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Leonardo's Liquid Bodies

I

We can roughly distinguish four stages in Leonardo's anatomical corpus [1]. The 1490s are marked by a domineering interest in anthropometry. The proportions of the male human body occupied the center of Leonardo's thought with the canonical figure in Venice as its most famous paradigm [2]. This line of thought was entirely embedded in the discourse on beauty, in which the correct human proportions were the conditions for perfection in the visual arts and architecture. The *Uomo Vitruviano*, however, complicated this discourse, assuming as its basis that the geometry of man (the center point of his length and width) changes with position, and therefore with movement (fig. 1). As a result, the *proportions* of the male human body at rest and their transformations by *movement* – the main categories of Leon Battista Alberti's treatises on the statue and on painting respectively – needed to be reconciled. The key concept of *historia* in painting forced painters to clarify their ideas about man in action, and consequently about the muscles involved in bodies in movement for these were the direct expressions of intentions and emotions. Around 1495, Leonardo postulated :

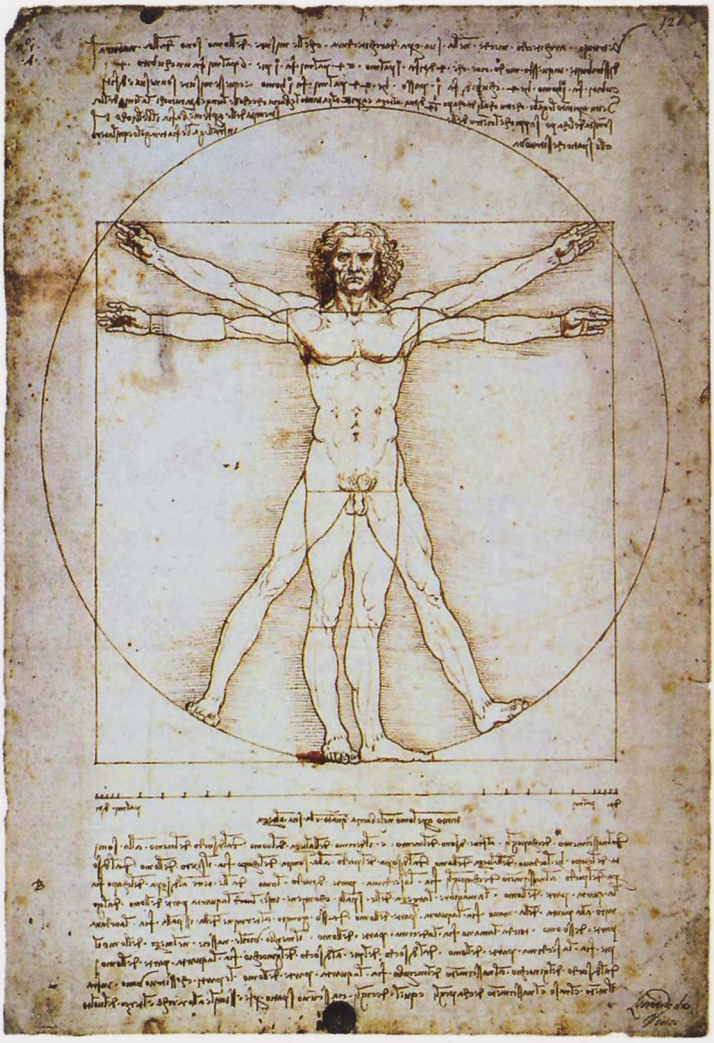
« De pittura. Necessaria cosa è al pittore per essere bon membrificatore nell'attitudine e gesti che far si possono per li nudi, di sapere la notomia di nervi, ossi, muscoli e lacerti per sapere nelli diversi movimenti e forze qual nervo o muscolo è di tal movimento causa, e sol quegli fare evidenti e ingrossati e non li altri per tutto, come molti fanno, che per parere gran disegnatori, fanno i loro inudi legnosi e sanza grazia, che pare a vederli un sacco di noci più presto che superfizie umana, ovvero un fasio di ravanelli più presto che muscolosi nudi » [3].

Interestingly, Leonardo integrated this argument into two larger discourses – the paragone of the visual arts on the one hand and

[1] I wish to express my gratitude to Jasmin Mersmann, Shawon Kinew, Fabio Frosini and Francesca Borgo for important suggestions, corrections, and assistance. My very brief periodization of Leonardo's anatomical studies follows mainly the detailed analysis by K. D. Keele / C. Pedretti (ed.), 1978-80 [KP] ; M. Kemp, 1972, pp. 200-225 ; M. Kemp, 1981 ; M. Clayton (ed.), 1992 ; D. Laurenza, *L'anatomia*, 2009. Interestingly enough, the chronological development of Leonardo's anatomy mirrors *grosso modo* the systematic model of Galen's anatomical analysis (from bones to muscles and, in the end, intestines, blood vessels, and nerves) ; on this, cf. A. Cunningham, 1997, p. 27.

[2] Cf. F. Zöllner, 1987, pp. 77-87 ; A. Perissa Torrini, 2009.

[3] Manuscript L 79r (L. da Vinci, 1987-1992).



1. *The proportions of man after Vitruvius*, Venice, Gallerie dell'Accademia, n° 228r, pen and brown ink, ca. 1492.

natural philosophy on the other. A deep knowledge of anatomy by painters became the equivalent of the sound knowledge of Latin for writers : « Questa dimostratione è tanto necessaria a buoni disegnatori quanto alli buoni grammatici la dirivazione de vocavoli latini, perché male farà li muscoli delle figure nelli movimenti e azioni di tal figure chi non sa quali sieno li muscoli che son causa delli lor movimenti » [4]. The convincing representation of bodies in movement was indispensable for one of the most striking achievements of painting, namely the overcoming of its limits through the illusion of movement on a static, flat surface. Furthermore, since Plato

[4] KP 62v / Windsor, Royal Library [W] 19021v / Anatomical Manuscript [Anat. Ms.] B 4v. On Leonardo's lost manuscript on painting and human movement, as mentioned by Luca Pacioli in 1498, see C. Pedretti, 1964, p. 3.

and Aristotle motion was conceived as the fundament of nature [5]. Consequently, for Leonardo dynamics included everything from the most abstract notion of time and the movements of the mind to the processes of perception and the physics of material objects :

« I moti sono di ___ nature, de' quali il primo è detto temporale, perché sol s'impaccia del movimento del tempo, e questo abbraccia in sé tutti li altri. Il secondo è della vita delle cose. Terzo è detto mentale, e questo sta ne' corpi animati. Quarto è quello delle spezie delle cose, che si spargon per l'aria per linie rette ; questo pare non essere sottoposto al tempo, perché è fatto in tempo indivisibile, e quella cosa che colla mente non si po dividere, non si trova infra noi. Quinto è quello de' soniti che vanno per l'aria, e questo è più tardo, e così degli odori e sapori ; e questo diren moto sensuale, l'altro è detto corporale, del quale fareno il nostro trattato » [6].

It hardly comes as a surprise that in Leonardo's « materialist » perspective, muscles provide the corporeal basis for language, psychology, and mimesis itself. On KP 51r, Leonardo investigates the muscles of the mouth and asks why those of man are more numerous than those of any other animal. In his answer, the sequence is revealing : Only the large number of muscles involved allow man to form consonants (the basis of *language*), to whistle (the first *musical* instrument, as it were), to express different *emotional* attitudes (such as laughing or weeping) and, last but not least, to allow for the « storcimenti strani li quali usano li buffoni nel contraffare li volti » (the principle of *mimesis*).

Quite typically for Leonardo, he took up his anatomical research only after a long break, around 1507, following the intense thought process around bodies in fierce movement which absorbed him in his preparations for the *Battle of Anghiari*. The resulting anatomical campaign in Florence, in the years 1507-8, expanded his view on the human body dramatically. This was the moment Leonardo transgressed any direct link to artistic representation decisively [7] and instead began to inquire about the concrete functions of organic life, including the beginning and the end of life. Contemporarily to his hydrological and hydrogeological studies, Leonardo focused on the « irrigation system » of the human body (to use Martin Kemp's phrase) – the movement of blood, the urino-genital, alimentary, nervous and respiratory systems. In comparison to his later achievements, many of these studies are still characterized by deduction and geometrical abstraction [8]. Anthropometrical studies disappeared almost completely, as well as the paradigm of the static bone structure – the *composition* – of the adult man. Instead, Leonardo developed « una concezione dinamica del corpo uma-

[5] Cf. F. Kaulbach, 1965.

[6] Codex Atlanticus 543v / 203 v old (L. da Vinci, 1973-1980).

[7] This was already explicitly criticized by Sabba da Castiglione in 1554 ; see B. Schultz, 1985, p. 68. Andrea Carlino, in turn, does not mention Leonardo (or any artist) as catalysts for the emancipation of Renaissance anatomy from practical purpose to science, or natural philosophy (A. Carlino, 1999b).

[8] Cf. KP 53v / W 19054 v (with regularly proportioned diameters of the branches of the trachea).

no » [9], with an obsessive interest in the variations of the human form as an effect of biographical circumstances, spanning from the embryo to old age, with countless contingent variables, the most influential of which were the passions, regular bodily activities and diseases. At the same time, Leonardo shifted from physiognomy to the dynamics of pathognomy, as Domenico Laurenza has shown [10]. Instead of the dominant interest in the two-dimensional silhouette of man (length and width), Leonardo realized the three-dimensionality of the body, his *rilievo*, the distribution of fat, muscles, tendons, etc. in space and the dynamics at work underneath the surface of the skin – in other words, the *depth* of man. In a Galenic perspective, Leonardo's focus shifted almost entirely from the traditional functions of the *anima sensitiva* and *rationalis* (still implicitly of central importance for the studies of the skull in the 1490s) to the nutritive, self-preserving functions of the *anima vegetativa* [11].

The third stage in Leonardo's anatomical research – masterfully documented in the so-called Anatomical Manuscript A in Windsor (KP 134r-151v / W 19001-19017) – can be dated to 1510-11, when Leonardo worked side by side with the brilliant young anatomist Marcantonio della Torre in Pavia [12]. Important medical texts were now available to Leonardo, among them Galen's *De usu partium* and Avicenna's *Canon*. This was the moment of breakthrough in the history of anatomical representation, marking a new step in Leonardo's systematic approach to anatomy. Instead of the extremely vast program some three years earlier, Leonardo now focused again on bones and muscles (significantly, the skull was largely omitted), and developed, for the first time, diagrammatic equivalents for the spatial disposition of muscles and for the transmission of force along individual strains of muscles.

The latter anticipates the functional approach of the last stage of Leonardo's anatomy, beginning in the winter of 1512-1513 on the Milanese countryside, and continuing in Rome the next year with its focus on the cardiovascular system of man [13]. Having clarified important aspects of the mechanics of limbs in 1510-1511, Leonardo embarked on a completely different area, the haemodynamics of the human body. To be sure, blood provides one of the most serious obstacles for anatomical research ; it « tigne di se ogni parte d'un medesimo colore e le vene che di tal sangue si votano non sono conosciute per la lor diminutione » [14]. Quite surprisingly, this most difficult topic – both for dissection and for representation – received Leonardo's « disproportionate attention » [15], at least in terms of the number of surviving sheets. Among the more than 5000 sheets of Leonardo's legacy, only about 200 deal with anatomical subjects but some sixty of these focus on the heart and the cardiovascular system.

[9] D. Laurenza, 2001, p. 139.

[10] D. Laurenza, 2001, pp. 127-155.

[11] Cf. D. Laurenza, 2004. For a recent approach to Leonardo's brain studies, cf. Tanja Klemm, 2010, pp. 35-54.

[12] See the groundbreaking, article by D. Laurenza, 2011.

[13] The fundamental contribution to this subject remains K. D. Keele, 1952. For the context, see C. R. S. Harris, 1973 ; T. Fuchs, 1992.

[14] KP 154r/ W 19061r / Quaderni d'anatomia [Quad.] I 2r.

[15] K. D. Keele, 1952, p. 40.

Once again, Leonardo's investigations aim at an understanding of the principles of organic life. Already during the previous campaign, Leonardo followed the traditional conviction that the whole body originates in the heart [16]. How is it related to the foundation of life ? In one of his extremely rare vivisections, Leonardo observed that the frog is able to move without head or heart but dies immediately if its spinal cord is pierced [17]. Also, since the embryo floats in the « clearest water » of the mother's womb, it cannot breathe, and therefore its heart does not beat (otherwise it would need to be cooled by the air of the lungs) [18]. Instead the body of the embryo is nourished and vivified by the cardiovascular system of the mother. Only after the birth of the baby does the heart's principal action begin : the heating and rarefaction of blood, which is concocted from nutriment in the liver, in order to distribute vital heat and nourishment to the rest of the body. As a generator of heat, the heart is particularly resistant to outer heat and fire [19].

As the main instrument of enlivenment, the heart – « instrumento mirabile invenzionato dal sommo maestro » [20] (on the papillary muscles) – evokes Leonardo's most religiously tinged praise. The question whether the heart moves spontaneously or whether it is moved by another organ determines the site of the (vegetative) soul in the human body :

« non abandonare li nervi reversi insino al core e vedi se tali nervi dan moto al core o se 'l core si move da se, e se tal moto vien dalli nervi reversivi che hanno l'origine nel cervello, allora tu sarai chiaro come l'anima ha la sedia nelli ventriculi del cervello e li spiriti vitali hanno l'origine dal ventriculo sinistro del core. E se tal movimento del core nasce da se medesimo, allora dirai che la sedia dell'anima è nel core e similmente quella delli spiriti vitali » [21].

II

Let us have a quick look at some features of Leonardo's previous anatomical drawings before returning to this final topic of Leonardo's anatomical research and to some peculiarities of its graphic representation [22]. I mentioned previously the denial of *depth* in Leonardo's early anthropometric studies, of which the *Uomo Vitruviano* is the most famous example. Before he carefully traced the outline of the figure, Leonardo defined the geometric framing : first the empty square, then the standing *uomo quadratus*, then the circle with its center in the navel and finally the *uomo ad circulum*. The silhouette is divided by the straight lines of canonical proportions. At the joints of the shoulders and the hip, the limbs over-

[16] Cf. KP 76v / W 19034v / Anat. Ms B 17v. See also D. Laurenza, 2001, pp. 49-92 (« cardiocentrismo »).

[17] KP 1v / W 12613r / Quad. V 21v.

[18] KP 200r / W 19128r / Quad. V 26r.

[19] KP 59v / W 19050v / Anat. Ms B 33v.

[20] KP 71r / W 19029r / Anat. Ms B 12r.

[21] KP 105r / W 19112r / Quad. IV 7r.

[22] For the history of anatomical illustrations in the Renaissance, see R. Herrlinger, 1967 ; R. P. Ciardi / L. Tongiorgi Tomasi (ed.), 1984 ; B. Schultz, 1985 ; K. B. Roberts / J. D. W. Tomlinson, 1992 ; Loris Premuda, 1993 ; A. Carlino / R. P. Ciardi / A. M. Petrioli Tofani, 2009 ; Cuir 2009.

lap, thereby becoming « transparent ». Only the head reveals some *rilievo* in its shading, a hint at Leonardo's contemporary interest in the proportions of the human skull and the location of the *sensus communis* inside the brain [23]. Except for the leonine head with its impressive mane and, to a lesser degree, the hands, any individual trace of Leonardo's line is suppressed in favor of accuracy and precision. This is a crypto-portrait of the approximately forty-year old Leone-Leonardo, the perfect painter who knows the numerical secrets of beauty and remains, at the same time, independent from the idiosyncrasies of style [24].

After 1500, Leonardo developed a masterful rendering of the anatomical layers underneath the skin (muscles, tissues, tendons, sinews, intestines etc.). Playing on the borderline between *ecorché* and soft, transparent skin (through the virtuoso display of *sfumato*), Leonardo produced, on the one hand, figures « infra l'anatomia e 'l vivo » (as he called them [25] ; fig. 2), and on the other, a full range of delicately transparent « windows » into the inner parts of the body. In *La ricerca dell'armonia*, Domenico Laurenza emphasized the enormous tension between analytical fragmentation and synthetic recomposition in Leonardo, in traditional categories, between *resolutio* and *compositio*, *corographia* and *cosmographia* [26]. Laurenza also demonstrated the extent to which Leonardo continuously struggled for the re-integration of individual body parts into the whole of the human body. Leonardo warned against the depiction of cut body fragments – the dominant model since Vesalius – as a « cosa monstruosa per averle tolto le sue parti » [27].

Leonardo's didactic representations of *gradually* removed layers instead seem to mirror the process of ageing and death : « comincia la tua anatomia all'omo perfetto e po' lo fa vecchio e men muscoloso, po' va spoliando a gradi insino all'ossa » [28]. The main goal for Leonardo, however, was always the re-composition of the entire, living body, either imaginatively through different views of the same body part (« in modo che tu resterai con vera e piena notitia di quello che tu voi sapere della figura dell'uomo » [29]), or through composite bodies with different levels of transparency. Exemplifying one of the topoi of the paragone, these drawings underline the power of images to show an invisible truth, the hidden reality of the human body. No description, but also no single dissection will ever reveal what these synthetic drawings are capable of demonstrating, Leonardo claims [30]. In this context, one particularly important graphic device deserves more attention : the « disappearance » of the contour line on the periphery of each representation, or the gradual *emergence* of form as a graphic equivalent for *sfumato*, where « l'occhio pensi di vedere, quello che egli non

[23] Cf. D. Laurenza, *L'uomo*, 2009, p. 122.

[24] Cf. F. Fehrenbach, 2011.

[25] KP 89r / W 12631r. Cf. C. Pedretti, 1979.

[26] D. Laurenza, 2003, pp. 31-72.

[27] Cf. KP 77r / W 19035r / Anat. Ms B 18r.

[28] KP 149r / W 19015r / Anat. Ms A 16r.

[29] KP 154r / W 19061r / Quad. I 2r.

[30] KP 113r / W 19070v.

2. *Anatomy of the legs*, KP 89r, Windsor Castle, Royal Library, pen and brown ink and black chalk, 190 x 305 mm, ca. 1504-1508.

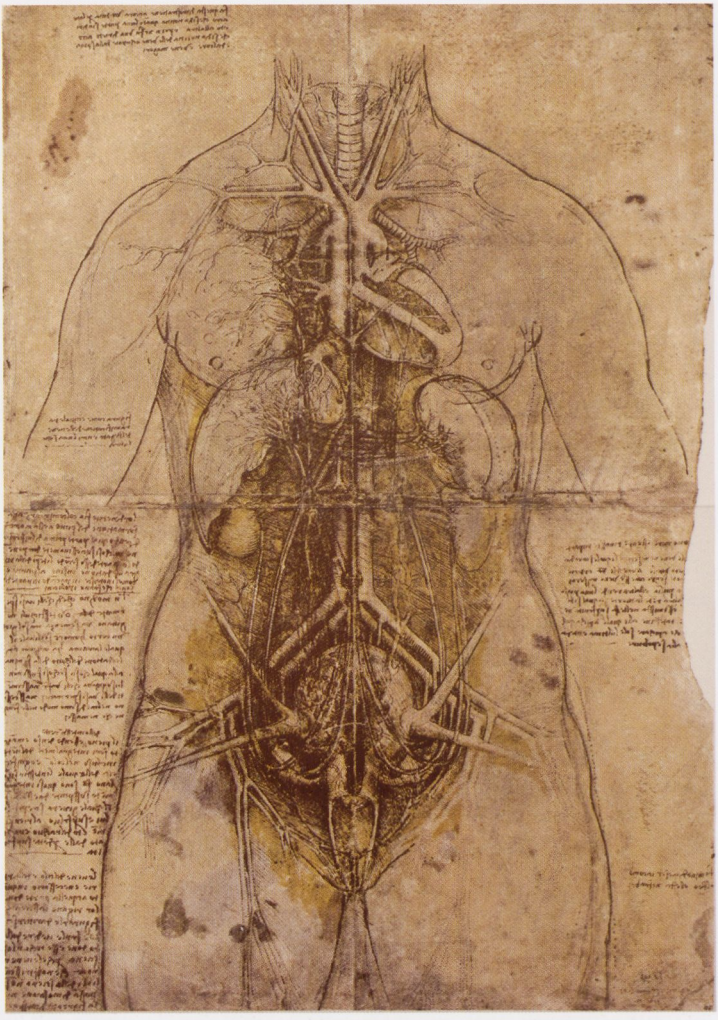
vede » (Daniele Barbaro) [31]. Gradual invisibility, rather than the sharp cut of dissection, alludes to hidden completeness. Fragments that smoothly fade into *nulla* provide the imaginative horizon for the integrity of living bodies [32].

III

The localization of single organs and limbs in the *cosmografia* of the whole body, Leonardo's main goal as an anatomist before 1512, provides knowledge about the spatial relationships and differences of form and surface but it does not directly account for the *function*

[31] Vitruvius, 1556, VII, 5. Cf. F. Fehrenbach, 2002.

[32] On Leonardo's contemporary meditations on the nature of « nought », see F. Frosini, *Nulla*, 2003, pp. 209-232 ; F. Fehrenbach, 2013 (forthcoming). On Leonardo's vivification of the anatomical cadaver, see R. A. Bernabeo, 1984, pp. 31-36 (34).



3. *Anatomy of the female torso*, KP 122r, Windsor Castle, Royal Library, pen and brown ink and wash, traces of black and red chalk and yellow wash, on paper covered with an ochre wash and pricked for transfer, 476 x 332 mm, ca. 1508-1510.

of organs. A synthetic drawing like the « Great Lady » in Windsor (KP 122r ; fig. 3) was probably intended to appear without any writing, but in his late focus on the *processes* of organic life, Leonardo needed to include the narrative structure of writing [33]. It is only at this moment of his scientific career that Leonardo explicitly acknowledged the necessity to combine both image and text [34]. This image-text synthesis culminates in his late cardiovascular studies.

In the quest for the basic functions of life after the winter of 1512-13, Leonardo focused on the complicated mechanism of haemodynamics. In a certain sense, these late studies continued

[33] Cf. the remarks by A. Nova, 2005, pp. 136-163. On Leonardo's complex reflections upon « figurare » and « descrivere », see most recently F. Frosini, 2011.

[34] Cf. KP 144v / W 19013v.

the agenda of Leonardo's earlier anatomical research program : « Questa opera si deve principare alla concettione dell'uomo e descrivere il modo della matrice e come il putto l'abita e in che grado lui risega in quella e 'l modo dello vivificarsi e cibarsi » [35]. And they never departed from Leonardo's early assumption : « Dove è vita, lì è calore e dov'è calore vitale, qui v'è movimento d'omori » [36].

In order to understand organic life, Leonardo had to explain the distribution of blood in the body, and therefore the activity of the heart. His thought experiments on the functions of the heart began with dissections of bulls and cows ; one of the main reasons for his move to Rome in 1513 may have been the hope to gain access to human corpses in order to complete his « giegrofia [sic] del core » [37]. One characteristic of the new campaign was a rigorous, sculptural « modeling » of the body. Leonardo recommended, for instance, pouring liquids (wax) into the cavities of the body : « Ma gitta prima la cera in essa porta d'un core di bo [bue] acciò che tu veda la vera figura d'essa porta » [38]. The same method was meant to provide a clearer idea of the hollow ventricles of the brain (fig. 4), the location of spirit-based mental operations :

« Fa 2 sfiatatoi ne' corni de' ventriculi maggiori e metti la cera fonduta collo scizatoio faccendo un buso nel ventriculo della memoria e enpi per tale buso li 3 ventriculi del cervello e poi quando la cera è rassodata disfa il cervello e vedrai la figura delli tre ventriculi di punto. Ma prima metti le canne sottili nelli sfiatatoi acciò che l'aria che è in essi ventriculi possa spirare e dar loco alla cera che entra in nelli ventriculi » [39].

In both cases, the taxidermist proceeds not only like a founder of bronze statues but, in doing so, he mirrors the processes of ageing and cognition. After pouring wax instead of blood into the chambers of the heart, the hardening of the liquid parallels the normal process of sclerosis in the vascular system of the animal as if in time-lapse [40]. In the case of brain « modeling », the preparer mirrors the direction of mental activity based on memory, with the movement of spirits from the back of the brain to its center (note that Leonardo's anatomical drawings themselves are usually based on memory ; only in some late sheets dedicated to bodily fluids there are traces of liquids from the actual dissection) [41].

The other aspect of the new functional rigor was the manufacture of anatomical models, in this case, a glass cast of the aorta (fig. 5) [42]. « Fa questa prova di vetro e movici dentro acqua e panico. / Il moto incidente apre le porte del core e 'l moto refresso le riserra » [43]. This arrangement was the direct offspring of Leonardo's hydrological studies of turbulences which culminated in the years

[35] KP 81v / W 19037v / Anat. Ms B 20v.

[36] Manuscript A 55v (L. da Vinci, 1987-1992).

[37] KP 165v / W 19078v / Quad. II 8v. On the availability of corpses in Rome, see A. Carlino, 1999b, pp. 69-119.

[38] KP 171r / W 19082r / Quad. II 12r.

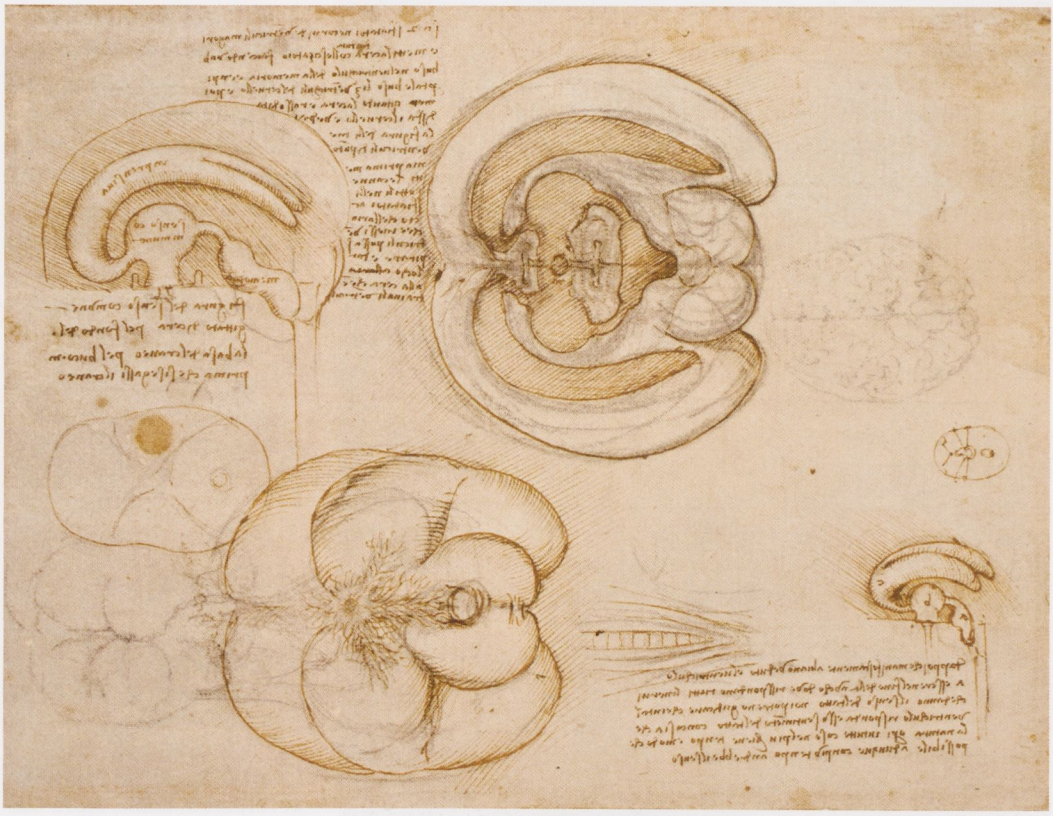
[39] KP 104r / W 19127r / Quad. V 7r.

[40] On Leonardo's vascular pathology, see K. D. Keele, 1952, pp. 117-121.

[41] On the regular direction of perception and cognition from the front part of the brain to its back, cf. *Libro di pittura* ch. 15 (L. da Vinci, 1995). For the early modern physiology of brain activity, see D. Summers, 1987. For visual representations, cf. E. Clarke / K. Dewhurst, 1996.

[42] KP 171r / W 19082r / Quad. II 12r.

[43] KP 115v / W 19116v / Quad. IV 11v.



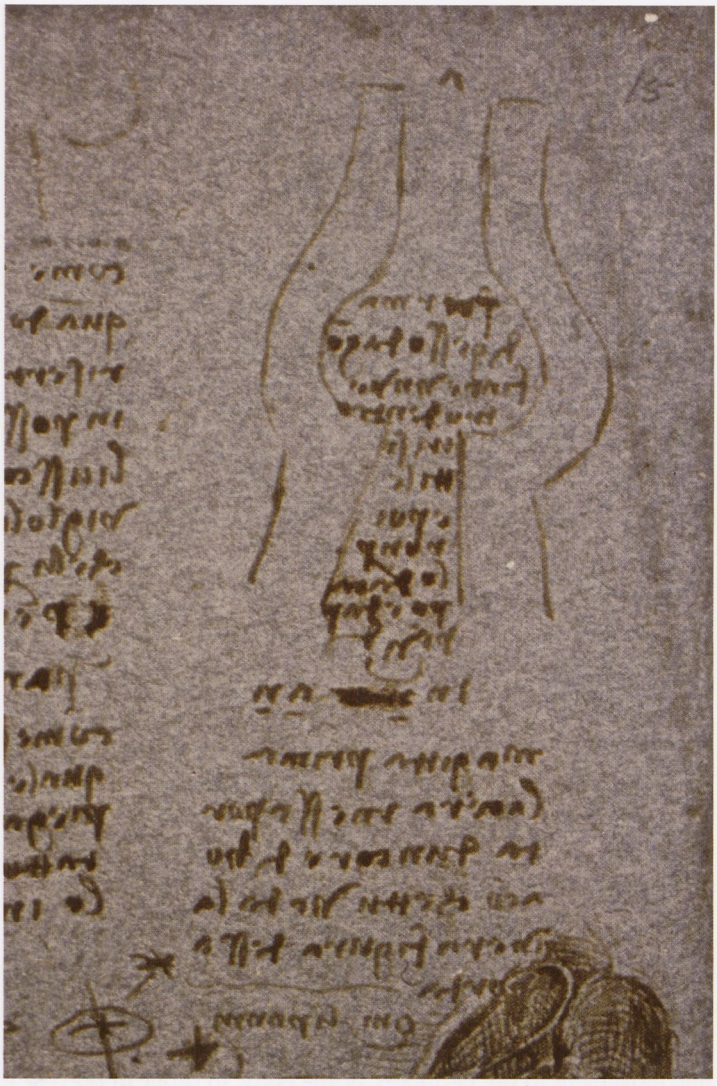
4. *Anatomy of the brain*, KP 104r, Windsor Castle, Royal Library, pen and brown ink (two shades) and black chalk, 200 x 262 mm, ca. 1506-1508.

around 1508 (fig. 6). There, he recommended marking the water by color or grains « perché mediante il moto d'essi grani potrai speditamente cognoscere il moto dell'acqua, che con seco gli porta e di questa tale sperienza potrai investigare molti belli moti, che accaggiano dell'uno elemento penetrato nell'altro » [44].

The planned glass model of the aorta points directly to another characteristic of Leonardo's late functional anatomy, the methodological reduction of variables, reflecting a mechanistic approach to vital functions, following his anatomical agenda of KP 143r : « Fa che 'l libro delli elementi machinali colla sua pratica vada inanzi alla dimostratione del moto e forza dell'uomo e altri animali e mediante quelli tu potrai provare ogni tua propositione ». In contrast to tradition, the arteries, for instance, are simple vessels without Galen's hypothesis of a proper dilation ; they are passive transmitters of the heart's pulse [45]. Furthermore, Leonardo does not thoroughly distinguish between the three traditional « liquid » bearers of life : *calor*

[44] Manuscript F 34r (L. da Vinci, 1987-1992). On Leonardo's hydrodynamics, cf. F. Fehrenbach, 1997, pp. 193-256.

[45] Cf. K. D. Keele, 1952, p. 93 ; on the *vis pulsifica, attrahens* etc. in later authors (Jean Fernel, for instance), see T. Fuchs, 1992, p. 36f. ; J. J. Bylebyl, 1985.

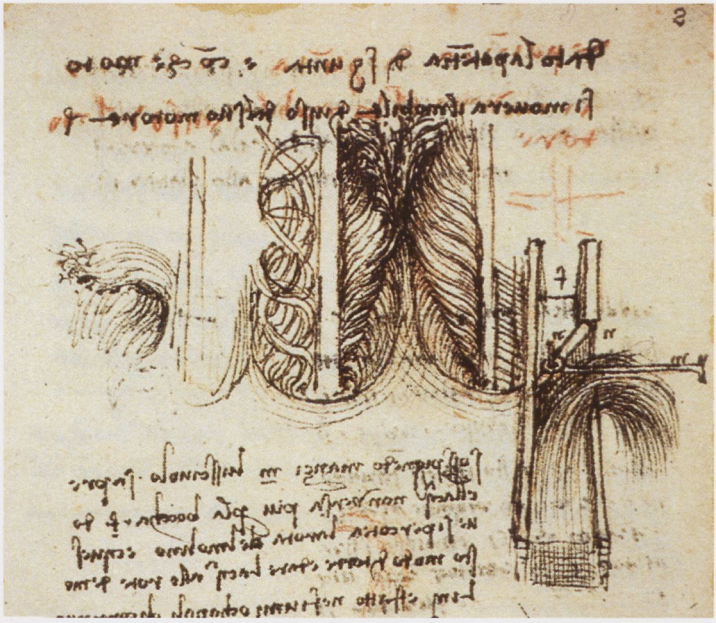


5. *Glass model of the aorta*, KP 171r, Windsor Castle, Royal Library, pen and brown ink, on blue paper, 283 x 204 mm, ca. 1513 (detail).

innatus, *spiritus vitalis*, and blood ; he is mainly interested in the distribution of warm blood [46]. Quite significantly, air from the lungs, the main ingredient of Galen's vital spirits, is categorically denied from entering the heart's vessels [47]. Traditionally, vital heat was the *deus ex machina* for the composition of heterogeneous materials (through *pepsis*, or concoction), but for Leonardo, who never showed a keen interest in chemistry, the main purpose for the heating of blood was its counter-natural movement against gravity – from the heart to the

[46] Cf. KP 115r / W 19117r (« li spiriti vitali [...] sempre si mantengano nel caldo e umido »). For a concise summary of traditional and contemporary (e.g., Gabriele Zerbi) views on the production and « rarefaction » of blood in the body, see A. Cunningham, 1997, pp. 49-51, p. 64. On Leonardo's concept of *spirito*, see F. Frosini, 1997, pp. 35-59. On the *calidum innatum*, cf. E. Mendelsohn, 1964 ; A. Pichot, 1993, pp. 87-109 ; G. Freudenthal, 1995 ; for the Renaissance : M. Mulsow, 1998 (esp. pp. 201-19) ; S. Perfetti, 2000, pp. 95-96.

[47] Cf. K. D. Keele, 1952, pp. 66-67.

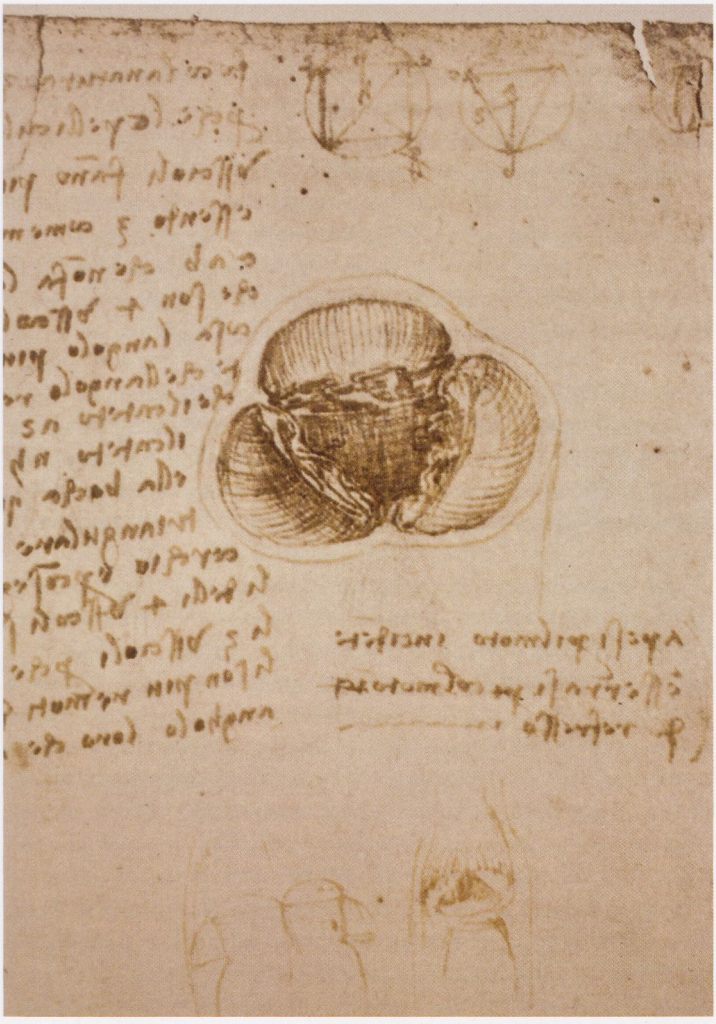


6. *Studies of flow*, Manuscript F 8r, pen and brown ink, ca. 1508.

upper parts of the body, and, from the lower parts to the intestines via the blood's reflux, as part of cyclical tissue metabolism [48].

In this context, it is significant that Leonardo tried to reduce the muscular agents in the heart to a minimum. The main purpose of his glass model of the aorta was precisely to demonstrate the plausibility of a self-regulated hydrodynamic mechanism. In the end, he even eliminated the traditional notion (since Hippocrates) [49] of the heart as an oven, endowed with *calor innatus*, in favor of a mechanistic model of heating based on hydrodynamics. Leonardo was convinced that, as an effect of cardiac systole, only a small portion of blood escaped the heart's ventricles and continued its slow, rhythmic movement to the periphery of the body. In order to prevent a larger quantity of blood from leaving the left chamber of the heart, its valves had to close quickly after contraction. Leonardo eliminated a second muscular agent, instead postulating a « neat little piece of natural engineering » [50] (fig. 7). Its function is concisely described by Martin Kemp : « This valve, constructed from three semilunar cusps, prevents the blood expelled into the artery from re-entering the heart. [...] On the contraction of the heart, blood forced its way between the center of the flexible cusps from beneath. The subsequent reflux of the blood in the vessel's neck filled the cusps, reclosing the aperture during the expansion of the ventricle » [51]. Therefore, the

[48] Cf. K. D. Keele, 1952, pp. 94-95, pp. 101-104.
[49] Cf. A. Pichot, 1993, p. 18.
[50] M. Kemp, 1981, p. 294.
[51] M. Kemp, 1981, p. 294.



7. *Study of the tricuspid valve*, KP 115v, Windsor Castle, Royal Library, pen and brown ink (two shades) over traces of black chalk, 307 x 438 mm, ca. 1508-1510 (detail).

rhythmic closing of the valve depends entirely on « the reaction of the surging blood to the flask-like neck of the pulmonary artery » [52].

IV

The turbulences of water became an obsession for Leonardo during the mid-1490s, and it was precisely this physics of *frusso e refrusso* which dominated Leonardo's late anatomies. Already around 1492, Leonardo wrote :

[52] M. Kemp, 1981, p. 301.

« Universalmente tutte le cose desiderano mantenersi in sua natura, onde il corso dell'acqua che si move cerca mantenere la potenzia della sua cagione, e se trova contrastante opposizione, finisce la lunghezza del cominciato corso per movimenti circulari e retorti. L'acqua che per istretta bocca versa declinando con furia ne' tardi corsi de' gran pelaghi, perché nella maggior quantità è maggiore potenzia e la maggiore potenzia fa resistenzia alla minore, in questo caso l'acqua sopra venente al pelago e percotendo la sua tarda acqua, quella, sendo sostenuta dall'altra, non po dare loco colla coveniente prestezza, e quella sopra venente non volendo tardare il suo corso, anzi fatta la sua percussione si volta indietro seguitando il primo movimento con circulari retrosi [...] » [53].

Leonardo never found an answer to the problem of the *motor* of the heart's rhythmic contractions – and therefore to the question of the soul's location in the body. However, it is hardly an exaggeration to assume that Leonardo had a mechanistic solution in mind when he tried to explain the motor of the « machine of man ».

His ingenious explanation for the heating of blood in the heart (the condition for its subsequent movement and vitalization of the body) points strongly in this direction. If water desires to rest with the maritime element [54], if every quantum of fluid, following Aristotle, wants to return to its proper sphere, the sphere of the oceans, then blood in the human body has a constant desire to reunite with the sea. As long as we live, our blood longs for the ocean. Only in the embryo does blood float weightlessly in the « chiarissima acqua » of the mother's womb [55], an ocean *en miniature*, as it were. How can our bodies overcome the natural « desire » of blood and set it, instead, into upward motion ? By elevating it through the element of heat, and by rarefaction. Exactly this is the purpose of cardiac systole and diastole :

« La revolutione del sangue nell'antiporto del core basa dell'arteria aorto serve a due effetti de' quali primo è che essa revolutione multiplicata per più aspetti fa in se gran confregatione la qual riscalda e assottiglia il sangue e aumenta e vivifica li spiriti vitali li quali sempre si mantengano nel caldo e umido. Il secondo effetto d'essa revolutione di sangue è di riserrare l'aperte porte del core col suo primo moto refresso con perfetta serratura » [56].
« e allora essendo interamente serrate esse tre porte allora le pariete si serrano con tale potentia intorno al rimanente del fugito sangue che li è forza che gran parte di quello si fuga d'esso ventriculo e penetri per li meati del pariete di mezzo e penetri nel sinistro ventriculo il quale assottigliato nella penetratione delli stretti meati si converte in ispiriti vitali lasciando ogni grossezza in esso destro ventriculo la qual grossezza [...] » [57].

[53] Manuscript A 60 r (L. da Vinci, 1987-1992).
[54] Cf. Manuscript C 26 v (L. da Vinci, 1987-1992).
[55] KP 200r / W 19128r / Quad. V 26r.
[56] KP 115r / W 19116r / Quad. IV 11r. – For a classical passage on the relationship of heart, warmth, spirit, blood and organic life, cf. Cicero, *De natura deorum*, II, 23-24.
[57] KP 155v / W 19062v / Quad. I 3v.

- a breathless, and, quite significantly, abruptly interrupted, narrative *discorso*. It could be a good paradigm for the difficulties of visualization Leonardo encountered in his later anatomical research, with its focus on the dynamics of fluids.

It was because of his conviction that « thick » blood (produced in the relatively cold liver) had to be « subtilized » and therefore heated that Leonardo never abandoned Galen's theory of minute pores in the septum separating the two chambers of the heart [58]. Through these, albeit (according to Leonardo) « invisible », pores, rarefied blood is squeezed into the adjacent chamber, in preparation for its slow travel through the animal body. Although Leonardo must have had some doubt about his mechanistic model (« Intendi se la revolution del latte quando si fa il burro si riscalda e con tal mezo potrai provare la valitudine delli orechi del core che ricevano e cacciano il sangue delle loro cavernosità e altri meati ; esser sol fatti per riscaldare e assottigliare il sangue [...] », he states on KP 116v), he was apparently convinced, in the end, that the internal turbulences in the heart provided the key to the production of vital heat :

« e la revolutione che fa il sangue in se medesimo raggirandosi con diverse revertigini e la confregatione che esso fa per le parieti e percussioni in esse cellule son causa di riscaldare esso sangue e farlo di grosso e viscioso sottile e penetrativo e atto a scorrere dal destro al sinistro ventriculo inferiore » [59].
« e così il caldo da vita a tutte le cose come si vede il caldo della gallina o delle tacine dare vita e nascimento alli pollicini e 'l sole quando ritorna fa fiorire e animare tutti li frutti » [60].

This is of crucial importance. If heat in the organism is innate, a property of the soul in an Aristotelian perspective (even if the soul descends from the sun, as Leonardo praises in his *Lalde del Sole* from ca. 1508) [61], there would be no need to investigate the mechanical production of heat in an otherwise cold body. If, instead, there is no *caldo infuso* in plants for instance, because their internal heat depends entirely on the sun (as Leonardo states in his late Manuscript G 32v), or if the warmth of the animal body is merely a result of haemodynamic friction, the soul would become obsolete for the production of heat.

One consequence of the marginalization of the soul would be the absence of a regulating, providential agent (a parallel to Galen's project, but without his countless local *vires* and *facultates*) [62]. Life would be a complicated mechanism with a strong need for self-regulation in order to avoid excess. The processes of life, the effects of organic functions, would need to be kept in balance continuously, throughout the lifetime of the organism, but ultimately in vain.

[58] On this subject, see R. Zwijnenberg, 2002, pp. 57-79.

[59] KP 156v / W 19063v / Quad. I 4v.

[60] KP 116r / W 19119r / Quad. IV 13r.

[61] Manuscript F 5r 4v (L. da Vinci, 1987-1992). Cf. C. Vasoli, 1973.

[62] Cf. A. Pichot, 1993, pp. 151, pp. 219-220.

As a result of his mechanistic approach, Leonardo reconceptualized the very notion of organic life. No longer was the entire organism conceived as living matter vivified by the soul (or innate heat) until death, but life itself and the very functions of life are described as a fragile, delicately balanced system of antagonistic forces, a permanent oscillation between life and death.

« Il corpo di qualunche cosa la qual si nutrica al continuo more e al continuo rinasce perché entrare non può nutrimento sennon in quelli lochi dove il passato nutrimento è spirato, e se li è spirato elli più non nutrisce e [da] vita. E se non li rende nutrimento equale al nutrimento partito, allora la vita manca di sua valitudine e se tu li levi esso nutrimento, la vita in tutto resta distrutta. Ma se tu ne' rendi tanto quanto se ne distrugge alla giornata, allora tanto rinasce di vita quanto se consuma, a similitudine del lume fatto dalla candela col nutrimento datoli dall'omore d'essa candela il quale lume ancora lui al continuo con velocissimo soccorso restaura di sotto quanto di sopra se ne consuma morendo e di splendida luce si converte morendo in tenebroso fumo la qual morte è continua [...]. E in istante tutto il lume è morto e tutto rigenerato insieme col moto del nutrimento suo [...]. E il medesimo accade nelli corpi delli animali mediante il battimento del core che genera l'onda del sangue per tutte le vene [...] Dico che la carne delli animali è rifatta dal sangue che al continuo si genera del lor nutrimento. E che essa carne si disfa e ritorna per le arterie miseraice e si rende alle intestine dove si putrefa di putrida e fetente morte come ci mostra nelle loro espulsioni e caligine come fa il fumo e foco dato per comperatione » [63].

Both processes, life and death, growth and decay, overlap continuously (« il sangue [...] al continuo more e rinasce » [64]) ; a « translation » of the famous stoic notion into biology [65]. Even more disturbing, the functions of life themselves are potentially destructive :

« e così con tale frusso e refrusso fatto con gran celerità il sangue si riscalda e si assottiglia e fassi di tanta caldezza che se non fussi 'l soccorso dal matece detto polmone, il quale tira l'aria fresca nel suo dilatarsi e la prieme e tocca le veste delle ramificationi delle vene e le rinfresca esso sangue verrebbe in tanta caldezza che soffoccherebbe il core e lo priverebbe di vita » [66].
« e questo tal caldo assottiglia il sangue e lo vapora e ne converte in aria e ne convertirebbe in fuoco elementare se il polmone colla freschezza del suo vento non soccorressi a tale eccesso » [67].

These are potentially life-threatening excesses within the system. Already the basic purpose for the movement of blood – nour-

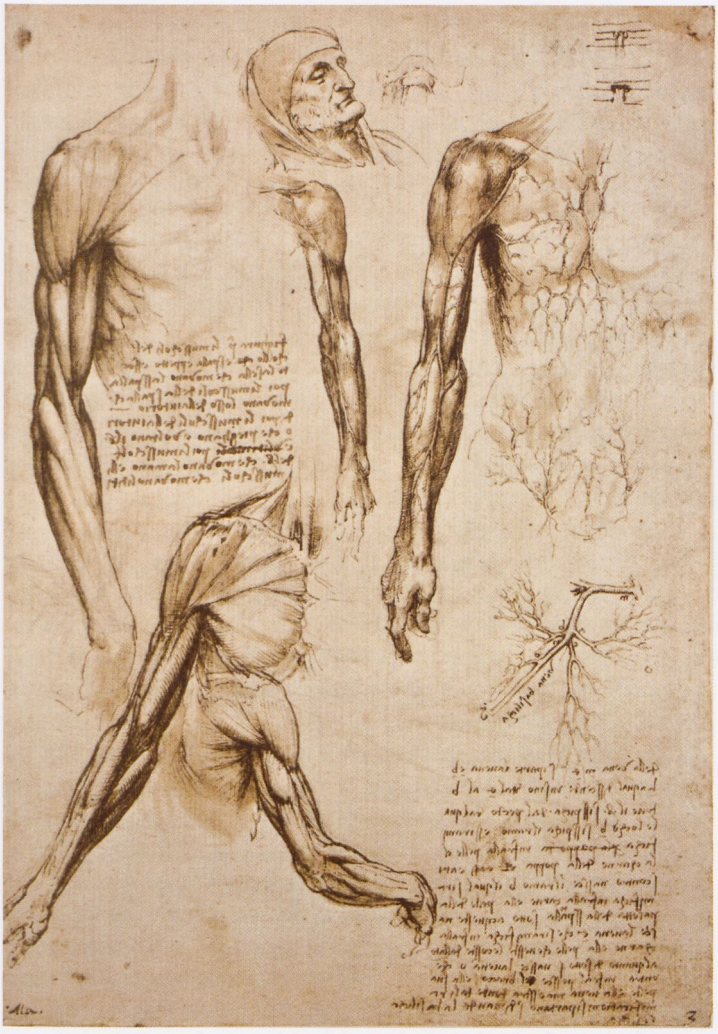
[63] KP 50r / W 19045r / Anat. Ms B 28r.

[64] KP 69v / W 19027v / Anat. Ms B 10v. Cf. KP 155v / W 19062v / Quad. I 3v.

[65] Cf. Seneca, *Ad Lucilium epistolae morales* XXIV, 20 : « Cotidie morimur ; cotidie enim demitur aliqua pars vitae, et tunc quoque, cum crescimus, vita decrescit. Infantiam amisimus, deinde pueritiam, deinde adulescentiam. Usque ad hesternum, quidquid transiit temporis, periit ; hunc ipsum, quem agimus, diem cum morte dividimus. Quemadmodum clepsydram non extremum stillicidium exhaurit, sed quidquid ante defluxit, sic ultima hora, qua esse desinimus, non sola mortem facit, sed sola consummat : tunc ad illam pervenimus, sed diu venimus. ». On the later tradition of the topos (Petrarca, *De remediis utriusque fortunae*, II, 117 ; F. Frezzi, *Il quadriregio*), see A. Tenenti, 1989, pp. 42, 46. Giovanni Pico della Mirandola's metaphysical treatise *De ente et uno* (V) provides another striking parallel for Leonardo's dictum : « Vita [...] semper fluens, semper admixta morti, magis denique mors vocanda quam vita ». (G. Pico della Mirandola, 1993, pp. 74-135).

[66] KP 155r / W 19062r / Quad. I 3r.

[67] KP 164r / W 19081r / Quad. II 11r.–Cf. KP 116r / W 19118-19r / Quad. IV 14v-13r. The necessity to cool down the heart through breathing was already emphasized by Aristotle, *De partibus animalium*, III, 6, 668b-669a ; *De anima* II, 8, 420b.



8. *Studies of veins and muscles*, KP 141r, Windsor Castle, Royal Library, pen and brown ink, with wash modeling over traces of black chalk, 289 x 199 mm, ca. 1509-10.

ishment and heat – leads to the normal process of ageing and, eventually, death. The walls of blood vessels thicken continuously *because* of the sediments of nourishment carried through the veins (cf. fig. 8). Vivification thus leads to the narrowing of blood vessels, and in the end to a lack of nourishment and vital heat [68]. Over time, « thick », saturated blood also prohibits the complete closing of the valve of the right ventricle ; as a consequence, the process of rarefaction is impeded, and « vital spirits » are lacking, « e per questo alli vecchi mancano tutti gli spiriti e spesso moiano parlando » [69]. The terminal exhaustion of vital spirits during speech provides a

[68] Cf. KP 69v / W 19027v / Anat. Ms B 10v.

[69] KP 155v / W 19062v / Quad. I 3v.

nice parallel to Leonardo's earlier paragone argument about the continuous « death » of poetry, or writing [70].

VI

Life is thus conceived as an oscillation, a dialectic process between antagonists, a fragile equilibrium, only a postponement of the final triumph of cooling-down [71] and sclerosis. The motor of enlivenment, the heart, works rhythmically. The heating, rarefying and distributing action of the pulse is a discontinuous process, interrupted by pauses, moments of stasis. « Come il frusso e refrusso delli 2 ventriculi superiori colli 2 inferiori son causa di mandare il nutrimento del sangue per le vene a scosse e interrotto » [72]. Between the waves of pulsation, blood comes to a standstill, and « l'impeto che rimane nel sangue » is consumed [73].

Leonardo's haemodynamics rely heavily on the notion of impetus. At the aortic valve, the flux of blood creates « molte altre revolutioni contrarie l'una l'altra successivamente l'una sopra l'altra sempre ritardando la velocità insin che l'inpeto se stessi consuma » [74]. « Il moto del liquido fatto per qualunche verso tanto procede nella sua principale revolutione quanto vive in lui l'impeto datoli dal suo primo motore » [75].

The concept of impetus as a force transmitted from the moving body to a passive object originated in late antique natural philosophy (Johannes Philoponus, 6th century AD) and was reformulated, at the end of the 13th century, in the context of commentaries to Petrus Lombardus' *Sentences* [76]. Two Franciscans, Petrus Johannes Olivi, the head of the Spirituals, and Franciscus de Marchia, the rector of the order's *studium* in Paris, were the first to revive the idea. In contrast to Aristotelian natural philosophy, both Franciscans negated any decisive role of the medium surrounding an object moved by a « counter-natural » force. Instead, they shaped the idea of a force actively transmitted by the mover onto the passive mobile ; a force that pushed the mobile further even after contact with its mover was lost. This force was called *vis impressa* by Olivi and *vis derelicta*, the force « left back » in the moved object, by de Marchia. Successive debates focused on the question of whether this force – now called *impetus* – diminished by itself or whether it would be perpetual without the counter-forces of gravity and friction. Impetus theory was powerfully elaborated by Nicolas Oresme, Jean Buridan and Albert of Saxony ; in Leonardo's time, it was the common fundament of physics [77].

Following this tradition, Leonardo described impetus as something added to each body in a state of non-natural movement ; the

[70] Cf. Leonardo da Vinci, *Libro di Pittura* ch. 15 on the « death » of the poet's imagination : « [...] ma la imaginatione non esce fuori d'esso senso comune, se non in quanto essa va alla memoria, et li si ferma et li muore [...] ». Cf. Leonardo da Vinci, *Libro di pittura*, ch. 9 : « Tutte le scientie, che finiscono in parole, hanno sì presto morte, come vita [...] ».

[71] On this topos since Hippocrates, cf. P. Mudry, 2006, p. 78.

[72] KP 159r / W 19066r / Quad. I 7r.

[73] KP 115v / W 19116v / Quad. IV 11v.

[74] KP 115v / W 19117r / Quad. IV 12r.

[75] KP 50r / W 19045r / Anat. Ms B 28r. – The passage is immediately followed by Leonardo's reflections upon the continuous death of the living organism.

[76] On impetus physics, see A. Maier, 1955 ; M. Wolff, 1978 ; N. Schneider, 1991.

[77] On Leonardo and impetus physics, cf. P. Duhem, 1906-1913, vol. 3, pp. 3-112 ; G. Castelfranco, 1966, pp. 18-24 ; F. Fehrenbach, 1997, pp. 239-245 ; F. Frosini, *Lessico*, 2003.

paradigmatic example being a stone thrown by an external mover. As a projectile, the stone follows a trajectory different from its natural inclination perpendicularly downwards, virtually towards the earth's center point [78]. However, the force infused into a stone which moves it « non-naturally » is not « corporeal » ; it neither adds weight to nor changes the form of the moving body. For Leonardo, impetus remains a transitional, continuously self-transcending entity that « vivifies » its objects during their movement. In his most important impetus-related texts, however, he describes it as a dynamic entity desiring its own death. Impetus (or *forza*, a related category) consumes itself, aided by the resistance of the medium (air, water, etc.) and « natural » gravity.

« Che cosa è forza. Forza dico essere una potenzia spirituale incorporea e invisibile, la quale con breve vita si causa in quelli corpi che per accidentale violenza stanno fori di lor naturale essere e riposo. Spirituale dissi, perché in essa forza è vita attiva ; incorporea e invisibile dico, perché il corpo, dove nascie, non crescie in peso ne in forma ; di poca vita perché sempre desidera vinciere la sua cagion, e, quella vinta, sé occide » [79].

Or, in a beautiful later remark : « [...] esso impeto fugatore del corpo dov'è creato si consuma e more insieme col moto d'esso corpo » [80]. The desire of the impetus to rest characterizes it as a liminal quality, the force that connects two states of rest through movement. To extinguish themselves, physical forces have to squander their energies through movement, leading to the object's rest, which is conceived as a form of « death » of force, or stasis. There is a vivifying, and, *at the same time*, suicidal entity at work in every object moving against its proper « nature » ; life and death overlap even in the inanimate realm of physical objects that move « against their nature ».

The consequences of impetus physics for Leonardo's late anatomies are striking. If the distribution of heat and nourishment in the body relies on « la revolutione [...] fatta dall'impeto infuso nel sangue della basa dell'arteria [the Aorta] » [81], then the force transmitted by a pulse « dies » continuously of exhaustion in the frictions created by turbulences. In other words, the living body produces permanently discontinuous counter-natural movements of blood in order to vivify itself (through nourishment and heat), but the body also continuously « dies », not only because of the consumption and decay of old blood and flesh, but also, and more fundamentally, because of the « suicidal » desire of impetus. This longing for death at the very center of enlivenment – the cardiac process – complements the dialectics of life

[78] For the Aristotelian tradition, cf. G. A. Seeck, 1975, pp. 384-90.

[79] Manuscript B 63r (L. da Vinci, 1987-1992). F. Frosini, *Lessico*, 2003 underlines the differences between the two notions, *impeto* and *forza*, but with one rare exception Leonardo ascribes to both forms of energy a « short life » and a desire to « die ». I believe this echoes the stoic idea that violent movements, for instance whirlwinds, long for their own exhaustion ; cf. Seneca, *Naturales Quaestiones*, VII, 9, 3.

[80] Codex Arundel 2r (London, British Museum ; ca. 1508/9 ; L. da Vinci, 1998).

[81] KP 115v / W 19117v / Quad. IV 12r. – Of course, this does not include the amount of blood produced (and directly distributed to the organism) by the liver ; cf. K. D. Keele, 1952, pp. 115-116.

and death, the entanglement of both states in the delicate equilibrium of the body.

VII

I would like to conclude with a few remarks on the *form* of Leonardo's visual representation, still a largely neglected field in studies on his anatomy. Clearly, the focus on haemodynamics is a direct offspring of Leonardo's hydrology. The representation of flux in the heart and blood vessels would have been impossible without the graphic apparatus developed by Leonardo around 1508, especially his elaborate rendering of turbulences. The amount of « conventionality » in these sketches is still a matter of debate [82], but the reference to the « diagrammatic » character of Leonardo's representations of hydrodynamics does not explain their astonishing concreteness. For Leonardo, the lines in his countless studies of eddies mark both material flux, represented by the abstraction of line (as in the abstract « lines of force » of muscles) and the separating layers between individual parts of a fluid in motion. In both cases, lines do not represent static material bodies, but contours of liquid quantities in motion, or separating layers of fluid. Still, those lines have a strong and direct visual impact. They demonstrate *ad oculos* the dynamics of agents deflected by other media. In their rough and swift execution, Leonardo's late hydrologic and haemodynamic sketches betray a lack of interest in formal beauty, geometrical order, and closed composition. They are stages in a larger continuity of flux. Rather than focusing on the composition of bodies, organs, and limbs, these functional drawings depict the structure of the organism as a transitional, instable, and fugitive constellation of antagonistic elements. In their « abstract », powerful lines and sometimes in their breathtaking spatial dynamics, Leonardo's sketches set the eyes and mind of the viewer in motion. The viewer dramatically encounters visual equivalents for the dynamics of her or his own temporal organic existence.

In his late representations of haemodynamics, Leonardo is the first anatomist who goes beyond the juxtaposition of the *visual* morphology of the body with the *description* of physiological processes [83]. Instead, he tried to visualize fluids in motion within the vessels of blood and the heart. Thus Leonardo developed his own version of the *humoral* medicine that had dominated the history of medicine since the hippocratic writings – a powerful paradigm that impeded visual representation within traditional codes [84]. For Leonardo, the dynamics of the living organism was based on the

[82] Cf. the classical essay by E. H. Gombrich, 1969.

[83] The dominant focus on morphology in the 16th century was criticized by Michelangelo's physician Realdo Colombo in 1559. It is revealing that he referred to vivisection in his passages on the movement of the heart and blood (cf. R. French, 1999, pp. 207-209). For the general context, see J. Sawday, 1995 ; A. Cunningham, 1997.

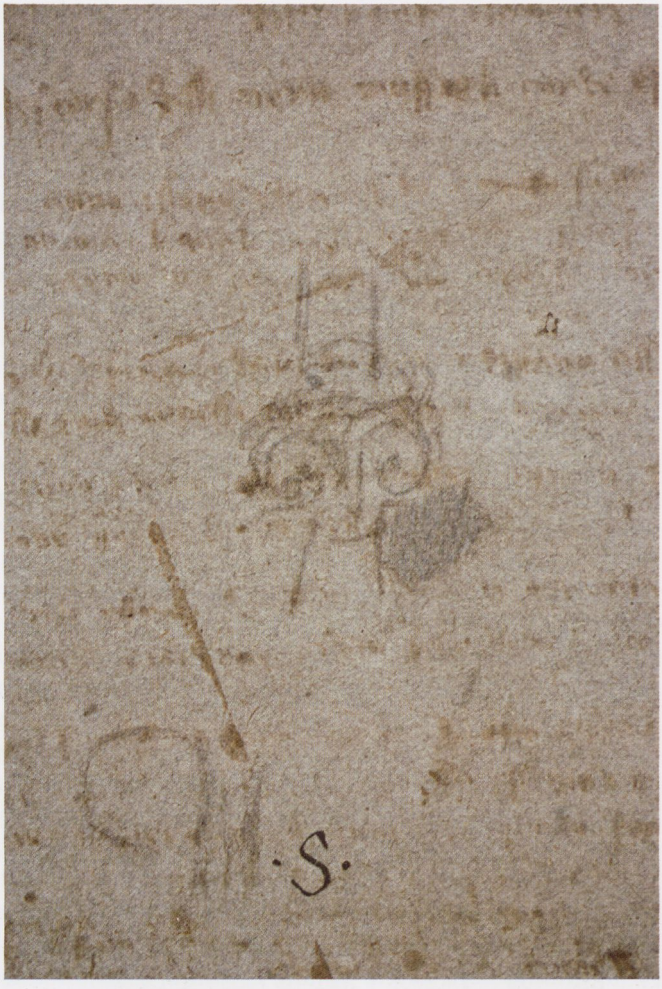
[84] Cf. A. Carlino, 1999b, pp. 122-123 ; H. Bober, 1948.

movement of liquids that he could neither directly observe nor adequately describe with words. At the same time, his synthetic drawings not only visualize the invisible, but these representations of the *corpo trasparente* confront the medium with its own limits. What keeps the body alive are fluids in motion, hidden underneath the skin, embedded in the flesh, and flowing behind the vascular walls. Skin, flesh, and vessels need to become transparent in order to show the liquid matter that enables life. In its complicated movements of and within the continuous substance of blood, a dynamic impulse, the impetus, consumes itself rhythmically.

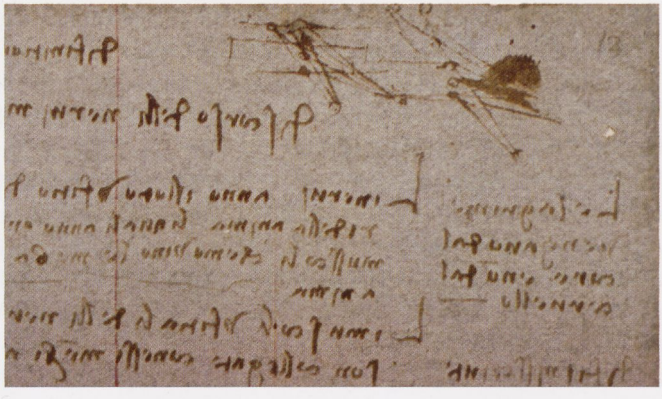
The eye of the beholder is then of crucial importance : it reads the static representation as the movement of the drawing hand. Leonardo must have realized that, in the case of haemodynamics, a material and biological continuity links the representation to its subject. The hand of the draftsman is vivified by the same turbulences of blood that the hand represents in pen and ink on the sheet of paper. When it touches the paper, the ink is still fluid like the matter it depicts. As if in time-lapse, the ink's rapid drying provides a material analogy for the process of ageing of the organism, or more precisely, for the withering and sclerosis of the veins. As a static remainder of the movement of the drawing hand, the sketches are waiting for the moment in which they are again « liquefied » by the eye, itself a living part of an organism depending on the nourishment and warming provided by the movement of blood. Moreover, as a precondition for visual perception the *humores* which constitute the different layers and « spheres » of the eye are the most perfectly transparent liquids of the human body. In his late cardiovascular and haemodynamic studies, Leonardo presents the hidden dynamics of life to an organ of complete transparency. The moving liquids of the human body are visualized for the vitreous eye which, in turn, is « att[o] a dare transito alli simulacra » [85], the images emitted by bodies across the transparent medium of air, or water, in order to move the subtle fluids of spirit within the brain. With the undesignated juxtaposition, on KP 175 (W 19088 / Quad. II 18), of the turbulences of blood (recto ; fig. 9) and two dioptric diagrams (verso ; fig. 10), Leonardo hints at this nexus of haemodynamics and optics.

Leonardo aimed at strategies to communicate and visually enhance the movement and the dynamics of the blood. Three small sketches on the lower left margin of KP 115r (W 19116-7r / Quad. IV 12-11r ; fig. 11), for instance, represent the closing mechanism of the tricuspid valve at the right chamber of the heart. In their sequence, they depict the dynamics of the process. The first sketch demonstrates diagrammatically the geometry of the

[85] Manuscript F 34r (L. da Vinci, 1987-1992).



9. *Study of the flow of blood,* KP 175r, Windsor Castle, Royal Library, Black chalk on blue paper, 280 x 204 mm, ca. 1513 (detail).



10. *Diagram of dioptrics,* KP 175v, Windsor Castle, Royal Library, pen and brown ink, ca. 1513 (detail).

organ at rest from above (like a ground plan, with letter marks). The second, instead, represents the triple vortex that rhythmically closes the valve from one side, like an elevation. Only the third sketch unleashes the spatial expansion and the power of the event with its central vortex breaking forth towards the viewer like a cataract.

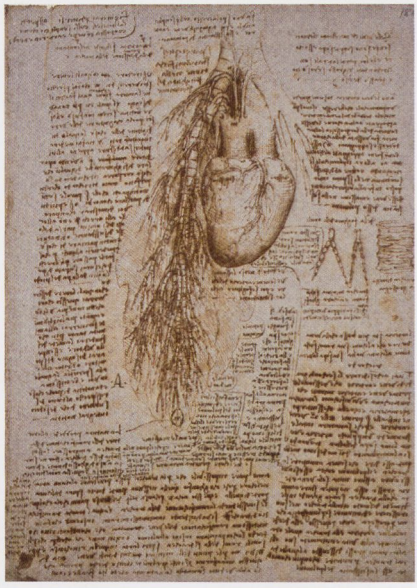
KP 116r (W 19118-19r / Quad. IV 14v-13r ; fig. 12) reverses the dynamics of space. The viewer is no longer exposed to the impact of blood flow ; instead, the eye is drawn into the depth of the « empty » chambers of the heart as if into a dark abyss. The large hollow space presents itself diagonally on the sheet and powerfully pushes aside the subsequent texts. The gaze of the viewer substitutes, as it were, the whirling blood that normally fills the inner space of the heart completely [86].

Leonardo's late cardiovascular studies on blue paper (KP 162-183) expand the possibilities of the graphic representation of the movement of blood. Blue is, of course, the color of the liquid elements, water and air, and, here, blue creates the depth on which the pulsating volume of the heart and the autonomous turbulences of blood seem to float. KP 162r (W 19071r / Quad. II 1r ; fig. 13) juxtaposes a voluminous heart which seems to pop out from the center of the sheet with the cascade of increasingly subtle veins that spring forth from the heart assimilating themselves to the linearity and delicacy of writing. It is this contrast of protruding volume and falling lines that emphasizes the pulsation of the heart and the downward stream of invisible blood in the branches of the veins (cf. similarly KP 163 / W 19072v / Quad. II 2v).

The denial of linear elegance in these late drawings has been observed by Leonardo scholars. Their roughness is directly related to the dynamics and power, as well as the inevitability and endangerment, of the movements of life. Sequences like the details of the walls of the valve on KP 165v (W 19078v/ Quad. II 8v ; fig. 14) have a pulsating quality and claim priority over the text added at a later stage. The increase of size and of three-dimensionality in the series of hearts on KP 166v (W 19073-4v / Quad. II 3v-4r ; fig. 15), from right to left, visualize the diastole of the organ as a space-creating, expansive force, as if the organ were able to stand out from the paper surface. And in the series of open and closed valves on KP 169v (W 19079v / Quad. II 9v ; fig. 16), seen from above and from below, the act of viewing itself creates a rhythmic, pulsating movement – analogous to the rhythm that keeps the viewer factually alive while « watching » Leonardo's sketches.

The sequences of some sheets end with the most dynamic aspect, the representation of haemodynamic turbulences ; as in

[86] Cf. the monumental central perspective of the « temple » architecture of the chambers of the heart on KP 170r / W 19080r / Quad. II 10r. Both drawings prefigure the enlargement of blood vessels in G. Fabrici, *De venarum ostiolis*, 1603 ; cf. K. B. Roberts / J. D. W. Tomlinson, 1992, pl. 60.

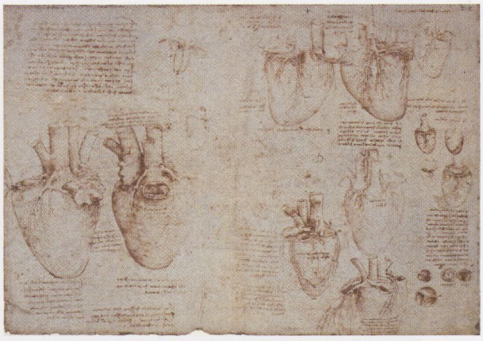


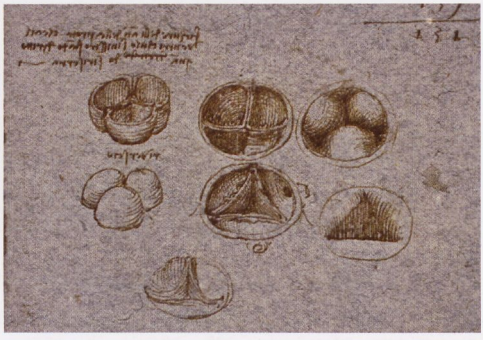
11. *Studies of haemodynamic flow at the tricuspid valve*, KP 115r, Windsor Castle, Royal Library, pen and brown ink, 307 x 438 mm, ca. 1508-1510 (detail).

12. *Studies of the chambers of the heart*, KP 116r, Windsor Castle, Royal Library pen and brown ink, 221 x 312 mm, ca. 1508-1510.

13. *Study of the heart and veins*, KP 162r, Windsor Castle, Royal Library, pen and brown ink, on blue paper, 288 x 203 mm, ca. 1513.

KP 171r (W 19082r ; Quad. II 12r ; fig. 17), leading from static vessels to the self-regulated movement of blood. On this sheet, Leonardo first sketched the glass model of a *porta del core*, an artificial, transparent vessel of blood for the observation of turbulences in liquids. Instead of whirling lines, text fills the flask-like container. This is followed by further text in the center describing the self-regulated, autonomous, and rhythmic closing of the valves. After this, Leonardo analyzes in sectional views the geometry of the organ, ending with the depiction of symmetrical pairs of powerful vortices within the vascular walls. These studies culminate on KP 172v (W 19083r / Quad. II 12r ; fig. 18), Leonardo's most elaborate representation of blood flow in the valves of the heart. On this sheet, Leonardo analytically breaks down the turbulences into bunches of individual strips, before condensing these bands again into compact, roll-like agglomerations. This sheet is remarkable for the





indissoluble intertwining of sketch and text in its making. Even more important, Leonardo depicts the majority of turbulences without vascular walls, and instead represents them as self-stabilizing, autonomous entities floating on the blue paper ground. Only with these drawings Leonardo achieves a visual equivalent for haemodynamic self-organization or self-stabilization. The agents are symmetrical eddies of blood without any supportive and fixed container (fig. 19). Their complicated rhythms are realized in the prolonged gaze of the viewer whose living, pulsating organism, meanwhile, moves gradually and inexorably closer to its own death.

14. *Studies of the valves of the heart*, KP 165v, Windsor Castle, Royal Library, pen and brown ink on blue paper, 284 x 209 mm, ca. 1513.

15. *Studies of the heart*, KP 166v, Windsor Castle, Royal Library, pen and brown ink on blue paper, 288 x 413 mm, ca. 1513.

16. *Studies of the tricuspid valve*, KP 169v, Windsor Castle, Royal Library, pen and brown ink on blue paper, 280 x 206 mm, ca. 1513 (detail).

17. *Studies of haemodynamic flow*, KP 171r, Windsor Castle, Royal Library, pen and brown ink, on blue paper, 283 x 204 mm, ca. 1513.

18. *Studies of haemodynamic flow*, KP 172v, Windsor Castle, Royal Library, pen and brown ink on blue paper, 286 x 205 mm, ca. 1513.

19. *Studies of haemodynamic flow*, KP 172v (detail).