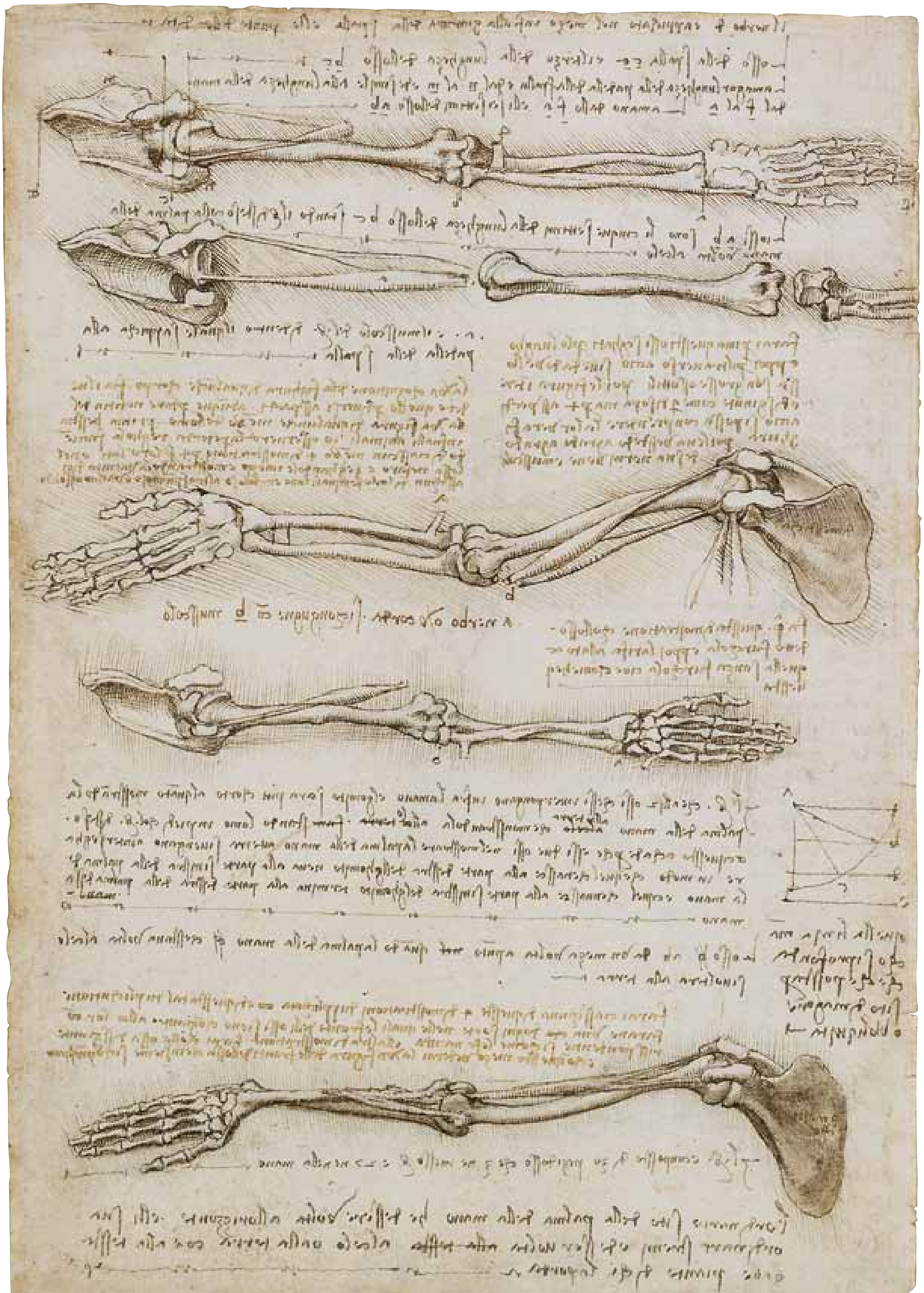
*c.*1510–11
Pen and ink with wash, over black chalk
29.3 × 20.1 cm
RL 19000v; MS A.1v; O'M&S 8; K&P 135v

The page is primarily concerned with the mechanism by which the arm turns to direct the palm upwards (supination) or downwards (pronation).

The upper two drawings show the arm and shoulder from above, held directly away from the side of the body with the palm facing upwards (supinated). In the first drawing the bones are in their natural positions, and in the second they are separated out to demonstrate their articulation. The biceps brachii muscle is beautifully illustrated, with its double origin (the name means 'two heads of the arm') on the scapula. Leonardo discovered that biceps has two actions, both bending the arm at the elbow and supinating the arm (turning the palm to face upwards). While there are other muscles whose sole purpose is supination, biceps is the strongest supinator of the forearm. It would be two centuries before Leonardo's observation was repeated.

The third drawing gives a front view of the arm (see key diagram below), with biceps cut away from its insertion on the radius and thus out of position, and two slips of pectoralis minor dangling from the coracoid process of the scapula. The small square marked between the ulna and radius near the wrist represents pronator quadratus (see no. 63b, lower right), one of the two muscles primarily responsible for pronation (rotating the radius over the ulna to turn the palm downwards) – the position of the arm in the fourth and fifth drawings on the page. Leonardo concluded that as the bones cross and thus become oblique during pronation, the forearm must shorten a little (as illustrated in the small geometrical diagram in the right margin), though this is difficult to observe in practice. The other primary muscle of pronation is pronator teres, which is seen on the forearm in the final drawing. Like biceps, pronator teres has two heads, on the humerus and the ulna, though the latter attachment is not clearly shown.





61 The bones of the arm and leg

*c.*1510–11
Pen and ink with wash, over black chalk
28.6 × 19.3 cm
RL 19004r; MS A.5r; O'M&S 9; K&P 138r

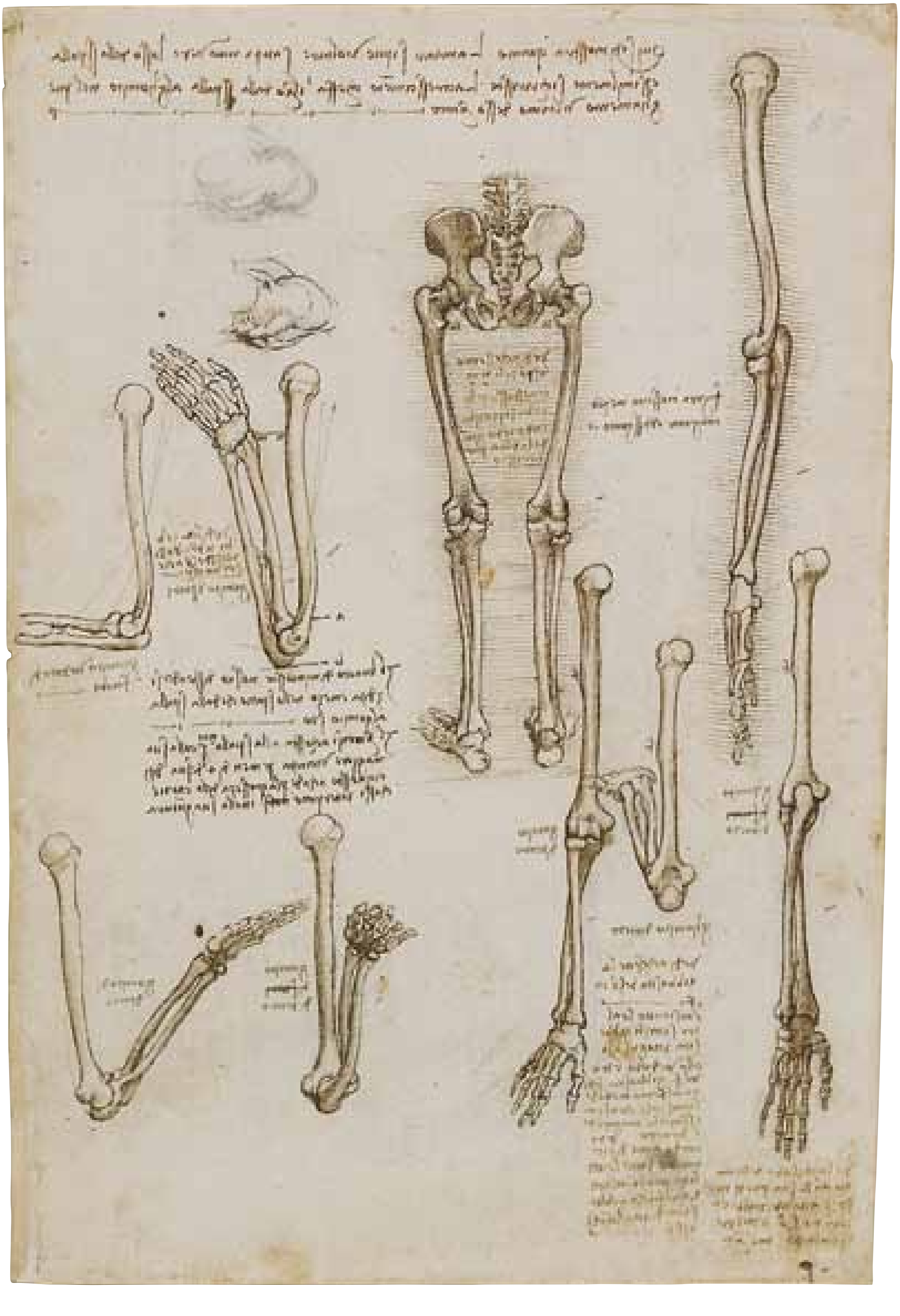
Most of the drawings are concerned with pronation and supination (turning the hand) when the arm is flexed or extended at the elbow, and demonstrate how this occurs without rotation of the humerus. There is no verbal explanation of the action (the role of biceps brachii was treated fully in no. 60) and the exceptionally beautiful drawings are left to speak for themselves.

An ancillary theme is the apparent change in the length of the arm during flexion and extension. In particular, Leonardo observed – as shown in the drawings at centre left – that during flexion, the olecranon process of the ulna (at the lowest point of the drawing to the left of centre) emerges from the olecranon fossa of the humerus to form the point of the elbow, so increasing the apparent length of the upper arm.

In the notes at lower right, Leonardo queries the purpose of the prominence *f,* about halfway down the humerus. He makes a note to 'see what purpose the gibbosity of the arm at *f* serves', followed by: 'I have looked at it, and find that the gibbosity *f* serves as the attachment of the muscle that raises the humerus'. This is the deltoid tuberosity, where the deltoid muscle is attached to the humerus.

In several of the drawings there is a jagged appearance to a portion of the inner margins of the ulna and radius. This may be the result of a healed bad break of both bones, or of ossification or calcification of the interosseous membrane that joined the two bones, due to ageing, diet or hard labour. Leonardo did not realise that these *'gobbi'* ('bumps') were not design features, and with faint pen lines at centre left he posited that they might be the sites of insertion of muscles of the upper arm.

The drawing at the centre of the sheet examines the lower spine, sacrum, pelvic girdle and lower limbs. The number of foramina (holes) in the sacrum is correct and the pelvic girdle is shown properly articulated and tilted – even Vesalius failed to capture this. The small note between the femurs correctly states that during childbirth the coccyx moves – it is pressed backwards by between 2.5 and 3.5 cm (1–1½ in) to allow a significant increase in the size of the birth canal.



62 The vertebral column

*c.*1510–11
Pen and ink with wash, over black chalk
28.6 × 20.0 cm
RL 19007v; MS A.8v; O'M&S 2; K&P 139v

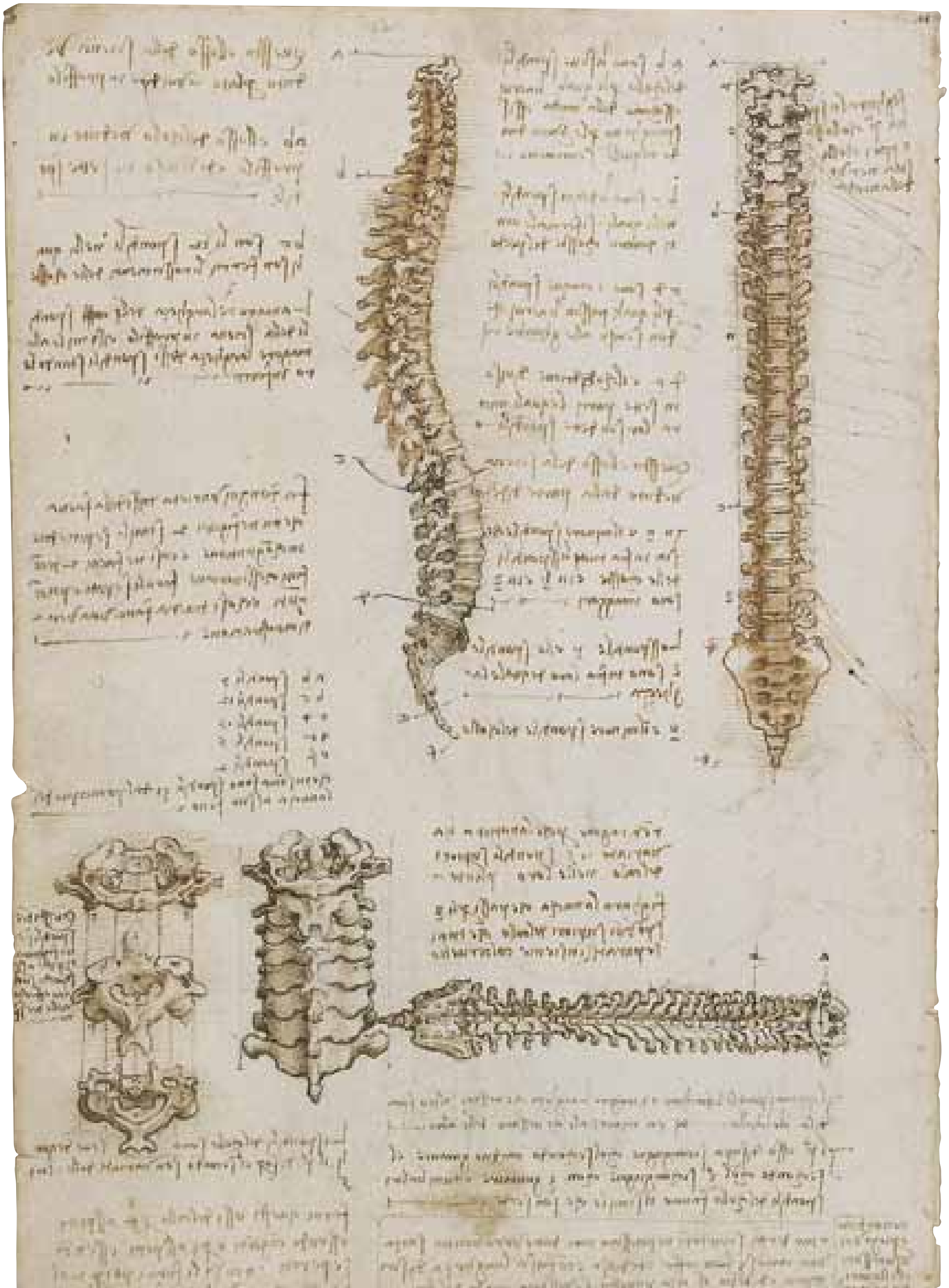
This is the first accurate depiction of the spine in history, and 500 years later no artist or anatomical illustrator has surpassed Leonardo's accomplishment.

The drawing at upper left depicts an ergonomically correct spine with its curvatures and sacral tilt perfectly shown. The only error is that Leonardo has shown 12 thoracic vertebral bodies (correctly) but 13 spines – between the second and third thoracic vertebrae is a spinous process with no vertebral body, but so convincing is Leonardo's drawing that even most anatomists fail to notice this until it is pointed out.

To the right is a correctly articulated frontal view of the spine. The subtlety of Leonardo's shading allows the curvatures to be clearly understood, and variations in the sizes of the vertebral bodies and transverse processes are carefully recorded – vertical lines on either side of the spine give the maximum width of the processes. To the right of the image, long oblique lines indicate where the spinal nerves would be, including the brachial and sacrolumbar plexus. The viewpoint of the image at lower right is a little unusual, showing the posterior aspect but from an elevated position; Leonardo's reasons for choosing this aspect are not explained in the accompanying notes – perhaps he wished to give a sense of the length of the posterior spinous processes.

The note at centre left is deceptively simple in its accuracy. It enumerates the vertebrae in a completely modern manner, though Leonardo did not have the vocabulary that we use. Thus he counts 7 cervical segments, 12 thoracic segments (he ignored his extra-spine mistake), 5 lumbar segments, 5 sacral segments and 2 coccygeal segments. Simply stating the correct number of fused sacral vertebrae would have secured Leonardo a place in anatomical history, but this last number requires comment. There is no correct number of separate segments to the coccyx – the 'tail' of the embryo develops and then degenerates, and the degree of degeneration accounts for variation between individuals in the number of segments. Modern textbooks state that it is composed of 2–3 or even 3–5 rudimentary segments; Leonardo saw two distinct segments in his subject, and we cannot say that he was wrong.

The drawing at lower left demonstrates how the first and second cervical vertebrae (atlas and axis) fit onto the third, using the diagrammatic convention of the 'exploded view'. The major variations in the shape of each of these vertebrae clearly intrigued Leonardo. To the right he presents a detailed view of the cervical vertebrae assembled, with vertical lines again indicating that the transverse processes of the first and last are equal in width.



63a The bones of the hand

*c.*1510–11
Pen and ink with wash, over black chalk
28.8 × 20.2 cm
RL 19009v; MS A.10v; O'M&S 10; K&P 143v

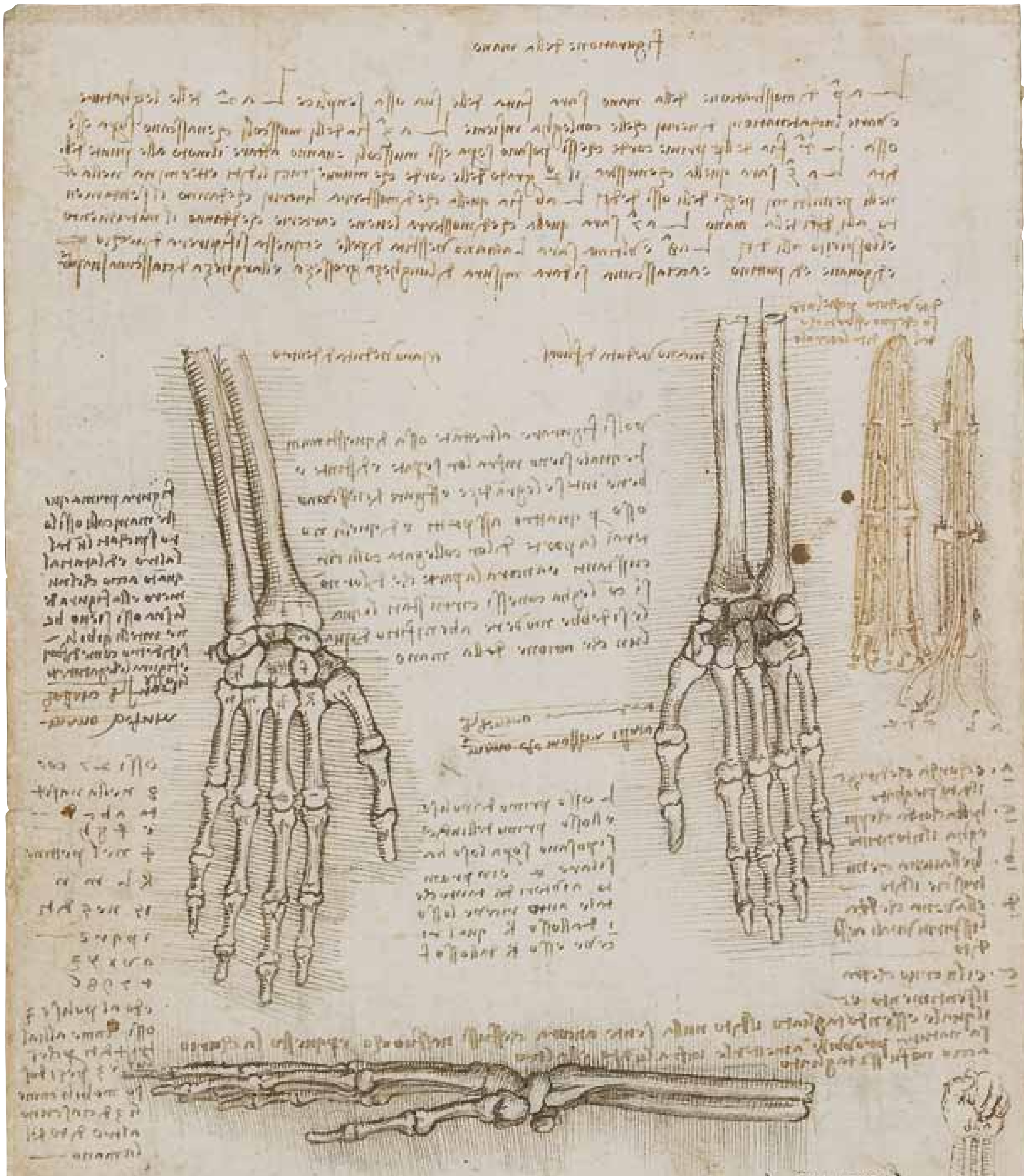
At the top of the page Leonardo sets out the sequence of depictions of the hand that he intended to provide:

> The first demonstration of the hand will be of its bones alone. The second, of the ligaments and various interconnections of tendons that join them together. The third will be of the muscles that arise on these bones. The fourth will be of the first tendons that are placed on these muscles, and give movement to the fingertips. The fifth will show the second rank of tendons, which move all the fingers and terminate on the penultimate piece of bone of the fingers. The sixth will show the nerves that give sensation to the fingers of the hand. The seventh will show the veins and arteries that give nourishment and spirit to the fingers. The eighth and last will be the hand clothed with skin, and this will be drawn for an old man, a young man and a child; and for each will be given the measurements of length, thickness and width for each of its parts

These intentions were mostly carried out, here and on nos 63b and 64a, though Leonardo did not, so far as we know, make a sequence of drawings of subjects of different ages. We also have no clear depiction of the second stage, showing the ligaments connecting the bones, though the drawing at lower left of no. 63b (which seems at first glance essentially to duplicate that at upper right here) may initially have been intended to be such a drawing.

The two largest drawings here give palmar (right) and dorsal (left) views of a right hand; below are views from either side, lateral then medial, with the thumb slightly lowered. Leonardo thus gives four orthogonal views of the same stage of dissection. But his ambitions were endless, and having made these four drawings he then stated his wish to depict each individual bone in four aspects. The magnitude of this task is emphasised by the note at centre left, which enumerates the 27 bones of the hand (identified by letters and numbers) – thus 108 individual drawings of those bones alone.

The drawings in the right margin show all the different structures coursing into the finger. Leonardo identifies the tendon of extensor digitorum, which straightens the finger; 'the vein that nourishes the finger'; the nerve; 'the vein that gives vital spirit to the finger' (i.e. the artery); and the tendon of flexor digitorum profundus, which bends the finger.



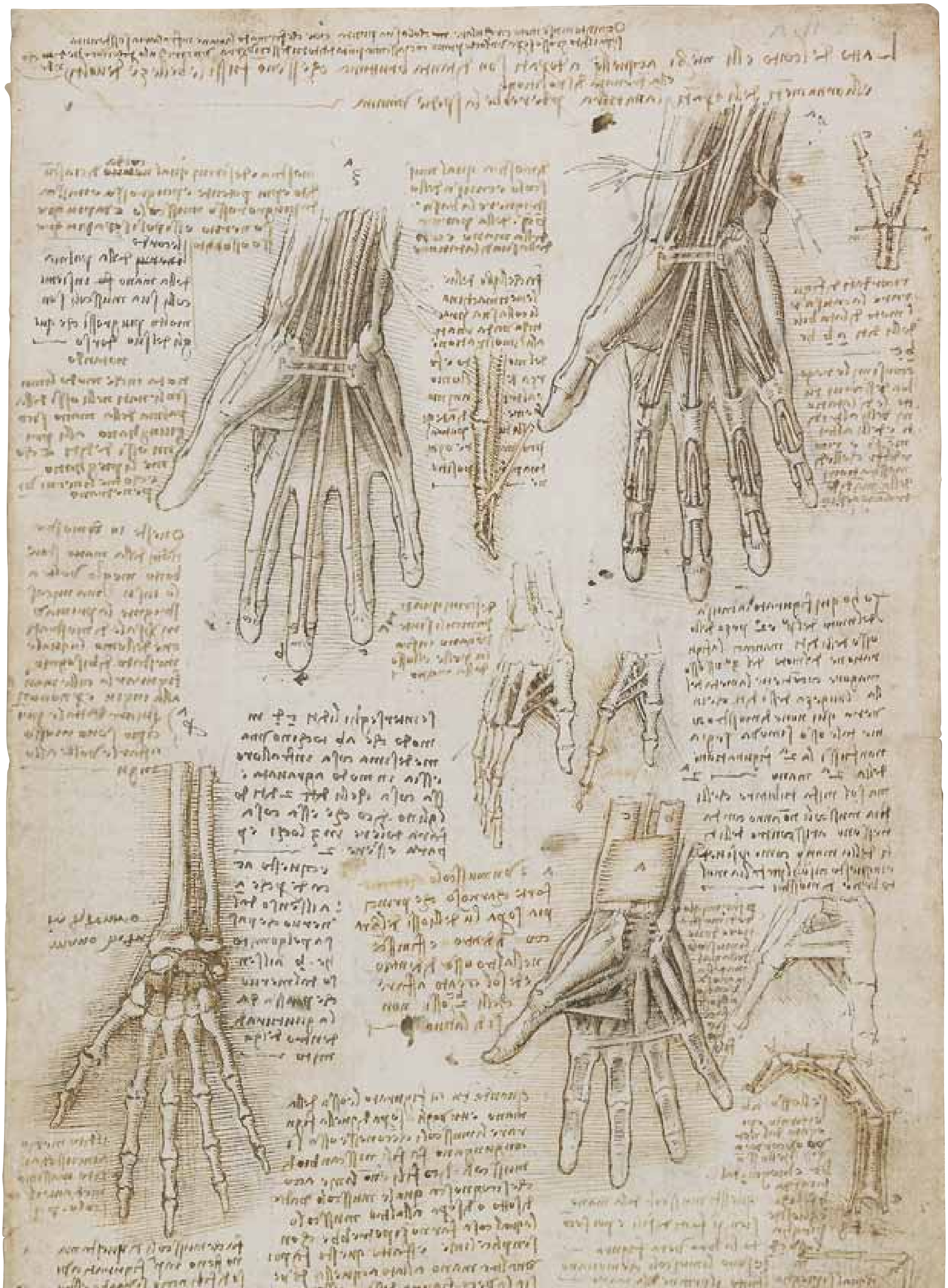
63b The bones, muscles and tendons of the hand

*c.*1510–11
Pen and ink with wash, over black chalk
28.8 × 20.2 cm
RL 19009r; MS A.10r; O'M&S 57; K&P 143r

These magnificent drawings are among the high points of Leonardo's career as an anatomist. They demonstrate with complete clarity the mechanical structure of the hand, not stripping it down as in a dissection but building it up in the manner of an engineer, and following in part the list of depictions given on the other side of the sheet (no. 63a). Leonardo begins at lower left with the bones (labelled '1st'), then adds the deep muscles and tendons of the palm and wrist at lower right ('2nd'), the first layer of tendons at upper left ('3rd'), and the second layer of tendons at upper right ('4th'). Two further drawings, adding the nerves and then the blood vessels, are labelled '5th' and '6th' on no. 64a.

The bones of the wrist are a little confused in the first drawing, and are more clearly rendered on no. 63a. A thread between the radius and the first metacarpal bone of the thumb is possibly the radial or lateral collateral ligament, or a tendon of abductor pollicis longus or extensor brevis. In the second drawing the bones are clothed in the deepest muscle and tendon. We see the thenar and hypothenar muscle compartments, controlling the thumb and little finger respectively, and the deep transverse metacarpal ligament spanning the knuckles to keep them from separating. The carpal tunnel is open, and pronator quadratus is shown connecting the radius to the ulna (cf. no. 60).

At upper left Leonardo adds the tendons of flexor digitorum profundus, running from the muscles on the anterior side of the ulna, through the carpal tunnel beneath the transverse carpal ligament (here represented by two threads) to the fingertips. The tendons of flexor digitorum superficialis are added at upper right, along with the ulnar and median nerves, reflected to the sides of the wrist, and some of the fibrous sheaths and annular ligaments that hold the tendons in place and thus allow the bending of the fingers, as demonstrated at lower right. As their names indicate, flexor digitorum profundus lies below superficialis, but its tendons attach further down the fingers, and consequently the tendons of profundus penetrate those of superficialis, as shown in the diagram at upper centre (this gap in the tendon of superficialis is named 'Camper's chiasm' after the anatomist Peter Camper, who described it in 1760–62; it should perhaps be renamed 'Leonardo's chiasm'). Leonardo was entranced by the elegance of this arrangement, and surrounded that detail with the note: 'Provide that the book on the elements of mechanics, with its practice, comes before the demonstration of the movement and force of man and other animals; and by these means you will be able to prove all your propositions.'



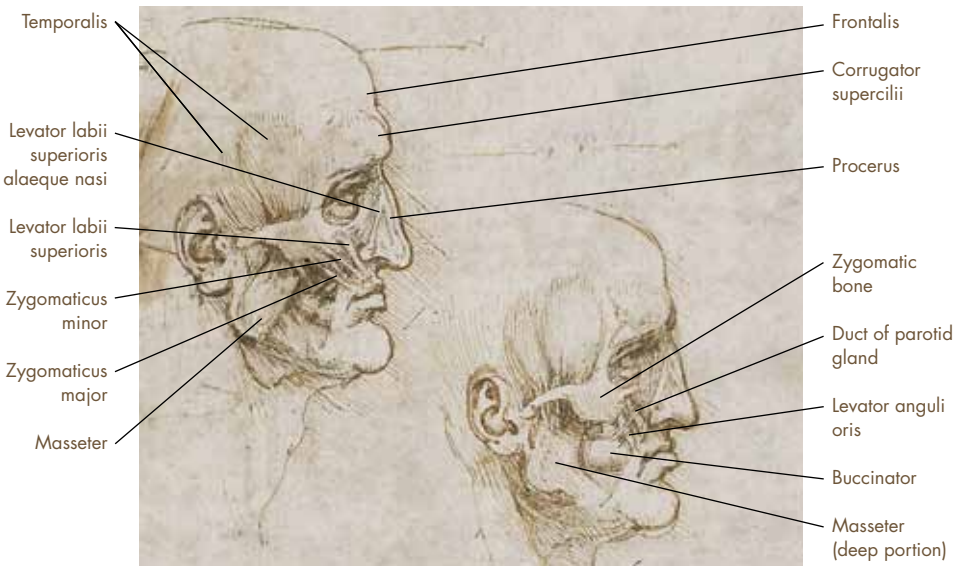
64a The muscles of the face and arm, and the nerves and veins of the hand

*c.*1510–11
Pen and ink with wash, over black chalk
28.8 × 20.0 cm
RL 19012v; MS A.13v; O'M&S 56; K&P 142v

Leonardo fits a remarkable amount of information onto this page. There are three main subjects: the hand; the muscles of the shoulder and arm, essentially repeating the drawings on no. 59a; and the muscles of the face, a subject treated nowhere else in Manuscript A.

The two studies of the hand continue the sequence begun on no. 63b. The drawing to the left depicts the entry of the median and ulnar nerves into the hand, with the correct distribution of the nerves for cutaneous sensation. The fibrous tendon sheaths are indicated, as is the transverse carpal ligament, with the median nerve and long flexors of the fingers passing through the carpal tunnel. In the drawing to the right the ulnar artery enters the palm and forms the superficial palmar arch, with the common palmar and proper palmar digital arteries distinct. Running across the palm is the superficial transverse metacarpal ligament (cf. its deep counterpart in the lower right drawing on no. 63b).

The studies of the facial muscles are highly accurate (see key diagram below). The drawing to the left depicts the superficial muscles, difficult to dissect as they may originate and/or insert into the deep surface of the skin. Leonardo attempted to identify the function of each muscle in the surrounding notes and reminds himself to determine whether the nerves that cause movement in the face issue directly from the brain – he has comprehended the difference between spinal nerves and cranial nerves. In the second drawing some of the superficial facial muscles have been removed to reveal the deeper structures.



64b The skeleton

*c.*1510–11
Pen and ink with wash, over black chalk
28.8 × 20.0 cm
RL 19012r; MS A.12r; O'M&S 1; K&P 142r

This page constitutes the most complete representation of a skeleton in the whole of Leonardo's surviving oeuvre. The vertebral curvature and oblique rib placement are well shown, and the drawing at lower right captures the correct tilt of the pelvic girdle, with a thread from the anterior surface of the ilium through the patella to the tibia illustrating the action of the quadriceps. That drawing is very similar to the equivalent study on no. 24, but Leonardo has here corrected the length of the ischium.

Whether Leonardo had attempted to visualise a complete skeleton or had actually joined dried bones back together, some errors of detail were perhaps inevitable. The scapula is too long (it should extend from around rib 2 to rib 8); the humerus is well drawn throughout, but the trochlea – the depression in the middle of its lower end, for articulation with the ulna – is on the wrong side of the humerus. In the side view at upper right, the angle of descent of the first two ribs is too acute, the front-to-back dimension of the thorax is somewhat excessive, and the last two floating ribs are far too long.

In the drawing at lower left, the articulations of the clavicle and first rib with the manubrium (labelled *m*) appear accurate, and Leonardo correctly places the articulation of the second rib at the sternal angle, where the manubrium joins the body of the sternum. But he shows separate sternal segments, and an odd arrangement of the lower ribs, in particular their cartilaginous connection to the sternum. He also depicts the acromion (the process of the scapula at the furthest point of the shoulder) as a separate bone: that this was deliberate is confirmed in a note, 'First depict the shoulder without the bone *a,* and then put it in'. In the young the acromion is connected to the body of the scapula by cartilage that later ossifies, and in some individuals it can remain separate, but elsewhere in the manuscript Leonardo plainly shows the acromion as a part of the scapula.

65a The muscles of the lower leg

*c.*1510–11
Pen and ink over traces of black chalk
29.5 × 20.0 cm
RL 19010v; MS A.11v; O'M&S K&P 147v

The main drawing depicts the medial (inside) aspect of the left leg, with the calf muscles, gastrocnemius and soleus, prominent. Leonardo treated the lateral and medial portions of gastrocnemius as distinct muscles, and recognised that these unite with soleus in the calcaneal (Achilles) tendon; he thus asks why there are 'three' muscles when one would suffice, and indeed some anatomists now describe soleus and the two portions of gastrocnemius as three components of a single muscle, triceps surae.

The structures running behind the medial malleolus or ankle include the tendon of flexor digitorum longus, the tibial nerve, the posterior tibial artery between these two, and the tendon of tibialis posterior. The tendon of tibialis anterior is prominent along the front contour of the ankle, with that of extensor hallucis longus passing along the upper contour of the foot to insert on the big toe. Much of the abductor hallucis muscle has been removed from the foot (cf. no. 65b) in order to show the tendon of tibialis posterior passing along the sole.

At centre right is a discussion of the statics of standing on the ball of the foot. Leonardo states that the ball of the foot and the heel are effectively equidistant from the axis of the ankle, that the pull exerted by the calf muscle must therefore be equal to the weight supported on the ball of the foot, and thus that the force felt at the joint of the ankle is twice that of the weight supported on the foot. (He makes a similar calculation on no. 59b, though there he states that the distance from the ankle to the ball of the foot is twice the distance from the ankle to the heel.) In the brief note alongside the drawing he describes the relaxation of the gastrocnemius muscle, stating that it *'disgonfiera',* literally 'deflates'. This is a reflection of the ancient physiology of the muscles that explained their contraction and relaxation as due to inflation and deflation (cf. no. 67).

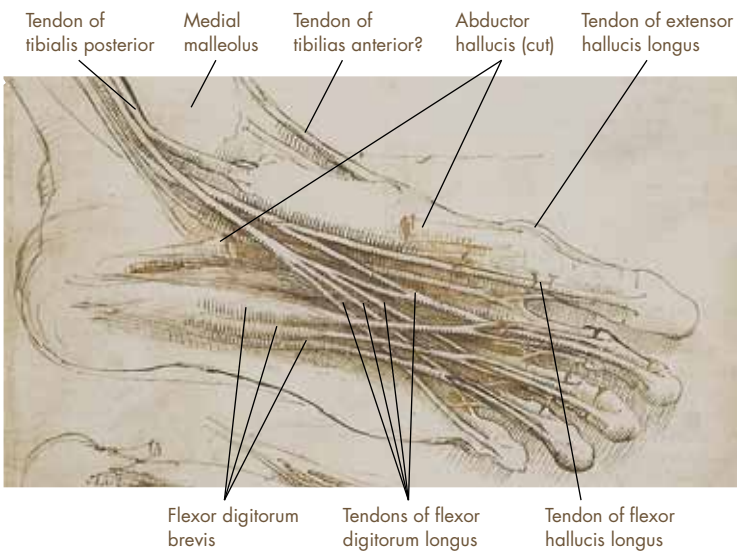
65b The muscles and tendons of the sole of the foot

*c.*1510–11
Pen and ink over some stylus
29.5 × 20.0 cm
RL 19010r; MS A.11r; O'M&S 79; K&P 147r

In the principal drawing above is an oblique view of the sole of the foot, with the plantar aponeurosis (the thick connective tissue that supports the arch of the foot) removed. Leonardo emphasises the muscles abductor hallucis, with its origin on the calcaneus or heel-bone and insertion on the first phalanx of the big toe, and flexor digitorum brevis, originating on the calcaneus then dividing into four tendons, each splitting around the tendons of flexor digitorum longus to insert on the second phalanges of the other toes. The medial and lateral plantar nerves are also shown, running parallel to flexor digitorum brevis, and Leonardo's dissection technique was precise enough to reveal the fine communications between branches of those nerves.

Below, the nerves have been removed, abductor hallucis cut and flexor digitorum brevis reduced in size (but not to threads) to show elements of the 'second layer' (see key diagram below). The penetration of the tendons of flexor digitorum brevis by those of flexor digitorum longus parallels the arrangement of the tendons in the fingers that had so impressed Leonardo in no. 63b. He thus noted that 'the hand is to the arm as the foot is to the leg', and reminded himself to make a series of drawings of the foot equivalent to those of the hand on nos 63a–64a:

> Draw a diagram of this foot with the bones alone, then leave in place the membrane that clothes them and draw a simple diagram of the nerves, and then on the same bones draw one of the tendons, and then one of the veins and arteries together. And finally a single diagram that contains arteries, veins, nerves, tendons, muscles and bones.




A. 12

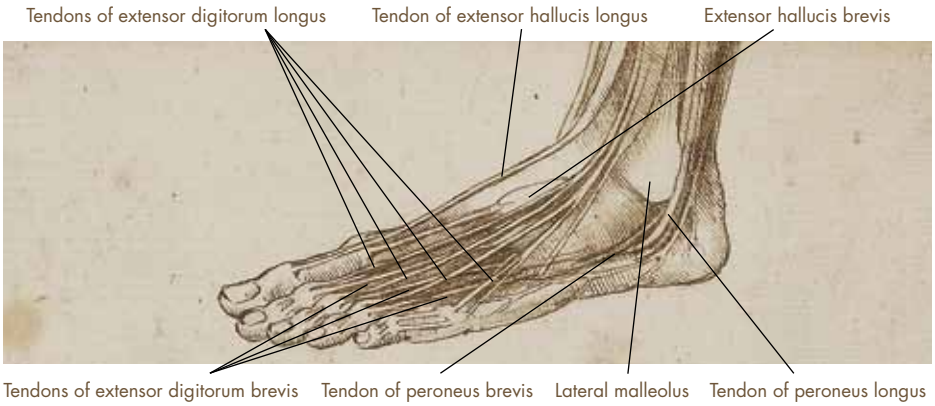
66 The tendons of the lower leg and foot

*c.*1510–11
Pen and ink over traces of black chalk
39.0 × 26.5 cm
RL 19016r; MS A.17r; O'M&S 75; K&P 150r

This page and the next stand apart from the rest of the material in Manuscript A. The sheets of paper are twice the size; each is dominated by a single drawing; the versos are blank; and many of the notes are written in a uniform shade of ink with the same pen – here in particular they have a neatness and regularity not found elsewhere in the manuscript.

The content, too, is subtly different. Here there is no attempt to describe the drawing directly; the content of the notes and drawing are related but independent and self-sufficient, and many of the notes read as summaries rather than exploratory passages. For example, Leonardo states as a principle, based on all the studies that have gone before, that the muscles within each 'component' of the limbs (e.g. shoulder, upper arm, lower arm, hand, fingers) do not move that component, but rather the next component along. The penultimate paragraph states that 'this winter of 1510 I believe I shall finish all this anatomy', which should probably be understood to mean, as elsewhere, 'this treatise on anatomy'. It is hard to avoid the conclusion that this is one of the last sheets compiled during this campaign of dissection.

The principal drawing concentrates on the interrelationship of the tendons on the upper side of the toes (see key diagram below). The tendons of extensor digitorum longus pass from the lower leg to the metatarsal-phalangeal joints of the four lesser toes (Leonardo has omitted the ligaments at the ankle). In the case of the three middle toes, those tendons are joined at that point, on the lateral side, by the tendons of extensor digitorum brevis (the bodies of that muscle, arising on the calcaneus, are not shown here; they can, however, be seen on no. 67). The longus and brevis tendons merge to form a broad aponeurosis that then divides into three slips on each toe, the central slip inserting into the second phalanx, the two lateral slips going on to insert into the third phalanx. Leonardo has shown this arrangement perfectly.



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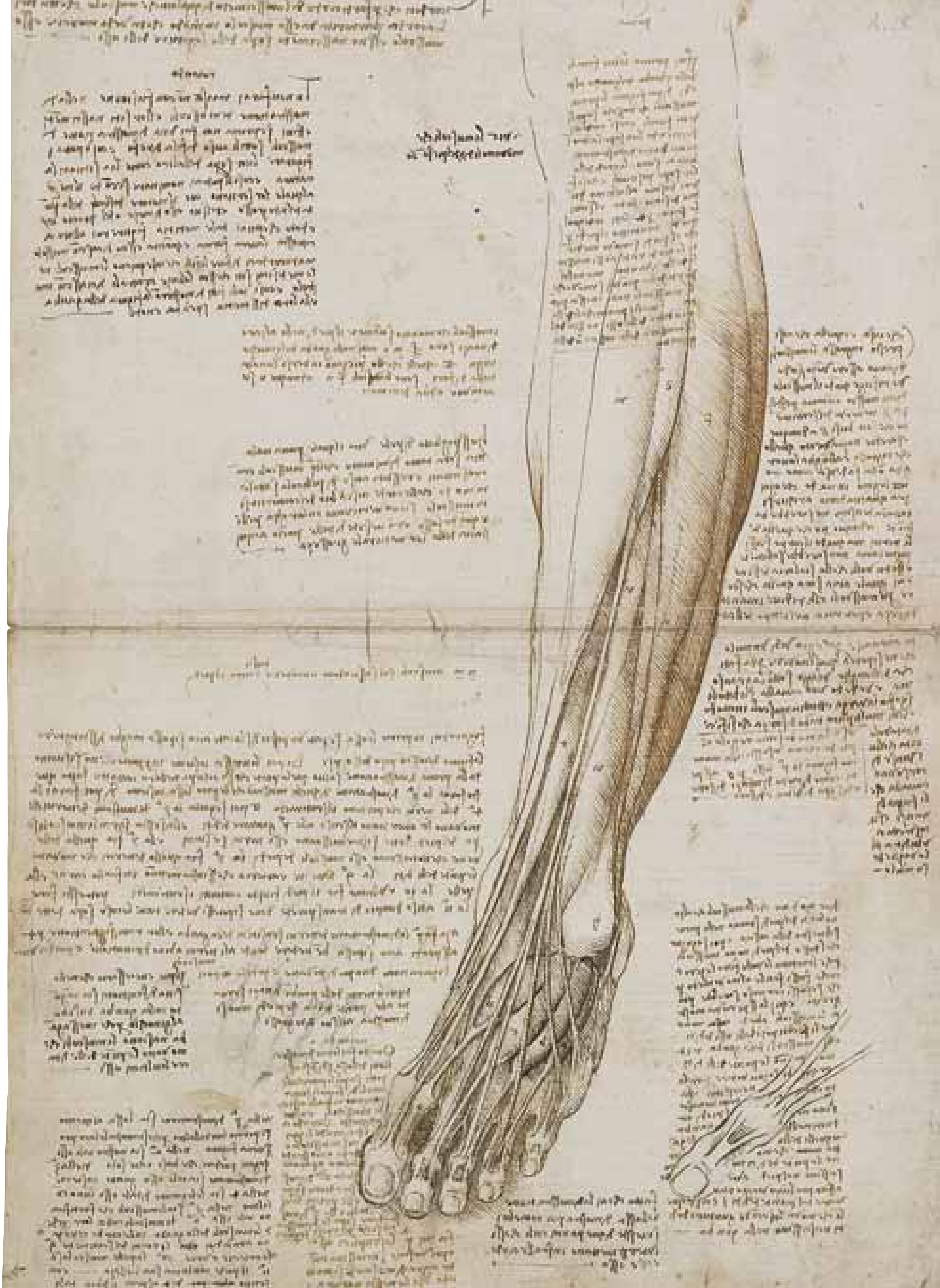
67 The muscles and tendons of the lower leg and foot

*c.*1510–11
Pen and ink over traces of black chalk
38.9 × 28.2 cm
RL 19017*r*; MS A.18r; O'M&S 74; K&P 151r

Many of the structures shown here are the same as those on no. 66 (see the key diagram to that sheet). The interactions of the tendons of extensor digitorum (and hallucis) longus and brevis are again well displayed – the inset diagram at lower right depicts the arrangement of the three middle toes, not the big toe, as its size might suggest – though the brevis muscles appear in the drawing to have their origins on the lateral malleolus rather than on the calcaneus. Several muscles of the lower leg are shown, including tibialis anterior, fibularis longus and fibularis tertius (not found in all individuals, and here correctly placed in the anterior crural compartment). Neither here nor in any other image of the human leg did Leonardo depict the tendinous structures known as retinacula, the dense fibrous bands that extend around the ankle to keep the tendons in place during flexion and extension (cf. his dissections of the bear's leg, nos 7–10).

In the notes, running to some 1,200 words, Leonardo revisits themes treated throughout the manuscript, with reminders or exhortations to draw the bones separately, from all sides, and then joined; then adding the muscles, drawing them as threads to convey their multilayered structure, and so on. He also considers the physiology of muscle 'enlargement' (contraction) and erection of the penis. Ancient Greek physiology held that muscles contracted by being inflated with 'pneuma', systemic air that circulated within the body and was involved in the functioning of the organs. Leonardo doubted that this 'air' could possibly inflate a muscle so quickly and deflate so quickly, and that the volume of air that would need to be compressed to harden a large muscle would be more than could be moved through the nerve fibres:

> What is it that enlarges a muscle so quickly? They say it is air. And where does it retreat to when the muscle diminishes with such speed? Into the nerves of feeling which are hollow. Then there would have to be a great wind to enlarge and elongate the penis and make it as dense as wood, such that air was reduced to such a density. Indeed there would not be enough in the nerves, and even if the whole body were full of air there would not be sufficient. And if you say that it is the air in the nerves, what air would it be that courses through the muscles and reduces to such hardness and power at the time of the carnal act? For once I saw a mule that could barely move from the fatigue of a long journey under a great load, and seeing a mare, immediately its penis and all its muscles swelled up, in such a way that its forces were multiplied and it reached such a speed that it caught up with the fleeing mare, which was forced to submit to the desires of the mule.



68 The male genito-urinary system

*c.*1508
Pen and ink over black chalk
27.2 × 19.2 cm
RL 19098v; QA III.4v; O'M&S 194; K&P 106v

The drawing at upper centre shows the bifurcation of the great vessels, with their ramifications into the iliac vessels surrounding a schematic depiction of the rectum and bladder. Another branch leaves the aorta and travels vertically down behind the rectum – probably the inferior mesenteric artery, greatly simplified. Above the pen drawing are black chalk outlines of the liver, spleen, kidneys and heart, with the right testicular vein travelling obliquely towards its junction with the vena cava.

In the two large drawings below, the ureters descend from the kidneys to the bladder (drawn too large). The rectum curves round behind the bladder, accompanied by a pair of vessels on either side – by comparison with the first drawing, these are probably intended to be the internal iliac vessels, with vesical branches to the bladder. The testicular arteries are seen passing down from the level of the kidneys; these actually leave the aorta itself a little below the renal arteries, but their origin is unclear in the drawing to the left, and in the sketch at upper right, both testicular arteries and veins seem to arise on the corresponding renal vessels (Leonardo's lingering difficulties with the relationship between the gonadal and renal vessels can be seen in nos 29a and 47a). The testes are correctly shown contained within a fluid-filled cavity; the vas deferens rises from the testicle, loops over the top of the pubic bone (in dotted cross-section in the drawing to the left, though drawn too large), and passes into the upper end of the seminal vesicle. The ejaculatory duct runs from the lower end of the seminal vesicle to join the urethra just below the bladder. Leonardo shows the urethra as the sole channel of the penis, and any notion that a 'spiritual' component is carried in a second channel from the spinal cord (cf. no. 2) has been abandoned. The anatomical detail and confidence of the drawing may appear to be an advance on no. 44b, but that sheet was more concerned with establishing schematic homologies than accurately depicting detail.

69 The rotation of the arm, and the foetus in the womb

*c.*1511
Pen and ink over black chalk
28.7 × 21.1 cm
RL 19103v; QA III.9v; O'M&S 212; K&P 196v

At centre and upper right are two studies of the arm, concentrating on the rotation of the hand and forearm (cf. nos 60, 61). Both drawings show biceps, originating from two heads on the scapula, inserting on the upper forearm, and responsible in part for supination (turning the arm so that the palm faces upwards); and pronator teres, originating mainly on the humerus with a secondary head on the ulna (as described by Leonardo in the accompanying notes), inserting on the radius and responsible for pronation. The muscles are reduced in thickness, and in the diagram at upper right they are further reduced to threads, with brachialis also shown along the left margin of the humerus. While brachialis can flex the arm regardless of the position of the forearm, biceps can only flex the arm when it is supinated, and thus it will supinate a pronated forearm.

This subtle understanding dates the sheet soon after completion of Manuscript A – the drawing at top right is essentially a continuation of those on no. 61. During this period Leonardo's attention would shift away from the mechanical aspects of the muscles and bones to the mysteries of the heart and reproduction. The small sketch at the centre of the page shows the foetus surrounded by its membranes; in the larger drawings to the left these membranes are peeled away and opened out, and in that at lower left the vagina is similarly sectioned, with an ovary and the uterine ligaments sketched to the left. Most of the drawings show the multiple, cotyledonous placenta derived from bovine dissection (nos 45, 46) but found throughout Leonardo's supposedly human embryological studies of this period. The details at centre and centre left investigate (in cross-section) whether these cotyledons bulge outwards, inwards, or both.

Leonardo was acutely conscious of the universality of reproduction. It is not fanciful to see botanical aspects in his drawings of the foetus in the womb, echoes of unfurling flowers or an opening nut, for in his note at centre left here he writes:

> All seeds have an umbilical cord which is broken when the seed is ripe. Likewise they have a uterus and membranes, as herbs and all seeds that are produced in pods demonstrate. But those which are produced in nutshells, such as hazelnuts and pistachios, have a long umbilical cord which shows itself in infancy.

70 The foetus, and the muscles attached to the pelvis

*c.*1511
Pen and ink over red and black chalk
30.4 × 21.3 cm
RL 19101r; QA III.7r; O'M&S 213; K&P 197v

Leonardo was fascinated by how a foetus could fit into the uterus of a woman – here he states that 'the length of a child when it is born is usually one *braccio* [*c.*60 cm]' but 'experience in the dead shows [the uterus] to be a quarter of a *braccio* in its greatest length in a woman'. He repeatedly drew the foetus curled up to occupy the smallest space possible, and in the long note in the left margin he tries to compare the size of the human uterus with that of the cow and the horse, in proportion to their bodies.

By curling the foetus up in this manner, Leonardo noted that the heel is pressed against the perineum. He therefore suggests that:

> During a great part of the period of life of the foetus its urination is through the umbilicus. And this happens because the heel of the right foot is comes between the anus and the penis and shuts off the passage of all urine. Nature has provided for this by making a channel in the fundus of the bladder [the urachus, the fibrous remnant of the allantois] through which urine goes from the bladder to the umbilicus and from the umbilical cord to the mouth of the uterus.

The two pen drawings at the top of the page examine the supposed action of muscles attached to the pubis. The external and internal abdominal oblique muscles are broad, flat sheets laid over one another, attached to the ribs above and inserting partly on the iliac crest and partly in aponeuroses which meet at the linea alba, the mid-line of the abdomen. Their muscle fibres run diagonally, those of the external obliques roughly perpendicular to those of the internal obliques, and it would appear to be this arrangement that Leonardo has tried to record (he has not shown the rectus abdominis muscles). He has, however, rendered the muscles as a series of long, thin structures, attached to the pubis below and to four unidentifiable points above, and crossing over at the mid-line, which they do not do (the same arrangement was sketched more than twenty years earlier on no. 4). Below the pubis Leonardo has shown the adductor muscles of the thigh, and his accompanying note states that the opposing pulls of the abdominal and adductor muscles stabilise the pubis; the reality is the reverse, with the pubis serving as an anchor point for the actions of the muscles.

D. 1.

71 The foetus in the womb

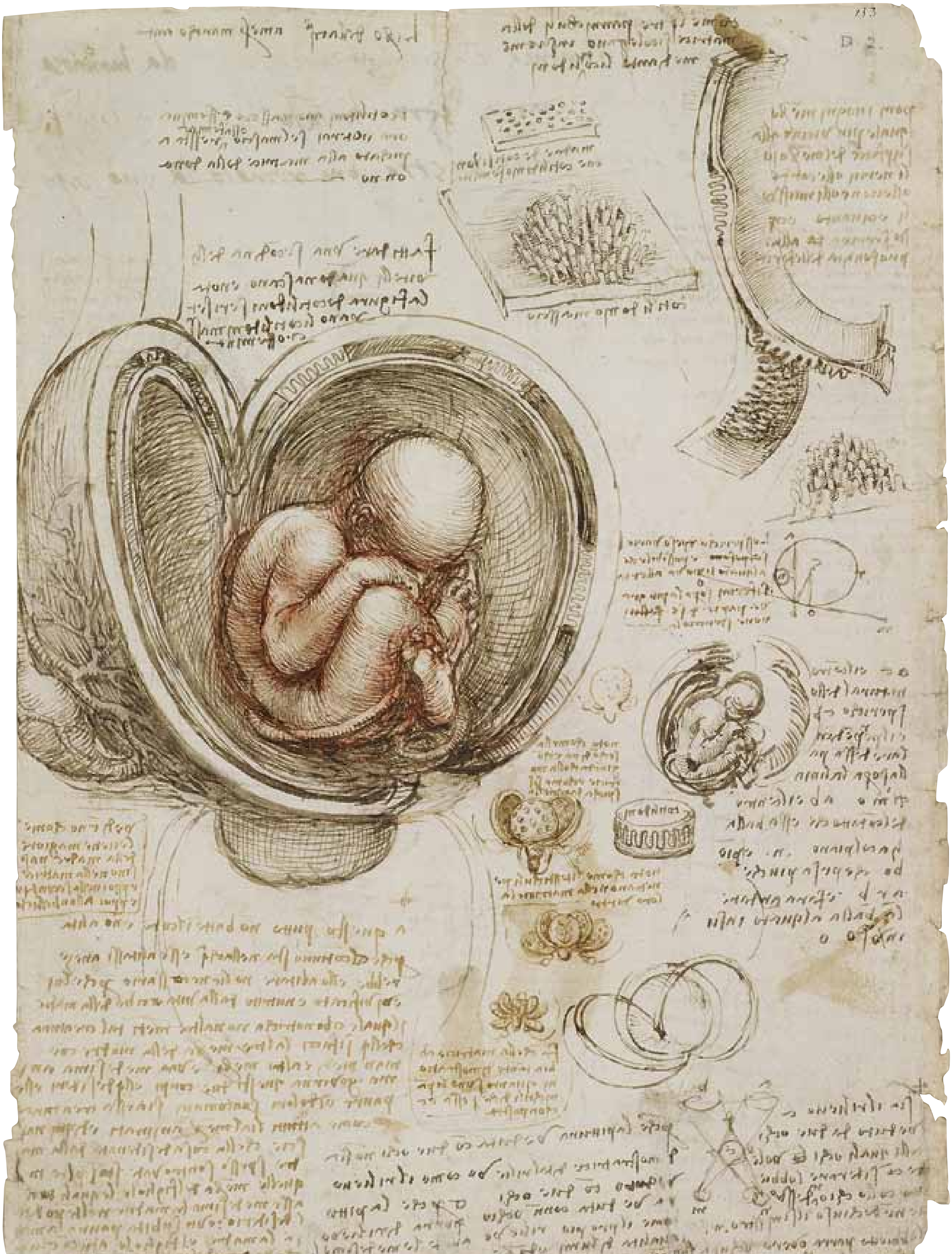
*c.*1511
Pen and ink over red chalk
30.4 × 22.0 cm
RL 19102r; QA III.8r; O'M&S 210; K&P 198r

Throughout his anatomical career Leonardo strove for objectivity, and colour is usually absent in the drawings themselves (if not the paper). But in his late embryological drawings he was clearly moved by the ineffable mystery of life, as he had been at the start of his anatomical researches 25 years before, and this sheet, perhaps the best known of all Leonardo's anatomical drawings, makes striking use of red chalk and dense curved hatching to evoke the coiled potential of the child in the womb. Leonardo's renewed concern with the immaterial aspects of the body is expressed in the note to lower left:

> In this child the heart does not beat and it does not breathe because it rests continually in water, and if it breathed it would drown. And breathing is not necessary because it is vivified and nourished by the life and food of the mother … And one and the same soul governs these two bodies, and desires, fears and pains are common to this creature as to all other animated parts. From this it arises that a thing desired by the mother is often found imprinted on those parts of the infant that have the same qualities in the mother at the time of her desire; and a sudden terror kills both mother and child. Therefore one concludes that the same soul governs and nourishes both bodies.

The principal drawing shows the foetus in 'complete breech' position with the legs crossed, though here the left heel is not pressed against the perineum as in no. 70. The umbilical cord is wrapped around the foetus's legs, but its connection to the placenta is not seen; in the left margin are an ovary and associated vessels. In the geometrical diagram at centre right Leonardo implies that the weight of the foetus's head might tip it over in the uterus for normal head-first delivery, by analogy with an eccentrically weighted sphere rolling a little way up an incline.

The small sketches below centre envisage the uterine membranes unfurling one by one like the petals of a flower, and in the main drawing this allows Leonardo to show the membranes in cross-section. Particular attention is given to the multiple cotyledonous placenta (derived from Leonardo's dissection of a cow recorded on no. 45), whose interdigitations are shown in the details at upper right. Leonardo never discovered that the human has a single, discoidal placenta, and his ongoing reliance on bovine material is indicated by the note 'get the secondine [foetal membranes] of calves when they are born and note the shape of the cotyledons'.



72 The diaphragm of a dog, and other studies

1513
Pen and ink on blue paper
27.5 × 20.7 cm
RL 19077v; QA II.7v; O'M&S 179; K&P 168v

The note along the top edge of the sheet reads 'On the 9th day of January 1513'. At that time the 60-year-old Leonardo was based at the family villa of his young assistant, Francesco Melzi, at Vaprio on the river Adda 20 miles (30 km) to the east of Milan. The sketch at centre left of this sheet records the plan of the castle at Trezzo, a little to the north of Vaprio, which fell to Venetian forces on 5 January 1513. While based at the Villa Melzi, Leonardo painted little, if at all. He designed improvements to the villa, and the architectural sketches here are presumably connected with that work. He also pursued his scientific studies, primarily his anatomical investigations – though without access to human corpses he had to use animals, including dogs, birds and oxen, as his subjects.

Here Leonardo notes at centre right: 'Look at the dead dog, its loins and diaphragm and the movement of its ribs.' The four oval drawings in the upper half of the sheet thus examine schematically the thorax of the dog. The sketch at upper centre shows the diaphragm lowered as in inspiration, with the heart and lungs briefly outlined. In the drawing at upper left, the diaphragm is raised in a dome, as in expiration, with the branching of the bronchi seen in the lungs and the oesophagus piercing the diaphragm at centre. The musculo-tendinous attachment of the diaphragm to the ribs is represented by the zig-zag margin, and the ribs with the intercostal muscles are exposed below. The fourth oval drawing, to left of centre, shows the diaphragm and lungs removed to reveal the vertebral column flanked by the ribs and a pair of muscles – possibly the psoas muscles out of position, or iliocostalis shown on the wrong side of the ribcage.

At lower left Leonardo states that movement of both the ribs and diaphragm are necessary for breathing. He understood that the diaphragm is a muscle, and that in its relaxed state the contents of the abdomen push it upwards into 'the shape and likeness of a very hollow spoon', as indicated at bottom centre.

The two very sketchy anatomical drawings in the centre of the upper half of the sheet distinguish between organs which are peritoneal (suspended within the peritoneal cavity) and those which are retroperitoneal, as the accompanying note explains: 'The ureters and the kidneys, the spermatic vessels and the diaphragm lie outside the peritoneum, also the great vessels and renal vessels; and the intestines are inside the peritoneum.'

73 The thoracic and abdominal cavities of an ox

*c.*1512–13
Pen and ink with red chalk
28.7 × 20.6 cm
RL 19108v; QA IV.2v; O'M&S 30; K&P 185v

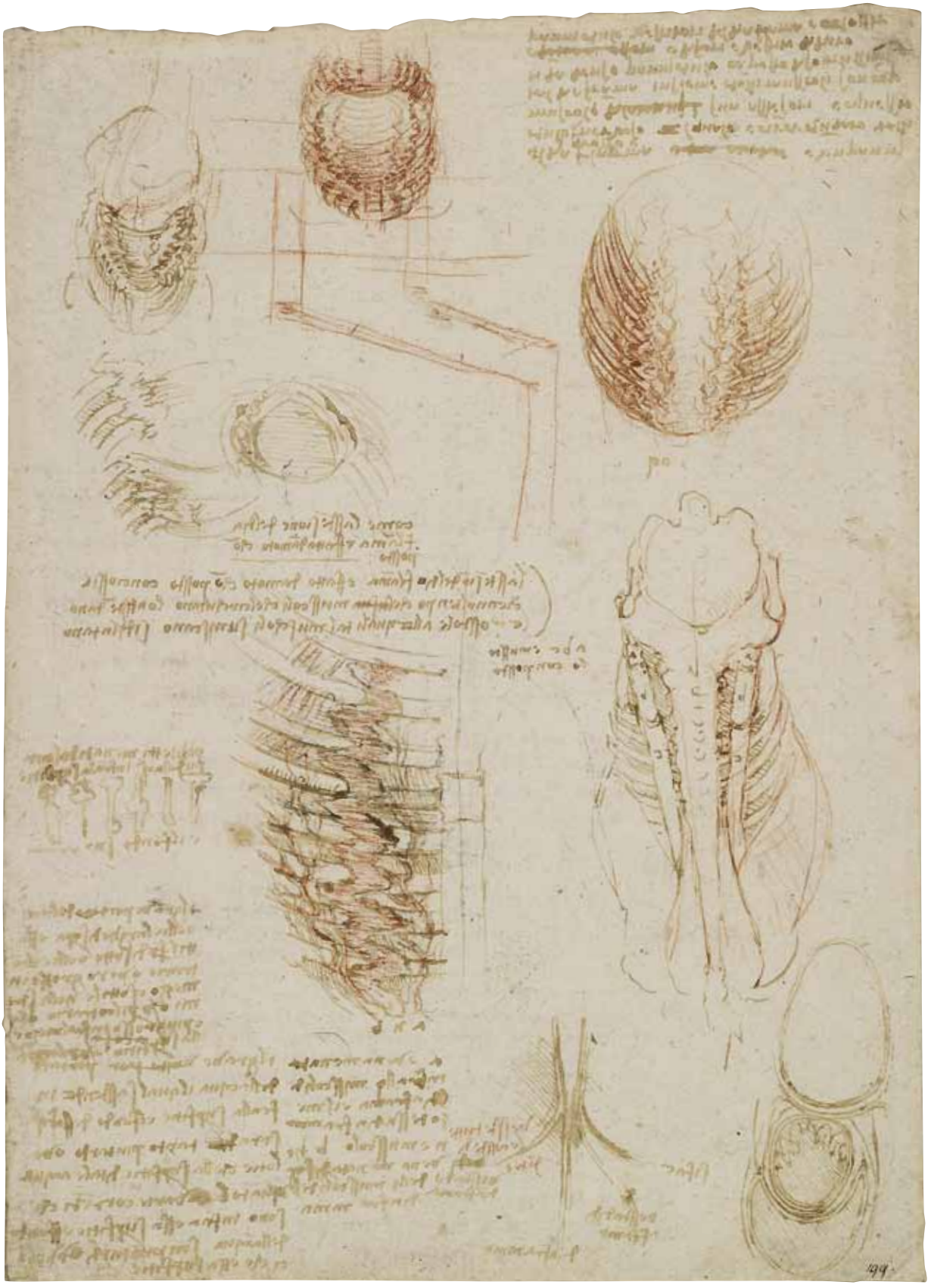
Leonardo compiled these drawings and notes from two different directions, so that those on the right of the sheet appear upside-down with respect to those on the left.

The largest study, at centre left, shows the abdominal cavity of the ox, with the longissimus dorsi muscles – the principal component of a rib-eye steak – prominent on either side of the spine. The drawing at lower left shows the inside of the thoracic cage of the ox (as indicated by the single word *'bo'* above the drawing). A detail of this region is enlarged to upper right: the zig-zag shape coloured with red chalk is a portion of the transversus thoracis muscle, flanked by 'a vessel directed between the muscles of the diaphragm and the middle of the diaphragm' and 'a vessel leading outside the muscles of the diaphragm'.

At bottom left Leonardo describes the diaphragm accurately as:

> a thick sinewy membrane which is surrounded by muscles, its extensors. And this diaphragm with its muscles is covered by a dense membrane composed of very fine ones. Outside it is clothed by a hard membrane [the pleura] lining the diaphragm and ribs.

Accordingly, the diagram at upper centre shows the membranes of the diaphragm peeled apart.



74 The thoracic and abdominal cavities of an ox

*c.*1512–13
Pen and ink with red chalk.
28.1 × 21.0 cm
RL 19109r; QA IV.3r; O'M&S 31; K&P 186r

This elegant page continues the studies of the ox seen on no. 73. Leonardo used the same pale ink as on that sheet for his initial notes and drawings, and then painstakingly went over many of them with a darker ink – this is particularly visible in the longest column of notes, where he skipped over those words that he had cancelled. The drawings also clarify many of the studies on earlier sheets, and while one might therefore expect that the page was to some degree a final expression of Leonardo's studies of the movement of the chest, many of the notes are questions rather than statements: 'What shape have the lobes situated between the diaphragm and the rest of the chest'; 'How the lateral muscles of the diaphragm are the cause of movement of the lung, and of the stomach and other intestines'; 'How the tendons of the neck raise the whole front part of the rib-cage by voluntary movement'; and so on.

At upper centre is a schematic view of the diaphragm separating the 'receptacle of the spiritual organs' (thorax) from the 'receptacle of the material organs' (abdomen). The drawing at the centre of the sheet essentially repeats that at the centre of no. 73, with the vessels more clearly shown. Below is a series of four details of the chest wall: to the right, the intercostal vessels and nerve; at the centre, two views of the insertion of the muscles of the diaphragm on the ribs, with the diaphragm peeled apart into four layers – a thoracic membrane, the musculo-tendinous component of the diaphragm proper, and two abdominal membranes (as also shown in the cross-section at top left); and at bottom left of the sheet, a view of the diaphragm in place on the ribs and pierced by the oesophagus.

At the centre of the left margin is a complex image that includes a view into the abdominal cavity with the kidneys placed on either side of the spine; the diaphragm partly inserting on the ribs and partly in cross-section, to show the slight bellies of its component muscles and its membranous layers; and a view into the thoracic cavity with the lungs and heart excised.

75 A bird's wing, and architectural studies

*c.*1512–13
Pen and ink, and red chalk
27.4 × 20.1 cm
RL 19107*v*; QA IV.1*v*; O'M&S 85; K&P 184*r*

Most of the page is concerned with improvements to the Villa Melzi, as on no. 72, and it may thus be dated to Leonardo's prolonged stay there in 1512–13.

At the centre is a study of a bird's left wing from above. A bird's wing is analogous to the upper limb of a quadruped in that it has a humerus, radius and ulna, but the bones of the wrist are reduced to two small nuggets, the digits are reduced in number and the bones are partly fused, for example in the carpometacarpus, the first major element in the 'hand'. Here the drawing concentrates on the central section of the radius and ulna, with the humerus lightly sketched to the right and the phalanges to the left. The quills of the secondary flight feathers are shown attached to the ulna, with a few primaries attached to the carpometacarpus and basal phalanx. Running along the upper side of the radius is the extensor carpi radialis muscle (*n m*), as shown in more detail on no. 76, and along the lower side of the ulna is the expansor secondarium muscle (*a b*), responsible for maintaining the correct angle of the secondaries. Leonardo correctly notes its function thus:

> The tendon *a b* moves all the tips of the feathers toward the elbow of the wings, in flexing the wings; but in extending the wing by means of the pull of the muscle *n m* those feathers direct their lengths towards the point of the wings.

The joints of the radius and ulna with the carpometacarpus and humerus are arranged so that the phalanges maintain approximately the same angle relative to the humerus whatever the position of the wing (sketched both extended and flexed at centre left). In red chalk at lower left Leonardo reduced this arrangement to a simple system of hinged rods, with the analogues of the radius and ulna forming a long parallelogram such that the analogues of the carpometacarpus and humerus remain parallel in any position.

76 The bones and muscles of a bird's wing

*c.*1512–13
Pen and ink over black chalk
22.2 × 20.4 cm
RL 12656r; K&P 187v

The first two anatomical studies here are dorsal views of a bird's right wing. Projecting forwards from the carpometacarpus is the first digit, the alula or 'bastard wing'; the second and third digits are fused to form the tip of the wing. Leonardo labelled the structure *a b* both in the upper anatomical study and in the sketch of a bird in flight in the right margin, noting *'a b* is of great importance because this part is the cause of keeping the bird steady in the air above the movement of the wind'. Elsewhere, Leonardo called the alula 'the rudder of the wing', and it is indeed used for manoeuvring in slow flight; while he might have overstated its importance in normal flight, his appreciation of its aerodynamic role is highly impressive.

Curving from the shoulder to the wrist is the tendon of the patagialis longus muscle, which forms the leading edge of much of the wing. Running from the distal end of the humerus and inserting by long tendons on the carpometacarpus are three muscles (extensor carpi radialis, an unidentified extensor, and ulnaris lateralis).

The third drawing shows the same wing from below, with key letters and a note to clarify the insertions of these muscles:

> Three tendons are placed over the joint. Of these the first [ulnaris lateralis] terminates underneath at *n* [on the carpometacarpus], the second tendon terminates at *c* [tip of the basal phalanx], and the third and last [extensor carpi radialis] passes over the joint *s* and ends at *t,* the tip of the wing.

These are not 'thread diagrams', as might first appear: a bird has relatively little muscle mass in the wings, for these muscles are used primarily for extending and retracting the (light) outer parts of the wing. The much larger muscle responsible for powering flight is pectoralis, the 'breast' muscle, originating on the keeled sternum; Leonardo has not indicated this muscle or its tendon inserting on the humerus.

The lines at the top of the page are a proportional analysis of the different sections of the bird's wing. In the absence of a scale, the species dissected by Leonardo cannot be identified, but the length of the 'hand' suggest that it was a bird capable of strong soaring flight, such as a raptor.

77 The heart, lungs and other organs

*c.*1508
Pen and ink over black chalk
28.3 × 21.9 cm
RL 19104v; QA III.10v; O'M&S 172; K&P 107r

Despite the confidence of the drawings, this representation of the cardiovascular system is based primarily on tradition, which continued to dominate Leonardo's depictions until after 1510 – in fact, the layout of the major organs and great vessels is essentially the same as on no. 1, drawn twenty years earlier. Several of the structures have been depicted here so as to fulfil their supposed function, not unlike no. 2, and it is clear that Leonardo's first-hand knowledge of the heart was still no more than rudimentary.

The vena cava arises from the liver as two essentially separate vessels, suggesting that the drawing should be dated before no. 29a, in which Leonardo demonstrated that the heart is the centre of the venous system as well as the arterial. Above the liver, the inferior vena cava joins directly to the superior vena cava, and at this junction are branches to the right lung and to the heart. In the drawing at centre left the vena cava and aorta are omitted entirely, and we see two branching systems from the right lung passing directly to the right ventricle of the heart, and two from the left lung passing to the left ventricle (there is no indication of the atria). At this time Leonardo thought that these branching systems carried air, not blood, as described at lower right:

> The wind reflected from the lung to the heart cannot enter the heart unless there is an outlet. Therefore two passages are necessary: one which, when the lung sends out air through the trachea, at the same time sends air into the concavity of the heart; and a second passage through which air issues from the heart and returns … through the said trachea, the passage of the lungs.

Among other errors one might note the bovine aortic arch, a recurring feature of Leonardo's heart studies; the vessels connecting the liver and spleen, which may be diagrammatic but even so are not correct; and the testicular arteries coursing posterior to the renal vessels. There are some accurate observations, such as the form of the seminal vesicles (studied in more detail on the companion sheet, no. 68), and the termination of the left testicular vein at the left renal vein; but Leonardo's great achievements in his subsequent studies of the heart are not even hinted at.

78 The atria and ventricles of the heart

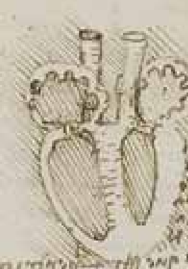
*c.*1511–12
Pen and ink
28.8 × 21.5 cm
RL 19062r; QA I.3r; O'M&S 91; K&P 155r

On the ventricles of the heart

The heart has four ventricles, that is two lower in the substance of the heart, and two upper outside the substance of the heart, and of these two are on the right and two are on the left. Those on the right are considerably larger than those on the left. The upper ones [atria] are separated by little doors or gateways of the heart from the lower ventricles. And the lower ventricles are separated by a porous wall through which the blood of the right ventricle penetrates into the left ventricle; and when the right lower ventricle closes, the left lower one opens and draws into itself the blood which the right offers it.

The upper ventricles continually make a flux and reflux of the blood, which is continually pulled or pushed through the lower ventricles from the upper. And since the upper ventricles are more suited for driving out of themselves the blood which dilates them than pulling it into themselves, Nature has so made it that by the closure of the lower ventricles (which close on their own) the blood which escapes from them is that which dilates the upper ventricles. These, through being composed of muscles and fleshy membranes, are suitable for dilatation and for receiving as much blood as is pushed into them. They are also suited by their powerful muscles for contracting with impetus and driving out of themselves the blood into the lower ventricles, of which when one opens the other closes . . . And thus by flux and reflux with great rapidity, the blood is heated and subtilised and is made so hot that but for the help of the bellows called the lungs, which draw in fresh air by dilating and pressing it into contact with the coats of the ramifications of the vessels refreshing them, the blood would become so hot that it would suffocate the heart and deprive it of life.

Leonardo thus provides the first description in medical science of the atria of the heart as active muscular entities. In the margin Leonardo sketches the heart in section, with the right ventricle (incorrectly) larger than the left, and the sections of the atria showing the pectinate (ridged) muscles; in humans, pectinate muscle comprises much of the right atrium, but on the left only a small portion of the atrial appendage comprises pectinate muscle. Dashes through the interventicular septum represent the supposed pores through which blood passed from right to left ventricle. Leonardo describes the 'little doors' between the atria and ventricles, but he does not yet appreciate that these are one-way valves – instead he describes the atria as expansion chambers serving only to exchange blood with the ventricles on the beating of the heart. He does, however, now describe the heart sending blood to the lungs rather than receiving air from the lungs (as described in no. *77*): his experimental refutation of this earlier physiology is given on no. 80.



161

79 The movement of the heart

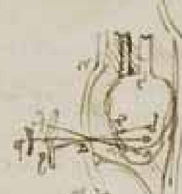
*c.*1511–12
Pen and ink
29.1 × 21.1 cm
RL 19065r; QA I.6r; O'M&S 95; K&P 158r

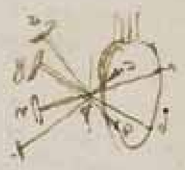
Anatomy
Whether the heart changes its position at death or not

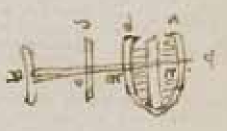
The change of the heart at death is the same as the change that it makes in the expulsion of the blood, or somewhat less. This is shown when they kill pigs in Tuscany, where they pierce the hearts of the pigs with an instrument called a spile, with which wine is drawn from casks. Turning the pig on its back and fastening it down firmly, they pierce its right side and its heart with this spile, pushing it straight inside. And if this spile pierces the heart when it is elongated, in its expulsion of blood the heart shortens and draws its wound upwards together with the point of the spile, and as much as it raises the point of the spile inside, so it lowers the handle outside. And then when the heart is distended and pushes its wound downwards, then the part of the spile outside makes a movement contrary to that of the part inside. . . . And this is does many times in such a way that at the end of life the external part of the spile remains in the middle between the two extremes which were the last contrary movements of the heart when it was alive . . . And this I have seen many times, and I have observed such measurements, and I have let such an instrument remain in the heart until the animal was cut up.

Leonardo goes on to discuss and illustrate how differing depths of penetration of the spile into the heart, and penetration at different moments in the cardiac cycle, affect the degree of movement of the handle. He thus deduces that the heart shortens and lengthens during the cardiac cycle, and that in death it comes to rest between these two extremes. It must be noted, however, that he does not describe here what we would recognise as systole (when the heart contracts, in all dimensions, to pump blood out) and diastole (when it relaxes and fills with blood); indeed, further down the page he refers to 'extension and dilatation' ('astensione e dilatatione'), suggesting that he believed that when the heart shortened, it grew correspondingly wider – that its shape changed but not its overall volume as it pumped blood backwards and forwards between the ventricles and atria.

[illegible]







[illegible]

80 The heart, bronchi and bronchial vessels

*c.*1511–13
Pen and ink on blue paper
28.8 × 20.3 cm
RL 19071r; QA II.1r; O'M&S 173; K&P 162r

The drawing is a view from behind of the heart, bronchi and bronchial vessels of an ox, the subject of most of Leonardo's heart dissections. The coronary sinus and circumflex branch of the left coronary artery are seen in the posterior left atrioventricular groove, with the middle cardiac vein and posterior interventricular artery descending in the posterior interventricular groove. Leonardo shows the branching of the bronchi, with their walls formed of regular cartilaginous tubes: in reality the trachea has evenly spaced C-shaped cartilages within its wall (as Leonardo had described on no. 35), the primary bronchi have large plates, and the amount of cartilage decreases through the secondary and tertiary bronchi. The bronchi are accompanied throughout by ramifying veins and arteries which Leonardo has attempted to represent as paired; he shows at least two left and one right bronchial arteries arising from the arch of the aorta, but the drainage of the bronchial veins is not indicated. At centre right are details of a 'trachea of medium size' (to the right) and a 'smallest trachea uninflated and inflated, which is doubled in capacity in its expansion' – Leonardo used the term 'trachea' to refer to all the passages of the respiratory tract.

The extensive notes include the following passage:

Whether air penetrates into the heart or not

To me it seems impossible that any air can penetrate into the heart through the trachea [i.e. bronchi], because if one inflates [the lung], no part of the air escapes from any part of it. And this occurs because of the dense membrane with which the entire ramification of the trachea is clothed. This ramification of the trachea as it goes on divides into the most minute branches together with the most minute ramification of the veins which accompany them in continuous contact right to the ends. It is not here that the enclosed air is breathed out through the fine branches of the trachea and penetrates through the pores of the smallest branches of these veins. But concerning this I shall not wholly affirm my first statement until I have seen the dissection which I have in hand.

Leonardo thus refutes the traditional belief that air passes from the lungs into the heart (as illustrated in no. 77), and indeed that air mixes directly with blood anywhere in the cardiopulmonary system. That this refutation is both experimental and provisional demonstrates Leonardo's maturity as a scientist. Had he omitted the word 'not' four lines from the end of the above passage, Leonardo would have provided a perfect description of gaseous exchange in the alveoli; but he had, of course, no knowledge of this process, and he maintained to the end of his life a belief that the lungs existed to cool the blood heated by its turbulence in the chambers of the heart.

81a The heart and coronary vessels

*c.*1511–13
Pen and ink on blue paper
28.8 × 41.3 cm
RL 19073v–4v; QA II.3v–4v; O'M&S 86–7; K&P 166v

The largest drawings on the left page of this double sheet give two views of an ox's heart with its auricular appendages. The pulmonary trunk has been removed to reveal the open three-cusped pulmonary valve. Rising from the centre of the heart is the aorta with its single brachiocephalic trunk; immediately adjacent are the superior and inferior vena cava – in the ox, the two venae cavae merge before they reach the atrium. The coronary arteries are seen leaving the base of the aorta and passing to either side of the pulmonary valve: the circumflex and anterior interventricular branches of the left coronary (travelling to the right as we look at the drawings) are particularly well shown. Above is a diagram in which the heart is sectioned longitudinally through each of the ventricles (cf. no. 84); Leonardo thus established that 'the right ventricle extends to a depth of three-quarters the length of the heart'.

The drawings on the right half of the sheet continue to examine the paths of the left and right coronary arteries. At upper centre, the left coronary artery is again shown splitting into its circumflex and anterior interventricular branches. In the drawing to the left of this, the heart is turned around to show the coronary sinus receiving veins from the left side of the heart and entering the right atrium at the base of the vena cava. Leonardo notes that the circumflex branch of the left coronary artery, labelled *H,* lies below the coronary sinus.

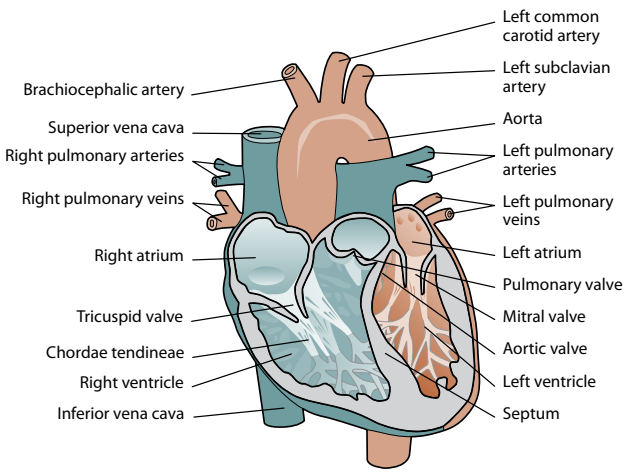


Fig. 21. Diagram of the human heart

In the smaller drawings at centre right, Leonardo emphasises the encircling 'crown' of the coronary arteries and coronary sinus around the base of the heart, noting that these vessels 'intersect like someone crossing his arms'. Below are four small diagrams of a three-cusped valve both open and closed.

Despite these direct physical observations of the anatomy of the heart, Leonardo's understanding of its physiology remained rudimentary, and the passage at top left essentially reprises the notes on flux and reflux between ventricles and atria quoted in no. 78.

81b The ventricles, papillary muscles and tricuspid valve

*c.*1511–13
Pen and ink on blue paper
28.8 × 41.3 cm
RL 19073r–4r; QA II.3r–4r; O'M&S 96, 106; K&P 166r

The left page of this double sheet features four sections of an ox's heart showing the papillary muscles within the ventricles. The accompanying notes suggest two roles for those muscles: in diastole, to prevent the ventricles from dilating too far and thus drawing too much blood from the vessels; and in systole, to prevent the ventricles from closing completely, so that space remains in the left ventricle for some blood to pass through the septum from the right ventricle. The note at the top of the sheet discusses the functioning of the valves, stating that while closing, the valves 'always give passage first to a quantity of blood before they shut' and thus 'return back some of the blood to which they had previously given passage'. Leonardo appreciated that the valves are one-way structures, but this was obviously incompatible with a belief in the continuous flux and reflux of the blood (represented by a see-saw faintly drawn towards the bottom of the page), and so he denied the effectiveness of the valves. As Leonardo's later studies confirmed their perfect closure, his acceptance of traditional physiology came under increasing tension.

The studies on the right-hand page present a significant advance in Leonardo's understanding of the papillary muscles. He had observed that they are connected to the cusps of the valves by the chordae tendineae, and that these cords reinforce the cusps (of both the tricuspid and mitral valves) when the valves are closed in systole:

> Nature has made the cords on the back side of the fleshy membrane of the three gates with which the gateway of the right ventricle is shut; and she has not made them on the front because these cusps feel more strain when they draw in blood than when they push it out.

The diagram along the top of the page is a sketch for the more finished drawing on no. 83, showing the tricuspid valve sectioned and opened out. Immediately below is a detail of the membranous sheaths of the chordae tendineae arising from the surface of the papillary muscle, and at lower centre is another 'opened-out' diagram that attempts to show how these membranous sheaths then flow onto the surfaces of the valve cusps.

In the right margin are geometrical diagrams analysing the structure of the tricuspid valve. Finally, at lower right is a section of the interventricular septum, with lines to indicate the fictitious pores through which subtilised blood was believed to pass from right to left ventricle: 'and thus it must be drawn in order to make it understood'.

82a The ventricles, valves and papillary muscles

*c.*1511–13
Pen and ink
22.1 × 31.2 cm
RL 19118v–19v; QA IV.13v–14r; O'M&S 102, 107; K&P 116v

The sheet was compiled by Leonardo as two distinct folios, though there are no stitch-marks down the central fold to suggest it was ever bound up. The sketches to upper right show the base of the bovine heart sectioned through, with the atria reflected to either side (represented by rough looping lines). The right ventricle is the crescent-shaped cavity at the top of each image, the left ventricle is the irregular triangle to lower right, the aortic valve is at the centre, and the pulmonary valve is to the left (Leonardo labels the pulmonary artery as the 'venous artery'). Adjacent to these sketches is a section through the left ventricle, with the aortic valve at top left; though Leonardo has shown papillary muscles and the chordae tendineae reaching up to the rim of the ventricle, the mitral valve is not really present.

The drawings towards the bottom of the left-hand page examine the interior of the right ventricle. That on the right imagines the triscuspid valve distended to give a view down into the ventricle: the chordae tendineae are shown arising from the papillary muscles and attaching most of the way around this aperture, with the moderator band dimly seen passing from centre left to lower right. The study at lower left is a section of the right ventricle at the level of the moderator band, with its two attachments labelled '*A*'. The view is now upwards towards the closed tricuspid valve. Leonardo was still uncertain about the correct number of papillary muscles (three in the right ventricle, two in the left) – in this drawing he depicts five, in the previous drawing four, and on the other side of the sheet two. In the right ventricle, the posterior and septal papillary muscles in particular can appear to be a small clusters of muscles. By the time he compiled no. 83 Leonardo had established the correct number in each ventricle.

The notes and sketches at upper left examine the spatial relationship between the ventricles and the superficial vessels of the heart. A further note seeks confirmation of Leonardo's beliefs about the source of heat in the heart:

> Observe whether the revolution of milk when butter is made, heats it. And by such means you will be able to test the power of the auricles [atria] of the heart, which receive and expel the blood from their cavities … these being made only in order to heat and refine the blood and make it more quickly penetrate the wall through which it passes from the right to the left ventricle.

At lower right is yet another study of the pronation and supination of the forearm, an action that Leonardo had analysed extensively a couple of years earlier in Manuscript A (nos 60, 61) and that continued to fascinate him – similar studies are found on the embryological sheet, no. 69.

82b The right ventricle and the valves of the heart

*c.*1511–13
Pen and ink
22.1 × 31.2 cm
RL 19118r–19r; QA IV.13r–14v; O'M&S 101, 108; K&P 116r

The three largest drawings on the right-hand page show the interior of the right ventricle from below, with the moderator band and two of the three papillary muscles prominent, and the chordae tendineae (particularly well drawn) extending up to the tightly closed cusps of the tricuspid valve. The geometrical diagram to the centre of the page purports to show the location of the papillary muscles on the walls of the ventricle; again only two are indicated. The moderator band is highlighted in the schematic view of the heart below. Leonardo referred to this band of tissue, extending between the interventricular septum and the base of the anterior papillary muscle, as 'the chain of the right ventricle', and until relatively recently it was thought to prevent overexpansion of the right ventricle; it is now known to play a role in the electrical conduction system of the heart.

On the left-hand page Leonardo considers the function of the pulmonary valve, which lies between the right ventricle and the pulmonary trunk. The first of the marginal drawings is a partly geometrical rendering of the valve: the semilunar attachments of the cusps are well indicated, with sketched lines on the uppermost cusp presumably representing the chordae. In a note Leonardo suggests that the curved, fleshy attachment of the cusps was designed to deflect the 'impetus' of the blood as it flows into the cusps when the valve closes, otherwise the 'impetus' would damage the cusps. Leonardo was increasingly concerned that his investigations should have a rational basis: scrawled in the top margin is the exhortation 'let no-one who is not a mathematician read my principles'.

The next marginal sketch is a cross-section of the aortic valve, showing the swirling of the blood in the sinus of Valsalva, studied exhaustively on nos 85–7. Next is a view of the base of the heart from above, rendered as a rounded triangle with the aortic valve at the centre ('in the principal position at the base of the heart, just as it holds principal place in the life of the animal'). Last is a sketch of the heart viewed from its apex, the right side to the top, with the anterior and posterior interventricular arteries meeting near the apex, as described in the accompanying note.

83 The right ventricle and tricuspid valve

*c.*1512–13
Pen and ink on blue paper
28.4 × 20.9 cm
RL 19078v; QA II.8v; O'M&S 105; K&P 165v

The largest drawing at the centre of the sheet shows the right ventricle sectioned longitudinally, thus revealing the papillary muscles (though their attachments are not apparent) and the chordae tendineae reaching up to the tricuspid valve. At centre right are two details of the valve when closed: the lower drawing shows it from the ventricular side, with the papillaries and chordae fanning out upwards; the upper drawing shows the valve from the atrial side, with letters purporting to indicate the points of attachment of the chordae on the other side of the cusps (Leonardo's shading seems to suggest, wrongly, that the cusps are concave from this side). Leonardo has represented the chordae as regular and symmetrical, and he has placed the papillaries so that each muscle serves one cusp only, whereas in reality the papillaries are placed between the cusps.

That layout is more correctly drawn in the diagram at the top of the page. Leonardo has envisaged cutting through the heart transversely both above and below the valve, thus giving a rough cylinder of the heart wall with the valve in the middle, and then cutting that cylinder longitudinally and opening out the tissue to a flat rectangle. The diagram therefore shows the three cusps of the valve lying flat against the heart wall, with the papillary muscles below and their chordae fanning out to the cusps. The moderator band is seen, cut, attaching below the papillaries at left and right. Again the chordae are arranged too symmetrically (and at upper left is a diagram that shows the chordae in three distinct ranks), though Leonardo has also indicated, below the lower line of the diagram, a more irregular arrangement.

At lower centre is a longitudinal section through the left ventricle, with the two papillary muscles serving the two cusps of the mitral valve. Most of the notes discuss the physical arrangement of the cusps and chordae, except for one note in which Leonardo tries again to reconcile his understanding of the efficient functioning of the tricuspid valve, which prevents blood from passing back from the right ventricle into the right atrium during systole, with the traditional physiology of the heart, which required the flux and reflux of the blood:

> And if it should seem necessary to you that these gates should not be closed completely, because some blood ought to be breathed out and given to the lung, in this case blood is provided which is blown out of the ventricle before [the valve] is completely closed.

In other words, Leonardo accepted that the valves did attain perfect closure, but persuaded himself that some blood escaped back through the valve as it was closing. This can happen due to disease, but in a normally functioning valve such regurgitation is non-existent.

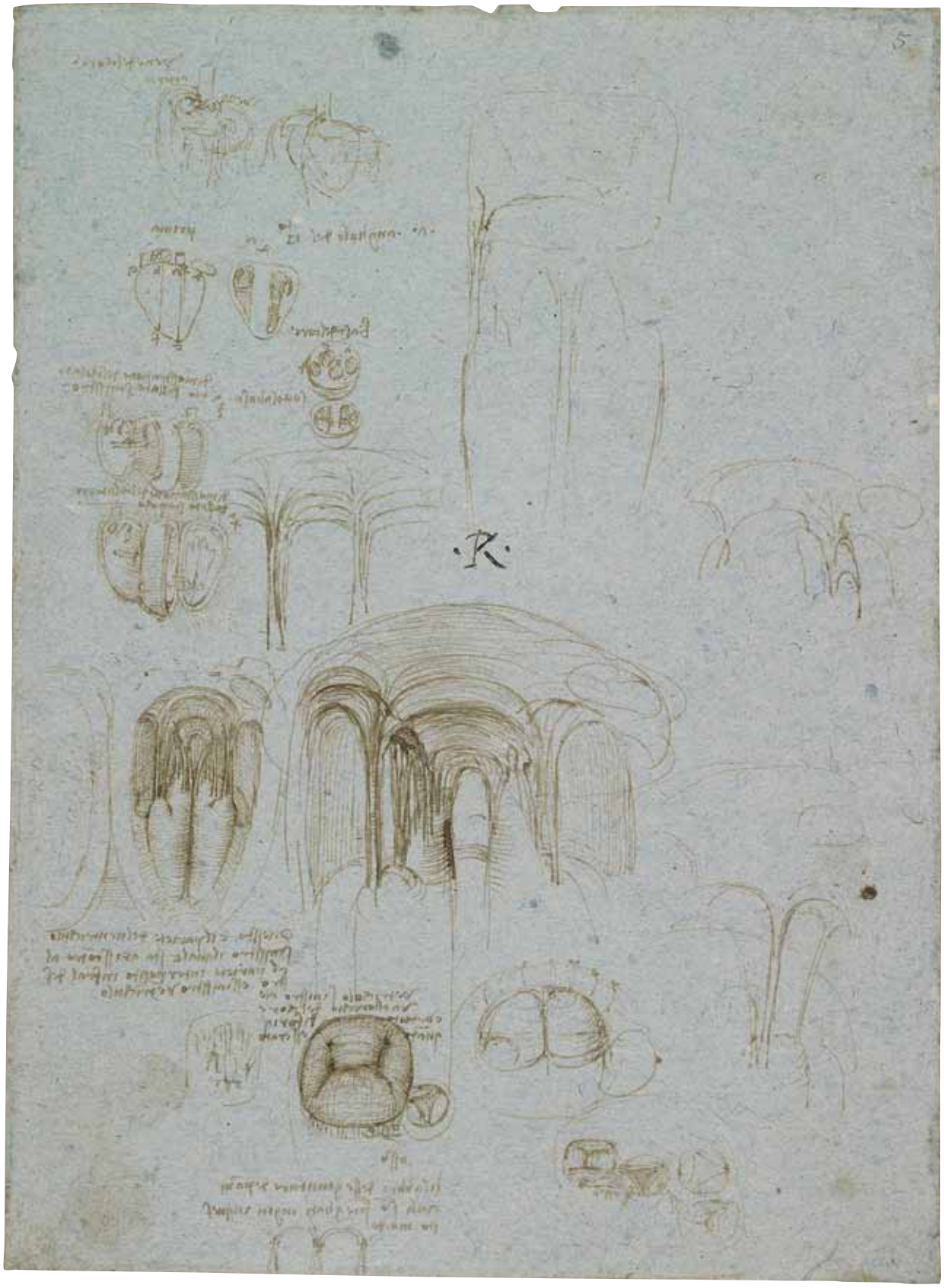
84 The left ventricle and mitral valve

*c.*1512–13
Pen and ink on blue paper
28.4 × 20.9 cm
RL 19080r; QA II.10r; O'M&S 104; K&P 170r

At top left are two rough sketches of the heart with the coronary and other superficial vessels. Below are three sections of the heart – a schematic longitudinal section with the atria and ventricles shaded, and two transverse sections, one at the approximate level of the valves to show (inaccurately) their relative positions, another lower down cutting through the ventricles. To the left of these is an outline of the heart with two vertical lines indicating the sections that would each cut through one ventricle only. The results of this are shown in the two sketches below, in which the heart is cut into three portions and opened out, thus exposing the inner surfaces of each ventricle.

The two largest studies at centre and centre left present details of the interior of the left ventricle. We see the two papillary muscles arising in the lower part of the ventricle, with the chordae tendineae connected to the cusps of the mitral valve. Below, the mitral valve is shown in closure, from the atrial side. The mitral valve is normally regarded as two-cusped, and indeed its alternative name is the bicuspid valve; but Leonardo has accurately shown, on either side of the major cusps, two smaller commissural cusps, which are relatively larger in the mitral valve of the ox and other large mammals than in the human.

A pale sketch at bottom right shows the four valves of the heart (which lie in approximately the same plane) from above; just below the mitral and aortic valves Leonardo has written *'osso',* referring to the two small bones that lie in the fibrous aortic ring of the bovine heart. In that drawing the mitral and tricuspid valves are closed and the aortic and pulmonary valves are open. This is the configuration during the second phase of systole, when the ventricles contract to pump blood into the aorta and pulmonary artery. If Leonardo did intend to display this configuration, rather than showing the valves arbitrarily open or closed, then this is an astonishing piece of observation and implies a very clear understanding of the sequence of operation of the heart.



85 The aortic valve

*c.*1512–13
Pen and ink on blue paper
28.3 × 20.4 cm
RL 19082r; QA II.12r; O'M&S 110; K&P 171r

The diagram at top right is a section through 'a mould of gypsum for blowing up inside with thin glass. . . . But first pour wax into the gate of an ox's heart so that you may see the true shape of the gate'. Thus Leonardo describes laconically one of his most brilliantly simple anatomical experiments. A couple of years earlier he had used wax injection to determine the shape of the cerebral ventricles (no. 48); here he applied the same technique to the aortic valve of an ox's heart. Discovering that immediately above the aortic valve is a widening of the root of the aorta (the sinus of Valsalva), Leonardo made a schematic glass model of that section of the heart (omitting, of course, the cusps of the valve). As noted on RL 19076v, he could then 'see in the glass what the blood does in the heart when it closes the little doors of the heart'. By pumping water with a suspension of panic-grass seeds through the glass model, Leonardo observed the turbulent eddies in the sinus, which he concluded were responsible for opening out the cusps when blood flow through the valve ceased after each beat of the heart; otherwise, he surmised, reflux of the blood would cause the cusps to crumple (as sketched at upper centre) rather than billowing out to close the valve.

At centre right is a cross-section through the upper part of the left ventricle and sinus of Valsalva, with the lower part of the ventricle sliced through and opened out (though the tubular structure on the wall of the ventricle is the wrong shape for a papillary muscle and in the wrong ventricle to be the moderator band). Leonardo incorrectly shows the wall of the ventricle thickening immediately below the valve: he stated that 'necessity has provided that the walls of the gateway enlarge, one opposite the other, in such a way that the gateway of the heart is closed by these walls as well as the shutting of the valve orifice by the fine membranes [valve cusps]'. On no. 44a, in studying the anal sphincter, Leonardo listed the heart as one of the other 'six apertures in the skin', and he evidently believed that there was some sphincter-like action in the closing of the aortic valve, in addition to the (perfectly understood) operation of the cusps.

Immediately adjacent is a longitudinal section through a ventricle, showing the papillary muscles and chordae attached to the cusps of the valve (the sketch is labelled 'right ventricle', though the valve appears to be bicuspid). And in the upper left portion of the sheet are a number of diagrams, without any explanatory notes, in which Leonardo muses on the geometrical principles of the three-cusped valves.

86 Blood flow through the aortic valve

*c.*1512–13
Pen and ink
28.6 × 20.5 cm
RL 19083v; QA II.13v; O'M&S 111; K&P 172v

In 20 sketches Leonardo continues to examine the flow of blood through the aortic valve and the eddies in the sinus of Valsalva, whose discovery he had recorded on the previous sheet. Leonardo found the subject of fluid dynamics perennially interesting, and he often attempted to analyse fluid flow in terms derived from both solid dynamics and optics – impetus, percussion, reflection, and so on, as here:

> We have demonstrated the beating of the heart to be by impetuses. If this were not so, the left [aortic] valve would not be able to shut, and the blood which was at first located above the valve would immediately descend. But the valve being opened by the impetus and percussion of the blood which the left ventricle drives out of itself [in systole], the valve stays open just as long as a small quantity of blood which issues from the heart keeps it free from obstruction. And at the same time the blood above it cannot descend because the wave of blood which percusses it proceeds in an opposite movement throughout all the arteries. And at the same time the remaining impetus of the blood which opened the valves, closes them again with its reflected movement, and the heart opens again [in diastole].
>
> On the reopening of the left ventricle, the blood contained in it ceases to issue from this ventricle, and at that time the blood which had issued from it would return into this ventricle together with that which is placed above it. But the remaining circumvolving impetus which still survives in the ejected blood is that which percusses the sides of the valves and closes them so that this blood cannot descend. And if there were not the revolving of the aforesaid circular movement of the blood newly driven out of the left ventricle, without doubt the penultimate blood driven out of this ventricle would return into the ventricle.

The essential role of the vortices in the sinus of Valsalva in the closing of the aortic valve was not posited again until 1912, and is now well established (see F. Robicsek, 'Leonardo da Vinci and the Sinuses of Valsalva', *Annals of Thoracic Surgery,* LII [1991], pp. 328–35). Leonardo's intuitive understanding of this mechanism is highly impressive.

87 Blood flow through the aortic valve

*c.*1512–13
Pen and ink, over some black chalk
30.7 × 43.8 cm
RL 19116v–17v; QA IV.11v–12r; O'M&S 113–14; K&P 115v

Most of the drawings on this double-page sheet again study the flow of blood through the aortic valve, concentrating on the eddies in the sinus of Valsalva that help to close the valve in diastole. Leonardo used a variety of illustrative techniques – cross-section, transparency and geometrical simplification – to visualise the pattern of vortices in the sinus.

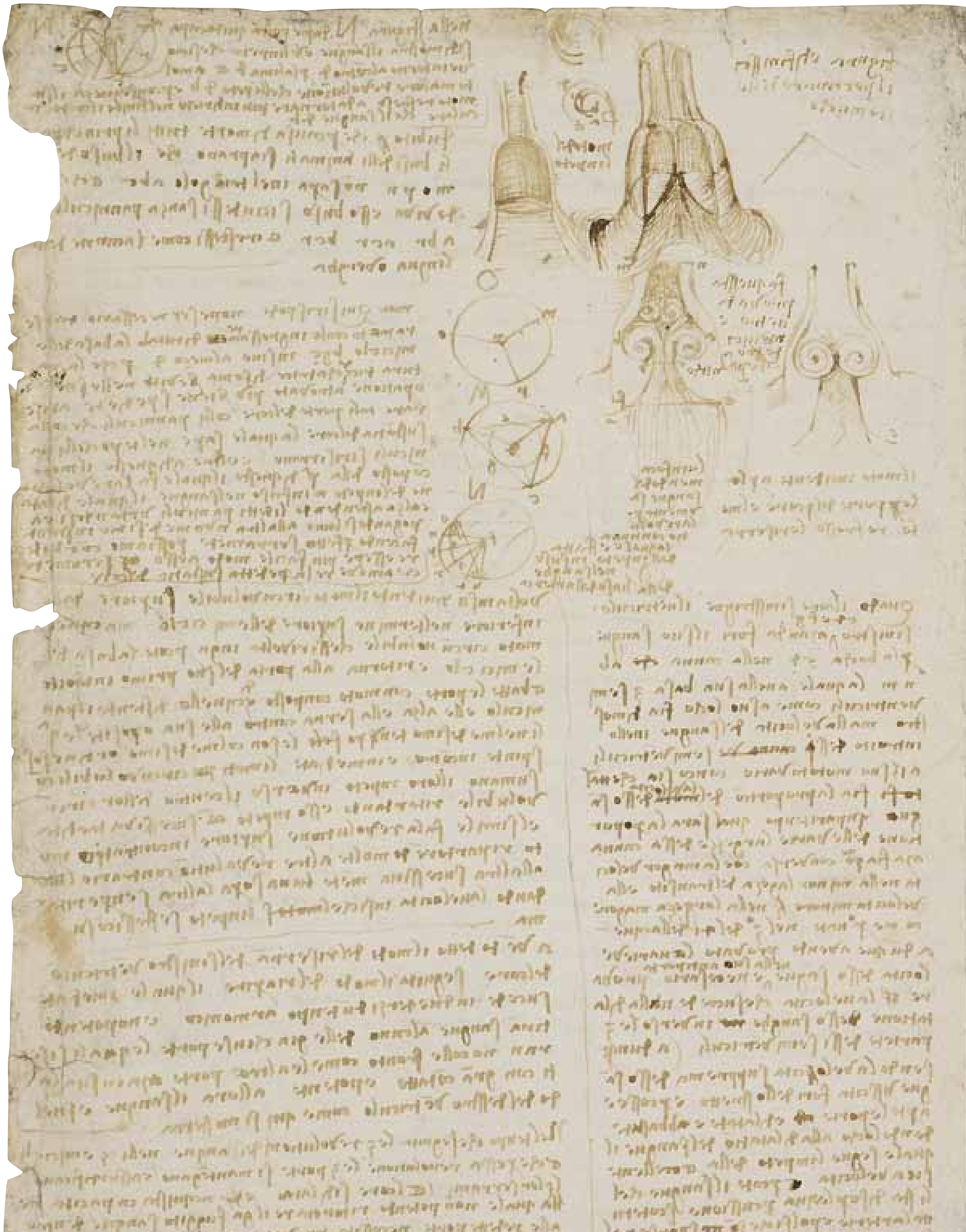
At upper right is a view of the aortic valve when open, showing the frilled appearance of the loose edges of the cusps as blood flows past them. The three-cusped structure of the aortic, tricuspid and pulmonary valves was analysed repeatedly by Leonardo in his studies at this time (the two- or four-cusped structure of the mitral valve – see no. 84 – is an artefact of foetal development). In pale ink in the margin above, Leonardo drew diagrams of a three- and four-cusped valve; while he acknowledged that 'the square orifice is more capacious than a triangular one within the same circle' – that is, a four-cusped valve would let more fluid through – he also noted that 'the membranes of four-cusped valves are weaker than those of three-cusped valves' because 'the more obtuse angle is stronger than the right-angle of the square'. A three-cusped structure was thus the optimum compromise between aperture size (greater with more cusps) and strength in closure (greater with fewer cusps).

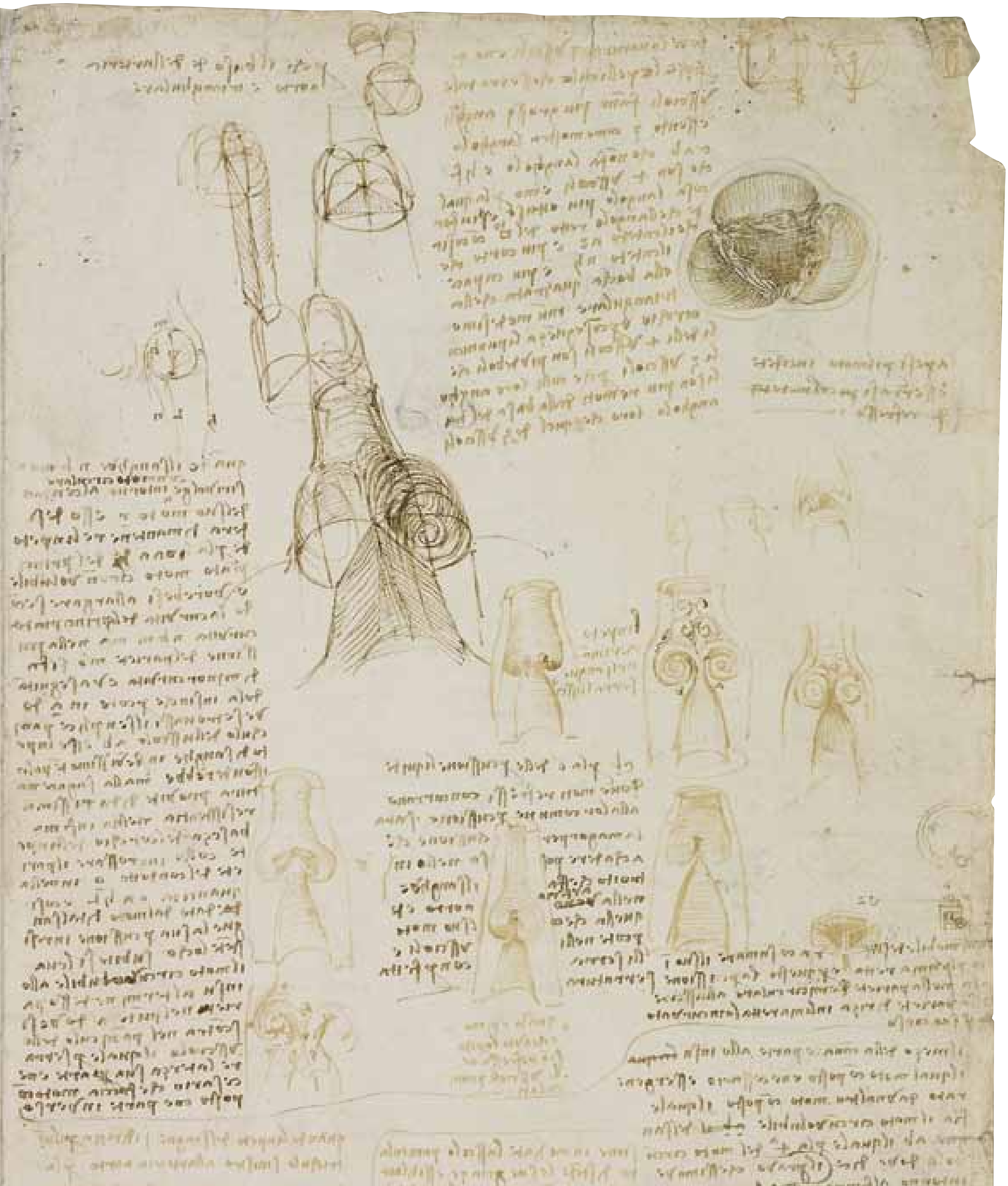
In notes running to over 1,500 words Leonardo once again explains in great depth the mechanism by which the aortic valve closes:

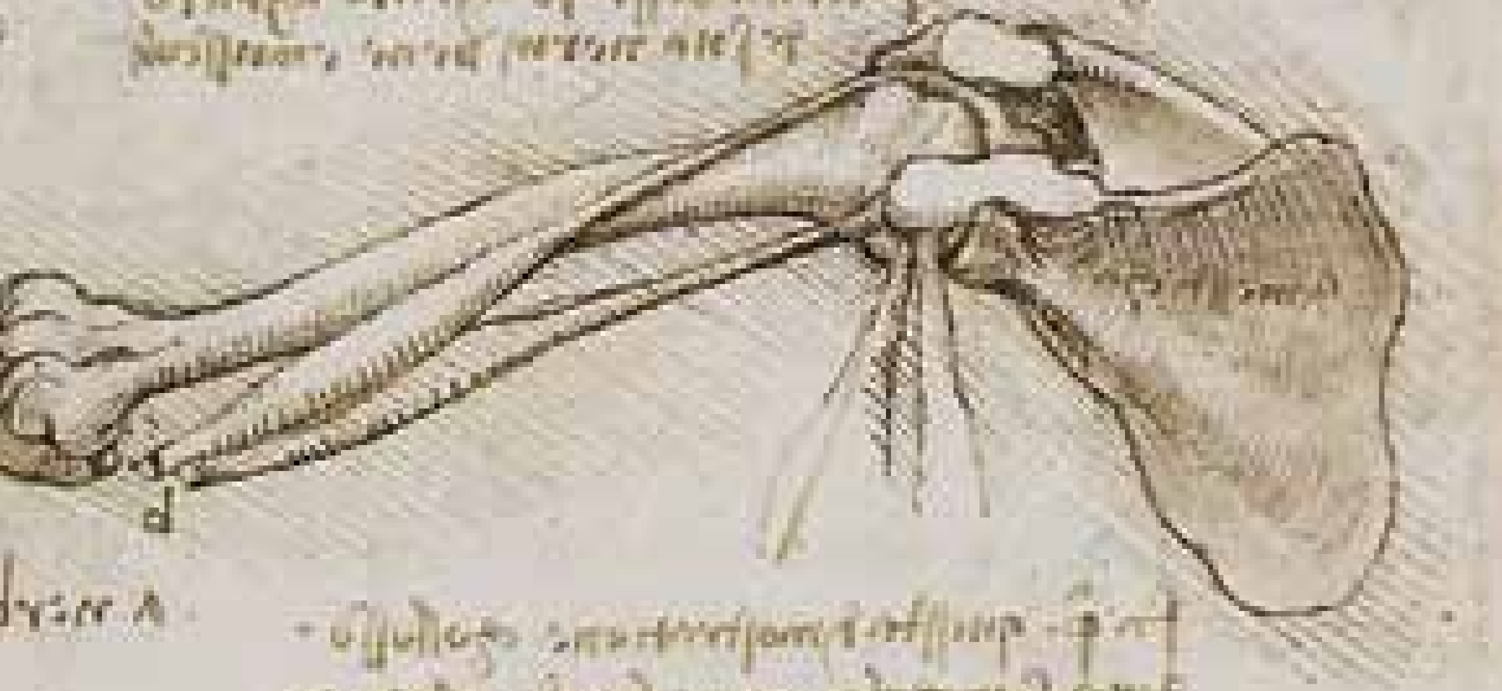
> When the impetus of the blood is directed by the left ventricle into the aorta through the orifice, it percusses and dilates the membranous valve-cusps and it rises upwards … and the impetus is divided at the narrow site of its percussion, and it revolves back along the curve and percusses the wall of the [sinus]. It then follows the circular motion imparted to it by the wall and percusses the membrane of the valve-cusp … which immediately extends its folds and dilates until it leans against the opposite valve-cusp which, by the opposite impetus, comes to meet it … And thus the three valve-cusps shut together in close contact until the impetus consumes itself. …

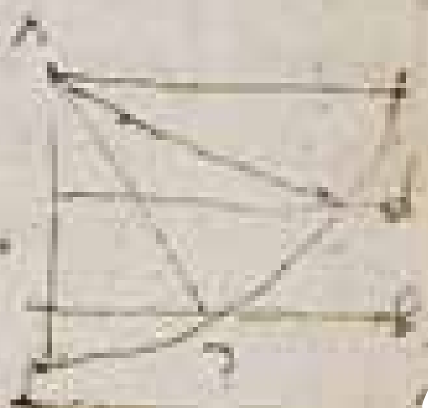
> Having described the manner in which the left ventricle of the heart closes, there follows the manner in which it reopens. This immediately succeeds in two-thirds of a harmonic tempo. Not being able to draw back any blood from the previously closed valve-cusps which are closed with their surfaces like the other valve-cusps, with their sides in great and powerful contact, the blood is at that time torn out of the right ventricle, as will be here demonstrated. During the time which follows the three revolutions of blood in the three hemicycles, and as by these three revolutions the three valve-cusps are maintained and strengthened in their closure, the heart dilates and acquires capacity. The previously expelled blood not being able to return into it inside the aforementioned valve-cusps, necessity provides for the extraction of blood from the right ventricle, which penetrates the wall interposed between the right and left ventricles through wide porosities. These porosities go on narrowing into pyramidal hollows until they become imperceptible ducts through which the viscous blood penetrates and proceeds to thin down to great fineness.

Once again, acute observation, in this case on the motion of the blood through the aortic valve, sits alongside an acceptance of traditional physiology. On the surface this is baffling: Leonardo had an almost perfect understanding of the action of the valves and the motion of the heart, yet he continued to believe that in diastole, blood was drawn into the left ventricle through pores in the interventricular septum, rather than from the pulmonary veins via the left atrium and mitral valve. He could not shake himself free from the ancient belief that the venous and arterial systems were independent and that both were centrifugal. We cannot know how Leonardo's researches would have proceeded if he had had no preconceptions, and this, one of Leonardo's last substantial sheets of anatomical study, captures vividly the fundamental challenge that faced him throughout his anatomical career – how to reconcile what he observed with what he believed.









Further Reading

Leonardo's anatomical studies were first properly published in a series of facsimile editions a century ago:

G. Piumati, *I manoscritti di Leonardo da Vinci della Reale Biblioteca di Windsor. Dell'Anatomia: Fogli A and Fogli B,* 2 vols, Paris 1898 and Turin 1901 (with transcriptions of Leonardo's notes, and translations into French)

Leonardo da Vinci: Quaderni d'Anatomia, 6 vols, Christiania 1911–16 (with transcriptions of Leonardo's notes, and translations into English and German)

The most widely available edition of Leonardo's anatomical work is C.D. O'Malley and J.B. Saunders, *Leonardo da Vinci on the Human Body,* New York 1952 (and later edns), which reproduces 215 of Leonardo's anatomical drawings and translates some of his notes into English.

All of Leonardo's drawings in the Royal Library are to be found in K. Clark and C. Pedretti, *The Drawings of Leonardo da Vinci in the Collection of Her Majesty The Queen at Windsor Castle,* 2nd edn, 3 vols, London 1968–9. The anatomical drawings are mostly in vol. 3, though the notes are not transcribed or translated, and there is little discussion of the anatomical content. All of Leonardo's drawings at Windsor can now also be seen on the Royal Collection's website (www.royalcollection.org.uk).

The most comprehensive edition of Leonardo's anatomical studies is K. Keele and C. Pedretti, *Leonardo da Vinci. Corpus of the Anatomical Studies in the Collection of Her Majesty The Queen at Windsor Castle,* 2 vols with facsimiles, London and New York 1979–80 (with transcriptions of Leonardo's notes, and translations into English). The meticulous translation of Leonardo's notes is unavoidably the basis of the translations given here.

Smaller selections of Leonardo's anatomical studies have been exhibited before, and the catalogues for those exhibitions are widely available:

K. Keele and J. Roberts, *Leonardo da Vinci. Anatomical Drawings from the Royal Collection,* Royal Academy of Arts, London 1977 (with subsequent showings in Florence and Hamburg in 1979; Mexico City, Adelaide and Melbourne in 1982; and New York in 1984)

M. Clayton and R. Philo, *Leonardo da Vinci. The Anatomy of Man,* Museum of Fine Arts, Houston 1992 (with subsequent showings in Philadelphia and Boston, and in Tokyo and Nagoya in 1995)

M. Clayton and R. Philo, *Leonardo da Vinci. The Mechanics of Man,* Vancouver Art Gallery, Vancouver 2010 (the whole of the Anatomical Manuscript A, and the basis of nos 52–67 in the present book)

The most satisfactory compendium of Leonardo's writings (on all subjects) remains J.-P. Richter, *The Literary Works of Leonardo da Vinci,* 2 vols, 2nd edn, Oxford 1939, which should be read in conjunction with C. Pedretti, *. . . A Commentary to J. Paul Richter's Edition,* 2 vols, Oxford 1977.

There follows a far from exhaustive list of other writings that focus, in whole or in part, on Leonardo's anatomical studies:

E. Belt, *Leonardo the Anatomist,* New York 1955

M. Cazort et al., *The Ingenious Machine of Nature. Four Centuries of Art and Anatomy,* National Gallery of Canada, Ottawa 1996

M. Clayton, *Leonardo da Vinci. The Divine and the Grotesque,* London 2002

S. Esche, *Leonardo da Vinci. Das anatomische Werk,* Basel 1954

K. Keele, *Leonardo da Vinci on the Movement of the Heart and Blood,* London 1952

K. Keele, *Leonardo da Vinci's Elements of the Science of Man,* New York 1983

M. Kemp, '"Il concetto dell'anima" in Leonardo's early skull studies', *Journal of the Warburg and Courtauld Institutes,* XXXIV (1971), pp. 115–34

M. Kemp, 'Dissection and divinity in Leonardo's late anatomies', *Journal of the Warburg and Courtauld Institutes,* XXXV (1972), pp. 200–225

M. Kemp, *Leonardo da Vinci. The Marvellous Works of Nature and Man,* London 1981

M. Kemp, *Leonardo da Vinci. Experience, Experiment and Design,* London 2006

M. Kemp and M. Wallace, *Spectacular Bodies. The Art and Science of the Human Body from Leonardo to Now,* exh. cat., Hayward Gallery, London 2000–2001

D. Laurenza, *De figura umana. Fisiognomica, anatomia e arte in Leonardo,* Florence 2001

J.P. McMurrich, *Leonardo da Vinci. The Anatomist,* Washington, DC 1930

C. Pedretti and P. Salvi, *Il tempio dell'anima. L'anatomia di Leonardo da Vinci fra Mondino e Berengario,* Foligno 2007

J. Roberts, 'An introduction to Leonardo's anatomical drawings', *Nine Lectures on Leonardo da Vinci,* London 1990, pp. 53–62

J.B. Schulz, *Art and Anatomy in Renaissance Italy,* Ann Arbor 1985

E.M. Todd, *The Neuroanatomy of Leonardo da Vinci,* Santa Barbara 1983

F.C. Wells and T. Crowe, 'Leonardo da Vinci as a paradigm for modern clinical research', *Journal of Thoracic and Cardiovascular Surgery,* CXXVII (2004), pp. 929–44

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For the story of all Leonardo's anatomical works, see Royal Collection Trust's multi-award-winning app, *Leonardo da Vinci: Anatomy*, produced in partnership with Touch Press and Primal Pictures.

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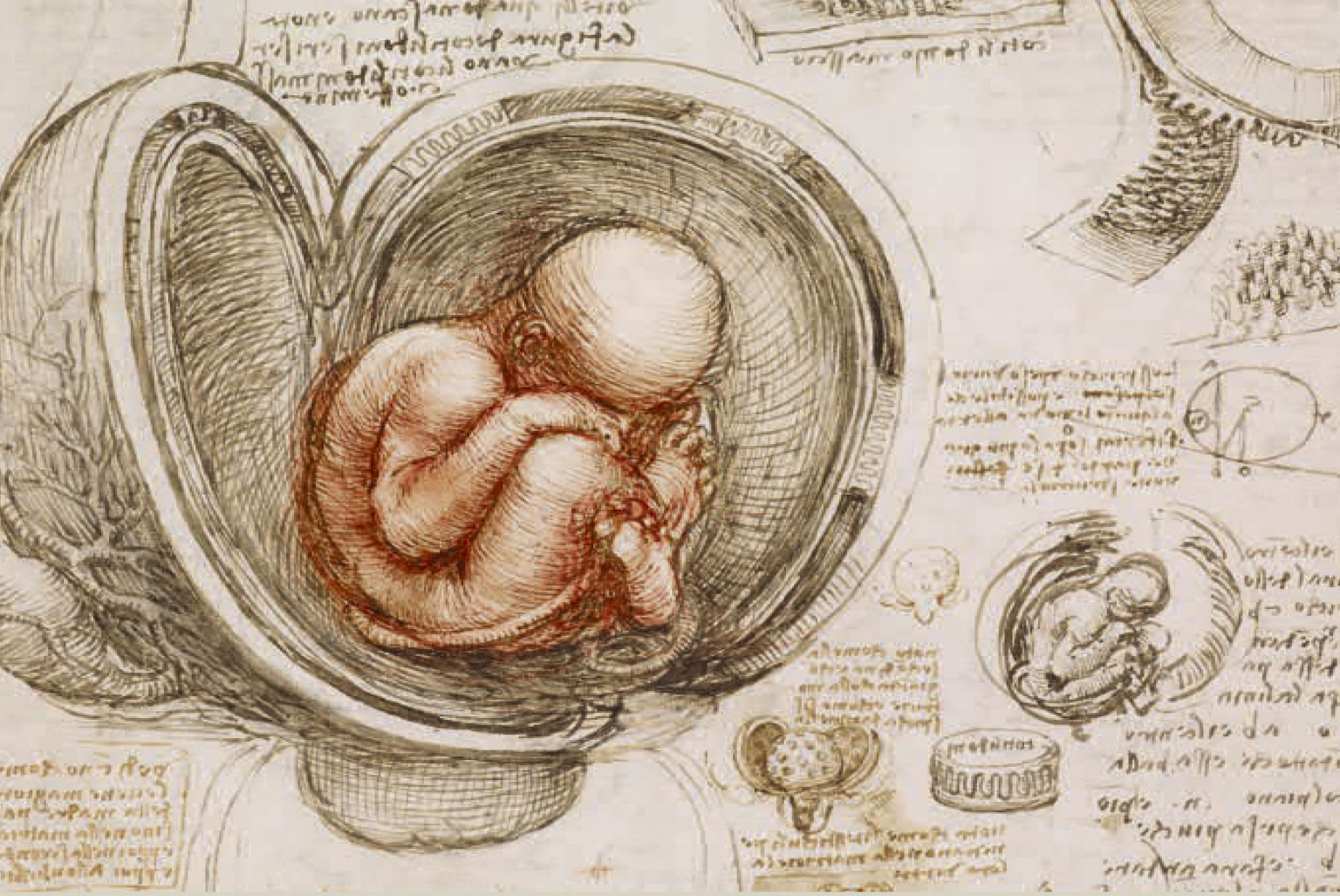

LEONARDO DA VINCI was one of the greatest anatomists ever to have lived. He dissected more than thirty human corpses, exploring every aspect of anatomy and physiology, and recorded his findings in drawings of unparalleled beauty and lucidity, and in notes that bear witness to his astonishing insights into the subject. Had Leonardo published his researches, he would have transformed European knowledge of anatomy. But his studies remained among his personal papers at his death, and were almost unknown until around 1900.

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