Leonardo Da Vinci e as Primeiras Observações Hemodinâmicas [19]

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RESUMO

Leonardo da Vinci foi um génio cujas realizações e pensamentos nos chegaram até hoje cinco séculos depois, com a frescura da inovação e a curiosidade da descobertas. Esta breve revisão é iniciada por um resumo da vida de Leonardo e pela referência às obras de arte mais relevantes que nos legou, para se concentrar no que terá sido o seu último grande desafio. Em determinado momento o entusiasmo do artista foi cedendo lugar ao do estudo da anatomia humana, não só para aperfeiçoar o traço de desenho mas, mais do que isso, para compreender o funcionamento do que, antes, era para Leonardo somente uma representação morfológica. Entre os seus interesses destaca-se o estudo do coração e dos vasos sanguíneos, que observou cuidadosamente em animais e autópsias humanas, para os reproduzir em desenho de qualidade superior junto com anotações de espantosa perspicácia. A experiência que adquirira ao observar os movimentos da água em condições de corrente e obstáculos, e as conclusões hidrodinâmicas que então obtivera, foram cruciais para a interpretação dos mecanismos do coração e da corrente sanguínea, a que se dedicou persistentemente entre cerca de 1508 e 1513.
Desses estudos, eternizados em desenhos de grande clareza, ressaltam os primeiros registos hemodinâmicos conhecidos, em que Leonardo evidencia as características do fluxo sanguíneo na aorta e grandes vasos e a importância do refluxo e dos redemoínhos pós-valvulares para o encerramento da válvula aórtica. Pela observação persistente e cuidada, e pela dedução, Leonardo antecipou respostas sobre

ABSTRACT

Leonardo da Vinci and the first hemodynamic observations

Leonardo da Vinci was a genius whose accomplishments and ideas come down to us today, five centuries later, with the freshness of innovation and the fascination of discovery. This brief review begins with a summary of Leonardo's life and a description of the most important works of art that he bequeathed us, and then concentrates on his last great challenge. There was a point at which Leonardo's passion for art gave way to the study of human anatomy, not only to improve his drawing but to go beyond what had been simply a representation of form to understand the underlying functioning.. Among his many interests, we focus on his study of the heart and blood vessels, which he observed carefully in animals and human autopsies, and reproduced in drawings of great quality with annotations of astonishing acuteness. The experience that he had acquired from observing the flow of water in currents and around obstacles, and the conclusions that he drew concerning hydrodynamics, were central to his interpretation of the mechanisms of the heart and of blood flow, to which he devoted much of his time between 1508 and 1513.
From these studies, immortalized in drawings of great clarity, come what are acknowledged to be the first hemodynamic records, in which Leonardo demonstrates the characteristics of blood flow in the aorta and great vessels and the importance of blood reflux and the formation of eddies in the sinus in aortic valve closure. Through his assiduous and careful

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pormenores hemodinâmicos que só recentemente, com tecnologia avançada, foram confirmados.

Palavras-Chave
Aorta; Aterosclerose; Coração; Circulação; Hemodinâmica; Vasos; Viscosidade sanguínea

BREVE RESENHA DE UMA VIDA[1]

Leonardo da Vinci (1452-1519), um dos maiores génios da Humanidade, nasceu há pouco mais de meio milénio numa aldeia próxima de Vinci, no ducado de Florença, então governado pelos Medici. Filho ilegítimo de um notário conceituado daquela região e de uma camponesa, na sua folha de registo figura com o nome completo de "Leonardo di ser Piero da Vinci", o que significava Leonardo, filho de (Mes)ser Piero; natural da Vinci.

Leonardo foi criado junto da família materna até atingir cerca de cinco anos de idade, após o que, na sequência do casamento da mãe, foi viver com o pai e parentes próximos que lhe providenciaram sustento e educação(1).

Devido à condição de ilegítimo, e conforme os costumes da época, Leonardo não pôde usufruir de instrução formal e, também, estava-lhe vedado o acesso a um conjunto de profissões respeitáveis. Deste modo, Leonardo aprendeu o essencial com professores particulares e, aos catorze anos de idade, o pai conseguiu a sua admissão como aprendiz de Andrea di Cione (mais conhecido por Andrea del Verrocchio), cujo estúdio era, na época, não só um respeitado centro artístico como também o ponto de encontro da vida intelectual de Florença. Consta que a sua admissão junto de Verrocchio foi particularmente facilitada depois do pai Piero ter mostrado ao seu amigo artista um desenho de Leonardo, perguntando-lhe se o filho teria mérito que justificasse o aprendizado(2).

Com Verrocchio durante cerca de uma década (de 1466 a 1476), Leonardo aprendeu a fazer tudo o que os estúdios-oficina da Renascença produziam, designadamente desenho, pintura, estatuária, decoração com diversos materiais, altares e

[1]Este assunto é analisado pormenorizadamente em outro artigo do autor, in: Boletim SPHM 2007; 22 (2): 6-28

observations, and his subsequent deductions, Leonardo put forward detailed findings on hemodynamic questions that advanced technology has only recently enabled us to confirm.

Key words
Aorta; Atherosclerosis; Circulation; Heart; Hemodynamics; Vessels; Viscosity

BRIEF SUMMARY OF LEONARDO'S LIFE[1]

Leonardo da Vinci (1452-1519), one of the greatest geniuses in history, was born over half a millennium ago in a village near the town of Vinci in the duchy of Florence, then ruled by the Medici family. He was the illegitimate son of a respected local notary and a peasant woman, and his birth certificate shows his full name as "Leonardo di ser Piero da Vinci", meaning Leonardo, son of (Mes)ser Piero of Vinci.

Leonardo was brought up in his mother's family until the age of five, when, following his mother's marriage, he went to live with his father's family, who raised and educated him(1).

The customs of the time meant that Leonardo, as an illegitimate child, could not be given a formal education, and was also barred from various respectable professions. He was therefore taught the basics by private tutors until, when he was fourteen, his father succeeded in arranging his apprenticeship to Andrea di Cione (better known as Andrea del Verrocchio), whose studio was at that time not only a well-known artistic center but also a meeting-point for the intellectuals of Florence. It is known that his acceptance by Verrocchio was helped by his father showing his artist friend one of Leonardo's drawings and asking if his son had sufficient talent to merit an apprenticeship(2).

Leonardo stayed with Verrocchio for ten years, from 1466 to 1476, and learned all the techniques of a Renaissance studio-workshop: drawing, painting, sculpture, decoration using different materials, altarpieces and votive objects. His studies naturally included observing and drawing the human body, particularly the appearance and arrangement of the body's visible structures in

[1] This subject is dealt with in more detail in another article by the same author (Boletim SPHM 2007; 22(2): 6-28).

objectos votivos. A aprendizagem incluía naturalmente a observação e desenho do corpo humano, em particular, o aspecto e disposição topográfica das estruturas visíveis em vários posicionamento, tais como músculos, articulações e relevo esquelético. No estúdio de Verrocchio, e decerto também nos de outros mestres artistas da época, era comum haver modelos em gesso de partes do corpo humano, bem como estátuas, por onde os aprendizes aprendiam e executavam os seus primeiros desenhos[3].

A qualidade dos desenhos sobre modelos vivos e paisagens e o talento multifacetado de Leonardo rapidamente impressionaram o seu mestre, pelo que em 1472, somente com vinte anos de idade, foi por ele proposto e admitido como membro da Corporação de São Lucas, constituída pelos artistas florentinos, que reunia juntamente com os físicos e boticários no Ospedale de Santa Maria Nuova. Devido aquele novo estatuto Leonardo obteve autorização para observar (e talvez dissecar pela primeira vez) cadáveres humanos naquele hospital, de modo a aperfeiçoar os conhecimentos sobre aspectos anatómicos importantes para desenho e representação pictórica[4,5].

A busca da perfeição que desde cedo caracterizou os trabalhos de Leonardo, junto com a tendência para se dispersar simultaneamente por vários assuntos foram, por um lado, o traço da genialidade e, numa perspectiva mais negativa, a causa provável por não concluir muitas das comissões iniciadas[3].

A sua primeira grande obra como artista independente (*A Madona do Cravo*) foi elaborado entre 1473 e 1475, apesar de ainda trabalhar junto de Verrocchio, colaborando em diversos trabalhos deste[2].

Nesse tempo Florença estava ornamentada por trabalhos de artistas conceituados, muitos dos quais ainda vivos e com sucesso garantido por via de constantes encomendas do governo local e de cidadãos ricos e influentes. Deste modo, ainda que Leonardo tivesse beneficiado de algumas comissões importantes por influência do pai (que ficaram no geral inacabadas), e de ter aberto *atelier* próprio entre 1476 e 1481, o seu futuro não se lhe afigurava fácil nem assegurado, como sucedia com outros dos seus contemporâneos. Parece que desgostoso com a situação Leonardo decidiu mudar-se para Milão em 1482, oferecendo os seus préstimos (como engenheiro militar, escultor

various positions, including muscles, joints and visible bone structure. In Verrocchio's studio, and doubtless also in those of other masters of the era, there were commonly plaster models of parts of the human body, as well as statues, which the apprentices would study and use for their first drawings[3].

The quality of his drawings from life and of landscapes, and his multifaceted talents, so impressed his master that in 1472, when he was still only twenty years old, Verrocchio put him forward for membership of the Guild of St. Luke, the corporation of Florentine artists, who met, together with the city's physicians and apothecaries, in Ospedale de Santa Maria Nuova (the Santa Maria Nuova Hospital). With his new status, Leonardo was able to observe human cadavers in the hospital, and perhaps to dissect them for the first time, and so improve his knowledge of the aspects of anatomy that are essential in painting and drawing[4,5].

The quest for perfection that characterized Leonardo's work from the beginning, together with his tendency to work on many projects at the same time, were simultaneously a mark of his genius and, less positively, the probable reason that he failed to complete many of his commissions[3].

His first great work as an independent artist, *Madonna with the Carnation*, was painted between 1473 and 1475, although he was still working with Verrocchio, and collaborated with him on several works[2].

At this time Florence was full of works by famous artists, many of them still alive and with assured success from the many commissions from the city's rulers and rich and influential citizens. As a result, although Leonardo obtained some important commissions through his father's influence (most of which remained unfinished), and despite having his own studio between 1476 and 1481, his future did not appear assured or easy, as was the case with some of his contemporaries. Apparently through dissatisfaction with this state of affairs, Leonardo decided in 1482 to move to Milan, offering his services as a military engineer, painter and sculptor to the Duke of Milan, Ludovico Sforza, who ruled the city, which rivaled Florence as one of the most important cities of Renaissance Europe. Even though the prospects of substantial commissions were better than in Florence, Leonardo was not fully accepted at the e pintor) ao duque Ludovico Sforza que então governava aquela cidade rival de Florença, também uma das principais urbes da Europa renascentista. Ainda que as perspectivas de vida e de encomendas vultuosas fossem maiores do que em Florença, é um facto que Leonardo não obteve receptividade da côrte de Milão antes de 1487. Nesse intervalo, Leonardo aproveitou o tempo para estabelecer-se como pintor, primeiro em associação com uma família de artistas locais que lhe granjearam bons contactos e, por fim, com atelier e ajudantes próprios[1].

Ao contrário do que sucedera em Florença, em que a maior parte dos trabalhos que lhe haviam sido encomendados ficaram por acabar, em Milão Leonardo concretizou trabalhos importantes, em que se incluem algumas das suas pinturas e retratos mais representativos, tais como *A Virgem dos Rochedos*, *A Última Ceia*, *Retrato de Cecília Gallerani* (*Senhora com Arminho*) e *La Belle Ferronière*[2]. São também atribuídos àquele período numerosos desenhos e ideias que Leonardo elaborou sobre fortificações militares, técnicas de cerco e defesa e um conjunto de equipamentos bélicos inéditos. Também são conhecidos diversos projectos de arquitectura monumental e planificações urbanísticas, estudos sobre a Natureza e, muito em especial, um vasto conjunto de desenhos anotados sobre quase todos os domínios do conhecimento contemporâneo, reveladores de uma espantosa clarividência e antecipação do que viria a ser caracterizado séculos depois como matéria científica. Para Leonardo nenhum conhecimento tinha valor se não fosse observado e confirmado experimentalmente, de acordo com o que existe na Natureza.[3]

No seguimento da peste que assolou Milão, em 1484, Leonardo ter-se-á decidido a registar os seus esquemas e registos codificados em folhas soltas de papel e pequenos cadernos com tipos, cor e conteúdos heterogéneos[1].

Perto de 1489 Leonardo decidiu também aprofundar os seus estudos sobre as proporções do corpo humano, bem como a sua constituição anatómica e fisiológica. Aqueles estudos tinham por objectivo inicial uma melhor definição antropométrica do corpo humano, com dimensões e posições ajustadas a uma representação mais exacta em desenho e quadro. De certo modo, aqueles estudos seguiram a linha de trabalhos anteriores de Leonardo, do princípio da sua vida artística em Florença. Os traços do quadro

court until 1487, and he used this period to establish himself as a painter, firstly collaborating with a family of local artists who provided him with useful contacts, and then with his own studio and assistants[1].

Unlike in Florence, where most of his commissions had been unfinished, in Milan Leonardo completed important works, including some of his most famous paintings, such as *The Virgin of the Rocks*, *the Last Supper*, the portrait of Cecilia Gallerani (*Lady with an Ermine*), and *La Belle Ferronière*[2]. Numerous ideas and drawings on military fortifications, siege and defense techniques, and a range of innovative war machines, are also attributed to this period. We also know of various projects for monuments and city plans, studies of nature, and a vast range of annotated drawings on almost all areas of contemporary knowledge that demonstrate astonishing foresight in anticipating what in later centuries would be known as scientific study. For Leonardo, knowledge had no value unless it was based on observation, in accordance with what existed in Nature, and confirmed by experiment[3].

Following the outbreak of plague in Milan in 1484, Leonardo decided to record his drawings and coded notes on separate sheets of paper and in small notebooks of different types, colors and contents[1].

Around 1489 he decided to undertake a more profound study of the proportions of the human body and its anatomical and physiological composition. His initial aim was to improve his understanding of anthropometrics in order to be able to represent the body's dimensions and positions more accurately in drawings and paintings. In some ways these studies continued the path of his previous works from the beginning of his artistic career in Florence; the unfinished painting *St. Jerome in the Wilderness*, begun nineteen years before, presents an image of suffering and a wealth of anatomical detail that prefigured Leonardo's interest in these subjects[2].

Even though at this time he only had access to a single human skull, Leonardo produced a remarkable series of drawings of its characteristics, as a whole and in sections, from various viewpoints, and put forward hypotheses concerning the cerebral ventricles. He also examined the structure and formation of the eye[3]. His interest in vision was closely related to his studies of the nature of light and its interaction with objects. For (inacabado) de *S. Jerónimo*, iniciado cerca de dezanove anos antes, apresenta uma mímica de sofrimento e um amplo conjunto de pormenores anatómicos que prenunciavam o interesse de Leonardo por aqueles assuntos[2].

Apesar de nessa data ter acesso somente a uma crânio humano, Leonardo elaborou um conjunto notável de desenhos sobre as características óssea, em conjunto e em cortes sob diversas orientações, além de adiantar propostas para a constituição dos ventrículos cerebrais e ter dedicado atenção à estrutura e formação do olho[3]. O seu interesse pela visão tinha muito a ver com a natureza da luz e respectiva interacção com os objectos. Para Leonardo, as cores, as sombras e as zonas iluminadas, a difusão, a reflexão e a absorção da luz eram questões fundamentais na formação e experiência que adquirira como pintor:

"That you ought, when representing objects above the eye and on one side--if you wish them to look detached from the wall--to show, between the shadow on the object and the shadow it casts a middle light, so that the body will appear to stand away from the wall."[6]

Ao interessar-se pelo processo da visão Leonardo terá refinado conhecimentos e, decerto também, a técnica artística, para depois se entusiasmar com as pesquisas numa perspectiva mais anatómica e fisiológica:

"Which nerve causes the motion of the eye so that the motion of one eye moves the other? "[7]

Ainda dessa época merecem referência as seguintes anotações, aparentemente destinadas a futuros aprendizes de arte anatómica:

"And again, remember to be very careful in giving your figures limbs, that they must appear to agree with the size of the body and likewise to the age. Thus a youth has limbs that are not very muscular not strongly veined, and the surface is delicate and round, and tender in colour. In man the limbs are sinewy and muscular, while in old men the surface is wrinkled, rugged and knotty, and the sinews very prominent…

… It is indispensable to a Painter who would be thoroughly familiar with the limbs in all the positions and actions of which they are capable, in the nude, to know the anatomy of the sinews, bones, muscles and tendons so that, in their various movements and exertions, he may know which nerve or muscle is the cause of each movement and show those only

Leonardo, color, shadow, and how light was diffused, reflected and absorbed were central to his training and experience as a painter:

"That you ought, when representing objects above the eye and on one side–if you wish them to look detached from the wall–to show, between the shadow on the object and the shadow it casts a middle light, so that the body will appear to stand away from the wall."[6]

His interest in the process of vision led Leonardo to refine his knowledge and his artistic techniques, and consequently his research came more and more to concentrate on anatomical and physiological aspects of the body:

"Which nerve causes the motion of the eye so that the motion of one eye moves the other?"[7]

During the same period he produced the following notes, apparently addressed to future students of the art of anatomy:

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... It is indispensable to a Painter who would be thoroughly familiar with the limbs in all the positions and actions of which they are capable, in the nude, to know the anatomy of the sinews, bones, muscles and tendons so that, in their various movements and exertions, he may know which nerve or muscle is the cause of each movement and show those only as prominent and thickened, and not the others all over [the limb], as many do who, to seem great draughtsmen, draw their nude figures looking like wood, devoid of grace; so that you would think you were looking at a sack of walnuts rather than the human form, or a bundle of radishes rather than the muscles of figures."[8]

Although he continued his studies in the following years, he produced much less in the area of anatomy and physiology due to his increasing responsibilities and the growing demand for his services at the Duke's court. However, his situation changed dramatically in 1498 when Milan was conquered by the armies of the French king Louis XII.

Leonardo remained in the occupied city for *as prominent and thickened, and not the others all over [the limb], as many do who, to seem great draughtsmen, draw their nude figures looking like wood, devoid of grace; so that you would think you were looking at a sack of walnuts rather than the human form, or a bundle of radishes rather than the muscles of figures".*[8]

Apesar de ter prosseguido os seus estudos nos anos imediatos, a sua produção no campo anatómico e fisiológico reduziu-se substancialmente com as crescentes responsabilidades e solicitações para que era requerido na corte de Ludovico. Porém, aquela situação alterou-se drasticamente em 1498, com a tomada de Milão pelo exército francês de Louis XII.

Leonardo permaneceu na cidade ocupada durante mais alguns meses, pois que a sua estadia era bem-vinda pela côrte francesa, já conhecedora e admiradora dos seus dotes artísticos[1]. Mas parece que Leonardo não terá suportado a visão dos archeiros franceses a treinarem a pontaria tendo como alvo o seu modelo em terracota do *Gran Cavalo* (que se destinava a uma estátua equestre de homenagem aos Sforza), pelo que abandonou Milão em Dezembro do mesmo ano, iniciando um périplo por várias cidades. Primeiro dirigiu-se a Mântua, depois foi para Veneza, até que, por fim, regressou a Florença em 1500, quase com cinquenta anos de idade, dando início ao período de vida em que teve maior produtividade artística[2].

Fig. 1
Estátua de Leonardo da Vinci no exterior da Gallery Uffizi, Florença. (Imagem do domínio público/Wikimedia Commons)
Fig. 1
Statue of Leonardo da Vinci outside the Uffizi Gallery, Florence (Image in the public domain/Wikimedia Commons)

several months; his presence was in fact welcomed by the French court, where his artistic talents were already known and admired[1]. But it seems that he could not bear to see his clay model of the *Gran Cavallo*, which was to be an equestrian monument in honor of the Sforza dynasty, being used for target practice by French archers, and left Milan in December. Thus began a period of wandering, to various cities; first Mantua, then Venice, until he returned to Florence in 1500.

Leonardo was now nearly fifty and entering the most productive period of his artistic life[2]. In the following six years he remained in Florence, working as an artist, military architect and engineer[1], and finally won the recognition he deserved from his countrymen (*Fig. 1*).

From 1506 to 1508 Leonardo divided his time between Florence and Milan, on the insistence of Louis XII, who put pressure on the Florentine authorities. Eventually, In 1508 he moved back to Milan, where he resumed the duties that he had performed for Ludovico, but this time for the city's French governor. At the same time, he continued to produce works of art, including the Mona Lisa (also known as La Gioconda), although he spent less time painting as he concentrated on his anatomical studies, dissecting corpses at the Ospedale Maggione with the help and guidance of the young anatomist Marcantonio della Torre[6,9]. From this period (1510-1514) date the following notes on an autopsy[10]:

"I have removed the skin from a man who was so shrunk by illness that the muscles were worn down and remained in a state like thin membrane, in such a way that the sinews instead of merging in muscles ended in wide membrane; and where the bones were covered by the skin they had very little over their natural size."[10]

This period came to an end when Massimiliano Sforza, Ludovico's son, reconquered Milan and drove out the French. Eventually Leonardo also decided to leave and accepted an invitation from Giuliano de Medici, brother of the new pope Leo X and an admirer, to move to Rome. Leonardo remained at the papal court from 1513 to 1516/17[1].

Now in his sixties, Leonardo was no longer in the vanguard as an artist, but had attained the status of a sage and was consulted on a wide range of subjects. With few demands on his time, he carried out experiments and filled sheets and

Nos seis anos seguintes Leonardo permaneceu ligado aquela cidade, como artista, engenheiro e arquitecto militar[1], tendo finalmente obtido o merecido reconhecimento dos conterrâneos (*Fig. 1*).

Entre 1506 e 1508 Leonardo reparte a sua actividade entre Florença e Milão, por insistência de Louis XII junto das autoridades de Florença. Finalmente, em 1508, Leonardo instala-se em Milão, onde retoma junto do governador francês da cidade as funções que já exercera na corte de Ludovico. Simultaneamente, prossegue a sua actividade de artista famoso, em que se destaca o quadro de *La Gioconda* (ou *Mona Lisa*), embora cada vez estivesse menos produtivo, à medida que aprofundava aos seus estudos anatómicos pela dissecção de corpos humanos no Ospedale Maggione, com o ensinamento e colaboração do jovem anatomista Marcoantonio della Torre[6,9]. Data desse período, de 1510 a 1514, a seguinte observação de uma autópsia que Leonardo registou nos seus apontamentos[10]:

"I have removed the skin from a man who was so shrunk by illness that the muscles were worn down and remained in a state like thin membrane, in such a way that the sinews instead of merging in muscles ended in wide membrane; and where the bones were covered by the skin they had very little over their natural size".[10]

Esta fase foi interrompida com a reconquista de Milão por Maximiano Sforza, filho de Ludovico, e a expulsão dos franceses. Ao fim de algum tempo Leonardo decidiu também sair, aceitando o convite de Guiliano de Medici, irmão do novo Papa Leão X e seu admirador, para se instalar em Roma. Leonardo permaneceu na corte papal de 1513 a 1516/17 (1).

Já sexagenário, Leonardo deixara de estar na vanguarda como artista mas ganhara o estatuto de sábio e de consultor experiente nos mais diversos assuntos. Com muito tempo para si, Leonardo realiza experiências e enche folhas soltas e cadernos com desenhos de trabalhos, ideias e anotações diárias sobre os mais diversos assuntos[11]. Entre algumas obras finais pintou o retrato de *S. João Baptista*, famoso pela utilização que Leonardo fez da técnica do *sfumato*[2]. No seguimento dos estudos hidráulicos que realizara cerca de dez anos antes, em Florença, enquanto acompanhara os exércitos de Cesare Borgia pela Itália Central, Leonardo aprofundou as observações sobre os movimentos da água e os efeitos de um

notebooks with drawings, designs, ideas and notes on a wide range of subjects[11]. Among his late works was the portrait of St. John the Baptist, famous for his use of the technique of shading known as *sfumato*[2]. Following on from his studies of hydraulics in Florence ten years before, when he accompanied the armies of Cesare Borgia around central Italy, Leonardo now spent much of his time making observations of the movement of water and the effects of flooding (which seems to have obsessed him); dozens of these drawings survive in the Leicester Codex. Along with his representations of waterfalls flowing over all kinds of obstacles, he paid particular attention to eddies and currents (*Fig. 2*), which seem to have been the basis of his later studies of the hemodynamics of the heart and aorta[12].

Fig. 2
Desenhos do fluxo e redemoínhos da água na presença de obstáculos e desníveis (cerca de 1508-1509). Pena e tinta sobre papel. Estes estudos foram importantes para o conceito elaborado por Leonardo sobre a contribuição dos redemoínhos pós-ejecção sanguínea ventricular no encerramento da válvula aórtica. (Imagem no domínio público/Wikimedia Commons)

Fig. 2
Drawings of flows and eddies in water passing obstacles and falling (c. 1508-1509). Pen and ink on paper. These studies were important in the development of Leonardo's ideas on the contribution of vortices in blood following ventricular ejection to the closure of the aortic valve. (Image in the public domain/ Wikimedia Commons)

eventual dilúvio (o que parecia ser uma obsessão pessoal), de que existem dezenas de desenhos (incluídos no Codex Leicester). A par da representação de cascatas de água a ultrapassarem toda a espécie obstáculos, Leonardo deu particular atenção aos redemoínhos e fluxos (*Fig. 2*) que, aparentemente, fundamentaram as suas posteriores interpretações hemodinâmicas no coração e na aorta.[12]

É neste período da sua vida que Leonardo desenvolve substancialmente os seus estudos anatómicos, através de autópsias realizadas no Ospedade de Spirito Santo durante as horas nocturnas, tendo como iluminação a luz de velas[9]. Tão grande desconforto, decerto acentuado pelo cheiro dos corpos em decomposição, não impediu que Leonardo nos legasse belíssimos e meticulosos desenhos do corpo humano, em que os aspectos humanos eram enriquecidos com espantosas interpretações fisiológicas.[3].

Aquelas conclusões foram possibilitadas não só pelas cerca de trinta autópsias de corpos humanos masculinos e femininos e de várias idades que Leonardo terá efectuado em cerca de trinta anos[13], mas também pelos estudos de experimentação animal, como ele próprio explica:

"I have found that in the composition of the human body as compared with the bodies of animals the organs of sense are duller and coarser"[14].

Porém, aqueles estudos não terão sido compreendidos e muito menos aceites na côrte papal. Leonardo, acusado de necromancia, resolveu abandonar Roma, aceitando o convite do novo rei francês Francois I, para pintor da sua corte e conselheiro pessoal.

Recebido com todas as honras em Cloux, perto do castelo real de Amboise, Leonardo continuou nos últimos anos de vida a elaborar projectos e experiências, esforçando-se ainda por ordenar os manuscritos, desenhos e cadernos de apontamentos que constituíam o registo de mais de três décadas de actividade intensa, como referiu Paul Richter:

"Leonardo frequently, and perhaps habitually, wrote in note books of a very small size and only moderately thick; in most of those which have been preserved undivided, each contains less than fifty leaves. Thus a considerable number of such volumes must have gone to make up a volume of the bulk of the '_Codex Atlanticus_' which now contains nearly 1200

During this period Leonardo continued his detailed studies of anatomy, performing autopsies by candlelight in the Ospedale Spirito Santo[9]. The inconvenience of working at night and the smell of decomposing bodies did not prevent him from producing beautiful, meticulous drawings of the human body, in which the anatomical forms were enriched by amazing physiological observations[3].

These insights were made possible not only by the thirty or so autopsies on male and female corpses of various ages that Leonardo performed over a period of thirty years[13], but also by his studies on animals, as he himself explains:

"I have found that in the composition of the human body as compared with the bodies of animals the organs of sense are duller and coarser."[14]

However, such studies were met with incomprehension and rejection by the papal court. Accused of necromancy, Leonardo resolved to leave Rome and accepted an invitation from the new French king, Francis I, to be his court painter and personal adviser.

Welcomed with great ceremony at Cloux, near the royal chateau of Amboise, he continued to work on projects and experiments throughout his last years. He also spent time organizing his manuscripts, drawings and notebooks, the record of over three decades of intense activity. Paul Richter writes:

"Leonardo frequently, and perhaps habitually, wrote in note books of a very small size and only moderately thick; in most of those which have been preserved undivided, each contains less than fifty leaves. Thus a considerable number of such volumes must have gone to make up a vo-lume of the bulk of the Codex Atlanticus which now contains nearly 1200 detached leaves. In the passage under consideration, which was evidently written at a late period of his life, Leonardo speaks of his Manuscript note-books as numbering 120."[15]

Leonardo died in 1519 and was buried in Amboise. He had not succeeded in publishing his precious notes in book form as he had intended:

"Begun at Florence, in the house of Piero di Braccio Martelli, on the 22nd day of March 1508. And this is to be a collection without order, taken from many papers which I have copied here, hoping to arrange them later each in its place, according to the subjects of which they may treat. But I believe that before I am at the end of this [task] I shall have to repeat

detached leaves. In the passage under consideration, which was evidently written at a late period of his life, Leonardo speaks of his Manuscript note-books as numbering 120"[15]

Em 1519, Leonardo morre e é sepultado em Amboise sem ter conseguido publicar em livro aqueles preciosos apontamentos, como tencionara:

"Begun at Florence, in the house of Piero di Braccio Martelli, on the 22nd day of March 1508. And this is to be a collection without order, taken from many papers which I have copied here, hoping to arrange them later each in its place, according to the subjects of which they may treat. But I believe that before I am at the end of this [task] I shall have to repeat the same things several times; for which, O reader! do not blame me, for the subjects are many and memory cannot retain them [all] and say: 'I will not write this because I wrote it before"[16].

Calcula-se que somente um terço daquelas folhas, cerca de 5000, tenham chegado até à actualidade[17], dispersas por dez colecções diferentes, nove das quais estão depositadas em instituições públicas (Codex-Arundel, Codex Atlanticus, Codex Trivulzianus, Codex On the Flight of Birds, Codex Ashburnham, Codex Forster, Codices de l'Institut de France, Windsor Folios, The Madrid Codices), sendo a restante (Codex Leicester) pertença de uma entidade privada.

Estudos do coração e dos vasos sanguíneos

Alterações vasculares e envelhecimento - No fim da vida Leonardo dedicou particular e demorada atenção ao estudo do coração e dos vasos sanguíneos, que iniciara pouco depois de 1490 (*Fig. 3*). Talvez esse renovado interesse tivesse surgido por um acaso, quando, numa das suas viagens a Florença, no Inverno de 1507/8, Leonardo conheceu um centenário que estava internado no Ospedade de Santa Maria Nuova. Na conversa que tiveram, aquele paciente contou a Leonardo que nunca estivera doente e, naquele momento, simplesmente sentia-se sem forças. E, parece que enquanto conversavam, o homem faleceu, sentado no leito, sem que qualquer sinal ou movimento prenunciasse o evento. Leonardo, ao realizar a autópsia quase de imediato, teve a possibilidade de observar lesões anatómicas vasculares, decerto típicas da aterosclerose e que, pelas suas palavras, teriam sido a causa da morte[19]:

the same things several times; for which, O reader! do not blame me, for the subjects are many and memory cannot retain them [all] and say: 'I will not write this because I wrote it before'."[16]

It is thought that around 5000 of these pages, only a third of the total, have survived to the present day[17], dispersed in ten different collections, nine of which are held in public institutions (the Arundel Manuscript, Codex Atlanticus, Codex Trivulzianus, Codex On the Flight of Birds, Codex Ashburnham, Codex Forster, Codices de l'Institut de France, the Windsor Folios, and the Madrid Codices), and the other, the Codex Leicester, is in private hands.

Studies of the heart and blood vessels

Vascular changes with age - Towards the end of his life, Leonardo spent much time on the study of the heart and blood vessels, which he had begun shortly after 1490 (*Fig. 3*). His interest may have been reawakened by a chance meeting on one of his trips to Florence in the winter of 1507/08 with a 100-year-old patient in the Ospedale Santa Maria Nuova. During their conversation, the old man told Leonardo that he had never been ill, and simply felt feeble. While they were still talking, with no warning sign or movement the man died as he sat on his bed. Leonardo performed an autopsy almost immediately, and was able to observe anatomical vascular lesions, almost certainly atherosclerotic, which, according to Leonardo, would have caused his death:

"... And this old man, a few hours before his death told me that he had lived one hundred years and that he did not feel any bodily ailment other than weakness; and thus while sitting on a bed in the hospital of Santa Maria Nuova at Florence, without any movement or sign of anything amiss he passed from this life. And I made an anatomy in order to see the cause of so sweet a death which I found to proceed from debility through lack of blood and failure of the artery which feeds the heart and the other lower organs, which I found to be dried shrunken and withered... "[19]

Later, Leonardo compared the lesions he had found in this autopsy with the arteries he observed in a two-year-old child, highlighting the reduced caliber and increased thickness of vessel walls in old age (*Fig. 4*), as well as sensitivity to cold and changes in the skin that he attributed to diminished blood flow:

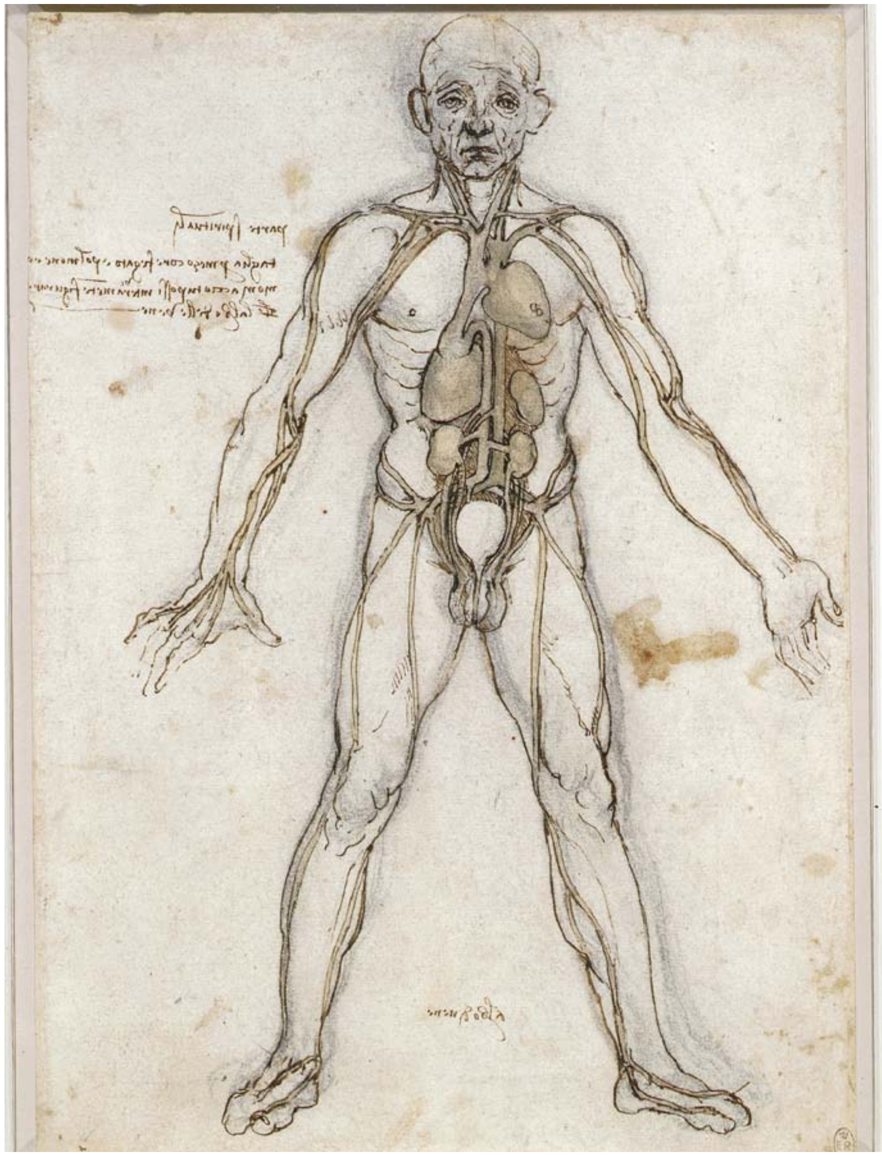


Fig. 3
Representação do corpo humano, com destaque para os principais órgãos e distribuição vascular. Este desenho (cerca de 1490; 912597r Royal Collection) corresponde a uma fase preparatória dos estudos anatómicos, em que Leonardo ainda seguia as ideias tradicionais de Mondino e Galeno. Por isso, a presente reprodução é como que um esboço das imagens anatómicas meticulosas e dos conceitos que Leonardo viria a apresentar cerca de vinte anos depois. (Courtesy of The Royal Collection ©2007, Her Majesty Queen Elizabeth II).

Fig. 3
Representation of the human body showing the main organs and distribution of blood vessels. This drawing, dating from around 1490 (Royal Collection, Windsor, 912597r), is from a preparatory stage in Leonardo's anatomical studies, when he was still following the traditional ideas of Mondino and Galen. It is thus like a preliminary sketch of the meticulously observed anatomical drawings that he produced twenty years later. (Courtesy of The Royal Collection ©2007, Her Majesty Queen Elizabeth II)

"... And this old man, a few hours before his death told me that he had lived one hundred years and that he did not feel any bodily ailment other than weakness; and thus while sitting on a bed in the hospital of Santa Maria Nuova at Florence, without any movement or sign of anything amiss he passed from this life. And I made an anatomy in order to see the cause of so sweet a death which I found to proceed from debility through lack of blood and failure of the artery which feeds the heart and the other lower organs, which I found to be dried shrunken and withered…"[19]

"... The other anatomy was that of a child of 2 years in which I found everything opposite to that of the old man. The old who enjoy good health die through lack of nourishment. This happens because the passage of the mesenteric vessels is continually narrowed by the thickening of the coats of these vessels. And the process continues until it affects the capillary vessels which are the first to close up entirely. As a consequence of this the old dread the cold more than the young, and those that are very old have a skin the colour of wood or dried chestnut because the skin is almost completely deprived of nourishment."[19]

Seguidamente, Leonardo estabeleceu a comparação entre as lesões daquela autópsia e as que observara numa criança de dois anos, para destacar a relação entre a redução do calibre e o aumento da espessura da parede vascular com a idade (*Fig. 4*), junto com a sensação de frio e alterações cutâneas atribuíveis à escassez de irrigação sanguínea:

"…The other anatomy was that of a child of 2 years in which I found everything opposite to that of the old man. The old who enjoy good health die through lack of nourishment. This happens because the passage of the mesenteric vessels is continually narrowed by the thickening of the coats of these vessels. And the process continues until it affects the capillary vessels which are the first to close up entirely. As a consequence of this the old dread the cold more than the young, and those that are very old have a skin the colour of wood or dried chestnut because the skin is almost completely deprived or nourishment."[19]

E continua:

"…The coats of the vessels behave in man as in oranges, in which the peel thickens and the pulp diminishes the order they become. And if you say that it is the thickened blood which ceases to flow through the vessels this is not true, for the blood in the vessels does not thicken because it continually dies and is renewed"[19]

Nestas espantosas anotações Leonardo quereria aludir a pulsatilidade em determinado sector arterial durante o fluxo sanguíneo (que impede a coagulação intravascular) ou à continuada renovação dos constituintes sanguíneos?

Qualquer daquelas hipóteses, a ser consignada, reflectiria uma antecipação de vários séculos quanto a mecanismos fundamentais hoje indiscutíveis, em que a fluidez sanguínea é essencial para uma normal circulação sanguínea e, por outro lado, os processos de senescência incluiem uma constante formação de novos elementos sanguíneos para substituição dos que são eliminados.

Adicionalmente, para Leonardo a diminuição do calibre vascular com a idade explicaria a diminuição do aporte de nutrientes aos tecidos periféricos e seria responsável por alterações tróficas e térmicas num sector. Ou seja, Leonardo estabeleceu o princípio do desenvolvimento da aterosclerose ao longo do envelhecimento, como se confirma noutro manuscrito, ainda a propósito da autópsia do centenário em Florença:

Fig. 4
Imagem das veias superficiais do membro superior esquerdo. Desenho a tinta com pena (cerca de 1508; The Royal Collection, 919027r). Este desenho terá sido motivado pelas observações de autópsia do centenário de Florença, e da sua comparação com a de uma criança de dois anos de idade. À esquerda do desenho principal é representado o aspecto tortuoso de um vaso (artéria?) daquele idoso, a par dos vasos escorreitos de uma criança (e dos jovens em geral). (Courtesy of The Royal Collection ©2007, Her Majesty Queen Elizabeth II).

Fig. 4
Drawing of the surface veins of the left arm. Pen and ink, c. 1508 (Royal Collection, Windsor, 919027r). This drawing was presumably inspired by Leonardo's observations of the autopsy studies of the old man and the two-year-old child in Florence. On the left of the main drawing is shown the twisted vessel, possibly an artery, from the old man, as well as the healthy vessels of a child and young people generally. (Courtesy of The Royal Collection ©2007, Her Majesty Queen Elizabeth II)

And he goes on:

"... The coats of the vessels behave in man as in oranges, in which the peel thickens and the pulp diminishes the older they become. And if you say that it is the thickened blood which ceases to flow through the vessels this is not true, for the blood in the vessels does not thicken because it continually dies and is renewed."[19]

In these astonishing observations, is Leonardo referring to pulsatile blood flow in the arteries, which prevents intravascular coagulation, or to the constant renewal of blood constituents?

Whatever the case, it would anticipate by several centuries our current understanding of

"One asks why the vessels in the old acquire great length and those which were formerly straight become tortuous and their coat thickens so much as to occlude and prevent the movement of the blood. From this arises the death of the old without disease. I judge that a thing is the more healthy the nearer it is to its nourishment and for this reason these vessels being the sheath of the blood which nourishes the body, are nourished the more in proportion to their nearness to the blood."… "Vessels which by the thickening of their coats in the old restrict the transit of the blood, and from this lack of nourishment the old, little by little with a slow death destroy their life without any fever; and this happens through lack of exercise since the blood is not warmed."[27]

Estas reflexões voltaram a ser novamente invocadas a propósito da interrupção do fluxo vascular nos idosos:

"Death in old men, when not from fever, is caused by the veins which go from the spleen to the valve of the liver, and which thicken so much in the walls that they become closed up and leave no passage for the blood that nourishes it. The incessant current of the blood through the veins makes these veins thicken and become callous, so that at last they close up and prevent the passage of the blood",[20],

em contraste com a irrigação nos jovens:

"I have found in the decrepit how the vessel which extends from the porta hepatis to the spleen passes behind the stomach and ramifies in the spleen; the vessels in the young are straight and full of blood, and in the old are tortuous, flattened, wrinkled and empty of blood"[12]

Em 1509, já com alguma experiência de dissecção, Leonardo referia (dirigindo-se aparentemente aos jovens estudantes de pintura e artística) a repugnância, o esforço e a persistência necessários para conhecer a verdade (em que incluía o perfeito conhecimento do sistema vascular), tendo que repetir tudo em vários cadáveres para identificar as diferenças:

"And you, who say that it would be better to watch an anatomist at work than to see these drawings, you would be right, if it were possible to observe all the things which are demonstrated in such drawings in a single figure, in which you, with all your cleverness, will not see nor obtain knowledge of more than some few veins, to obtain a true and perfect knowledge of which I have dissected more than ten human bodies, destroying all the other members, and removing the very minutest particles of the flesh by which these veins are

fundamental mechanisms, that the fluidity of the blood is essential to normal circulation and that even in old age new blood constituents are constantly being produced to replace those that are eliminated.

Furthermore, Leonardo considered that the narrowing of vascular caliber with age would cause a reduction in the supply of nutrients that would lead to trophic and thermal alterations in peripheral tissues. He thus established the principle that atherosclerosis develops with increasing age, as he makes explicit in another manuscript, also on the subject of the autopsy on the centenarian in Florence:

"One asks why the vessels in the old acquire great length and those which were formerly straight become tortuous and their coat thickens so much as to occlude and prevent the movement of the blood. From this arises the death of the old without disease. I judge that a thing is the more healthy the nearer it is to its nourishment and for this reason these vessels being the sheath of the blood which nourishes the body, are nourished the more in proportion to their nearness to the blood... Vessels which by the thickening of their coats in the old restrict the transit of the blood, and from this lack of nourishment the old, little by little with a slow death destroy their life without any fever; and this happens through lack of exercise since the blood is not warmed."[27]

He returned to the subject in relation to the obstruction of blood flow in the elderly:

"Death in old men, when not from fever, is caused by the veins which go from the spleen to the valve of the liver, and which thicken so much in the walls that they become closed up and leave no passage for the blood that nourishes it. The incessant current of the blood through the veins makes these veins thicken and become callous, so that at last they close up and prevent the passage of the blood"[20],

in contrast to blood flow in the young:

"I have found in the decrepit how the vessel which extends from the porta hepatis to the spleen passes behind the stomach and ramifies in the spleen; the vessels in the young are straight and full of blood, and in the old are tortuous, flattened, wrinkled and empty of blood."[12]

In 1509, apparently addressing young students of the arts, Leonardo, by now experienced in dissection, described the unpleasantness of the experience and the effort and persistence *surrounded, without causing them to bleed, excepting the insensible bleeding of the capillary veins; and as one single body would not last so long, since it was necessary to proceed with several bodies by degrees, until I came to an end and had a complete knowledge; this I repeated twice, to learn the differences."*[21]

Anatomia cardíaca - Os estudos de Leonardo sobre o coração humano apoiaram-se inicialmente nos ensinamentos anatómicos de Mondino e, depois de 1510, beneficiaram da colaboração pessoal de Marcantonio della Torre. Este anatomista da Universidade de Pádua morreria dois anos mais tarde, o que talvez tenha obstado aos propósitos que Leonardo alimentara, de incluir os seus estudos anatómicos num tratado de anatomia com a designação de "Livro de Pintura e do Movimento Humano" como referiu nos seus apontamentos:

"This work must begin with the conception of man, and describe the nature of the womb and how the foetus lives in it, up to what stage it resides there, and in what way it quickens into life and feeds… Then I will describe which are the members, which, after the boy is born, grow more than the others, and determine the proportions of a boy of one year.

Then describe the fully grown man and woman, with their proportions, and the nature of their complexions, colour, and physiognomy.

Then how they are composed of veins, tendons, muscles and bones. This I shall do at the end of the book… Further I would describe attitudes and movements. Then perspective, concerning the functions and effects of the eye; and of hearing--here I will speak of music--, and treat of the other senses.

And then describe the nature of the senses. This mechanism of man we will demonstrate in ... figures…

…This depicting of mine of the human body will be as clear to you as if you had the natural man before you; and the reason is that if you wish thoroughly to know the parts of man, anatomically, you--or your eye--require to see it from different aspects, considering it from below and from above and from its sides, turning it about and seeking the origin of each member; and in this way the natural anatomy is sufficient for your comprehension."[23]

Aqueles propósitos foram confirmados numa carta que o seu amigo Luca Pacioli escreveu ao duque de Milão, em 1498, mas nunca foram concretizados, pelo que os desenhos anatómicos viriam a ser incluídos num tratado de pintura editado cerca de 1651[9,17]. Porém, a obra de Leonardo seria conhecida na sua expressão quase

required to learn the truth, including a thorough knowledge of the vascular system, for which the process must be repeated on several cadavers to discover the differences:

"And you, who say that it would be better to watch an anatomist at work than to see these drawings, you would be right, if it were possible to observe all the things which are demonstrated in such drawings in a single figure, in which you, with all your cleverness, will not see nor obtain knowledge of more than some few veins, to obtain a true and perfect knowledge of which I have dissected more than ten human bodies, destroying all the other members, and removing the very minutest particles of the flesh by which these veins are surrounded, without causing them to bleed, excepting the insensible bleeding of the capillary veins; and as one single body would not last so long, since it was necessary to proceed with several bodies by degrees, until I came to an end and had a complete knowledge; this I repeated twice, to learn the differences."[21]

Cardiac anatomy - Leonardo's studies of the human heart were based mainly on the anatomical teachings of Mondino, while after 1510 he benefited from his collaboration with Marcantonio della Torre, the anatomist from the University of Padua. The death of della Torre two years later may have thwarted Leonardo's plans to include his anatomical studies in a treatise on anatomy, to be titled the *Book of Painting and Human Movement*, as described in his notes:

"This work must begin with the conception of man, and describe the nature of the womb and how the foetus lives in it, up to what stage it resides there, and in what way it quickens into life and feeds... Then I will describe which are the members, which, after the boy is born, grow more than the others, and determine the proportions of a boy of one year.

Then describe the fully grown man and woman, with their proportions, and the nature of their complexions, colour, and physiognomy.

Then how they are composed of veins, tendons, muscles and bones. This I shall do at the end of the book... Further I would describe attitudes and movements. Then perspective, concerning the functions and effects of the eye; and of hearing--here I will speak of music--, and treat of the other senses.

And then describe the nature of the senses. This mechanism of man we will demonstrate in ... figures...

... This depicting of mine of the human body will be as clear to you as if you had the natural man before you; and the reason is that if you wish thoroughly to know the parts of man, anatomically, you--or your eye--require to see it from different

total somente no século XIX[17].

Leonardo excluiu que o coração fosse a "sede da força vital" (conceito metafísico proposto por Platão, depois apoiado por Aristóteles e Galeno), ao verificar que uma rã de que removera a cabeça, os órgãos internos e também o coração continuava a dar sinais de vida, que cessava somente quando seccionava determinado nervo. Daqui resultou a opinião (então herética) de que a vida não residiria no coração mas estaria no tecido nervoso[11].

De acordo com Galeno, não seria digno que o coração (como "sede da alma") fosse um vulgar músculo ou a sua função se limitasse à de um músculo. Leonardo verificou que a contracção cardíaca resultava de um conjunto de formas musculares interligadas em diversos sentidos, dotadas de contracção intrínseca, que se distendiam longitudinalmente em função da quantidade de sangue contido no órgão:

"Their contraction is generated intrinsically by means of their muscles. Owing to their diverse obliquities and concatentation or interwoven state without any flesh between their intertwinings, these muscles are without any villi so as to be capable of stretching longitudinally in accordance with the requirements of the superabundance of blood that sometimes beats against the external membrane which clothes these muscles"[23]

Deste modo, o coração tinha funções mecânicas por ser músculo, pelo que, no entender de Leonardo, não haveria motivos para o associar com as interpretações metafísicas ou relacioná-lo com a alma.

Leonardo começou por observar a contracção cardíaca por vivissecção animal, sendo os desenhos do coração produzidos inicialmente a partir de órgãos de bovino e também em suínos.

Seguidamente, efectuou um estudo pormenorizado sobre as cavidades cardíacas através de modelos de cera, pelo que detectou a disposição das cordas tendinosas e relacionou a sua acção com a expansão e a contracção cardíacas. Os desenhos mais representativos, que incluíam o estudo das válvulas e do funcionamento cardíaco global, foram executados cerca de 1515 a partir de um coração de bovino (*Fig. 5*). A propósito, Leonardo sugeriu que a forma tricúspide da válvula aórtica seria melhor apreciada num coração de boi com as suas câmaras preenchidas com cera:

aspects, considering it from below and from above and from its sides, turning it about and seeking the origin of each member; and in this way the natural anatomy is sufficient for your comprehension."[23]

These proposals were confirmed in a letter that Leonardo's friend Luca Pacioli wrote to the Duke of Milan in 1498, but the project never materialized; the anatomical drawings were eventually included in a treatise on painting published in 1651[9,17]. Leonardo's work was not published in its entirety until the 19th century[17].

Leonardo did not accept Plato's metaphysical concept, later supported by Aristotle and Galen, that the heart was the seat of the vital force; after removing the head of a frog and its internal organs, including the heart, he had found that it continued to show signs of life, which only ceased when the appropriate nerve was severed. This led him to the then heretical opinion that the seat of life is not in the heart but in the nerves[11].

According to Galen, it was not fitting that the heart, the seat of the soul, should be merely a muscle or that its function should be only that of a muscle. Leonardo found that the heart's contraction resulted from a set of muscles that were interlinked in different directions and that could contract by themselves, stretching lengthwise according to the quantity of blood that the heart contained:

"Their contraction is generated intrinsically by means of their muscles. Owing to their diverse obliquities and concatentation or interwoven state without any flesh between their intertwinings, these muscles are without any villi so as to be capable of stretching longitudinally in accordance with the requirements of the superabundance of blood that sometimes beats against the external membrane which clothes these muscles."[23]

The heart was thus a muscle that had mechanical functions, and so for Leonardo there was no reason to seek metaphysical explanations or to link it with the soul.

Leonardo began his studies of cardiac contraction by vivisection of animals, and his first drawings of the heart were of those of cattle and pigs. Later, he performed detailed studies of the cardiac chambers by modeling them in wax; from these he discovered the position of the chordae tendineae and how their movement was related to cardiac expansion and contraction. The most accurate of his drawings on this theme, dating

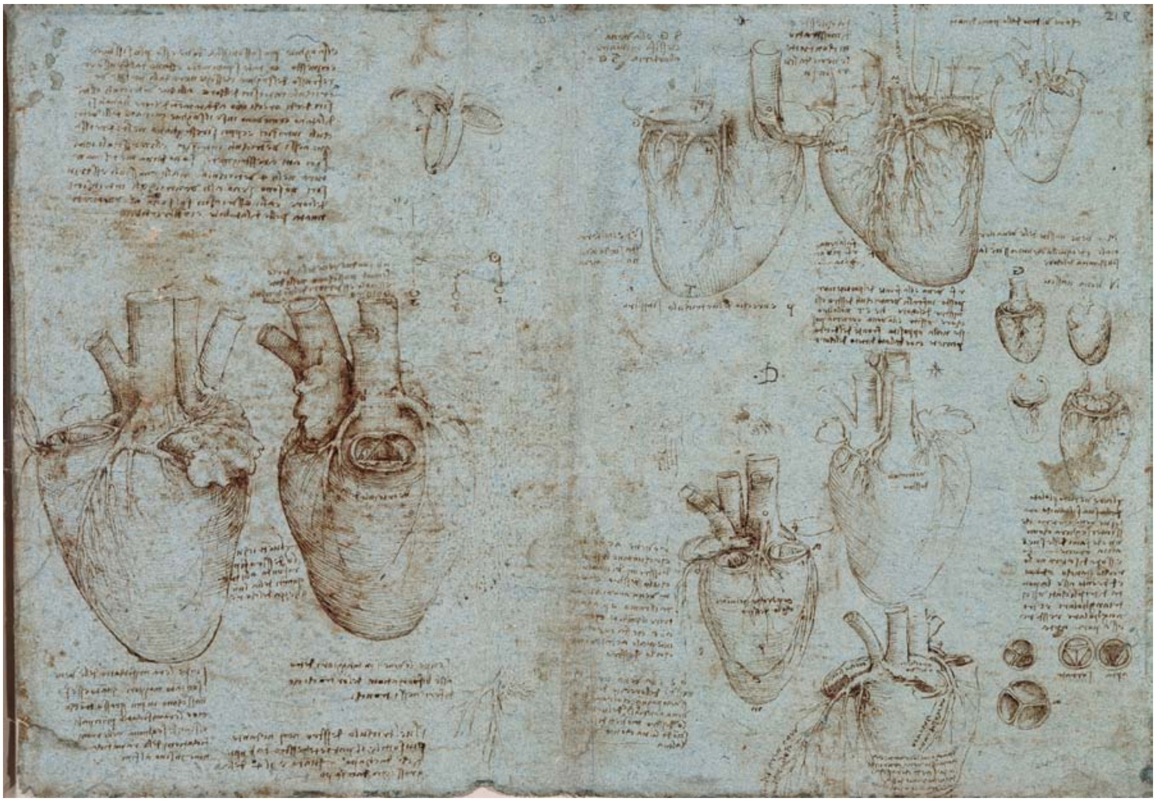


Fig. 5
Estudos sobre o coração. Desenho à pena com tinta castanha, em papel preparado com coloração azul (cerca de 1515-16; The Royal Collection, 919073v-19074v). O coração (que se presume ser de porco) é representado no seu conjunto e sob diversas representações e ângulos de observação. É dada particular atenção às válvulas cardíacas e à abertura para as artérias pulmonar e aorta. A válvula aórtica é evidenciada em abertura. A tricúspide é analisada separadamente, no extremo inferior direito da folha, nas configurações de abertura e encerramento. (Courtesy of The Royal Collection ©2007, Her Majesty Queen Elizabeth II).
Fig. 5
Studies of the heart. Pen and brown ink on blue prepared paper, c. 1515-1516 (Royal Collection, Windsor, 919073-74v). The heart, probably that of a pig, is shown in its entirety and from various viewpoints. Particular attention is paid to the cardiac valves and their openings to the pulmonary arteries and the aorta. The aortic valve is shown open, while the tricuspid valve is shown separately at the bottom right of the sheet in both open and closed positions. (Courtesy of The Royal Collection ©2007, Her Majesty Queen Elizabeth II)

"but first four wax into their value of a bull's heart so that you may sec the three shape of the valve"[24].

Demonstrou que o coração não se limitava a duas câmaras, resultantes da dilatação localizada de vasos esvaziados (como era então aceite), sendo, em alternativa, constituído por quatro câmaras independentes com capacidade de distensão e contracção; as câmaras superiores (aurículas) eram estruturalmente diferentes dos vasos e a contracção decorria separadamente do ventrículo:

"At one and the same time in one and the same subject two opposite motions cannot take place, that is repentance and desire. Therefore, if the right upper [auricle] and lower ventricles are one and the same, it is necessary that the whole should cause at the same time one and the same effect, and not two effects arising from two diametrically opposite purposes"[25]

from around 1515 and including studies of the cardiac valves and overall cardiac function, are of an ox's heart (*Fig. 5*). Commenting on them, Leonardo suggested that the tricuspid form of the aortic valve could be better appreciated by examining a bull's heart in which the chambers had been filled with wax:

"but first pour wax into the valve of a bull's heart so that you may see the true shape of the valve."[24]

He demonstrated that the heart did not have only two chambers that were formed by local dilatation of empty vessels, as had been believed previously, but in fact had four chambers that could expand and contract independently, and that the upper chambers (the atria) were structurally distinct from the blood vessels and that they contracted separately from the ventricles:

Adicionalmente, cerca de 1513, Leonardo observou que a contracção e a pulsação estavam associadas, comparando-as com o fluxo e refluxo das mares e também à perfusão que se verifica nas plantas:

"…the beating of the heart… generates a wave of blood through all of the vessels, which continually dilate, and contract. The dilatation occurs on the reception of the superabundant blood, and the contraction is due to the departure of the superabundance of the blood received, and the pulse teaches this to us when we touch the aforesaid vessels in any part of the living body with the fingers".[26]

Aquelas observações conciliavam-se com a perspectiva de Leonardo de que o corpo humano (microcosmo) e a Terra (macrocosmo) seriam governados por leis mecânicas universais[1,3,11]. Deste modo, justificar-se-ia que os mares, as vias aquíferas por um lado, e o sangue e a vasculatura por outro, fossem equivalentes funcionais, respectivamente na Terra e no corpo humano, como reflecte no início das suas pesquisas anatómicas:

"By the ancients man has been called the world in miniature; and certainly this name is well bestowed, because, inasmuch as man is composed of earth, water, air and fire, his body resembles that of the earth; and as man has in him bones the supports and framework of his flesh, the world has its rocks the supports of the earth; as man has in him a pool of blood in which the lungs rise and fall in breathing, so the body of the earth has its ocean tide which likewise rises and falls every six hours, as if the world breathed; as in that pool of blood veins have their origin, which ramify all over the human body, so likewise the ocean sea fills the body of the earth with infinite springs of water".[27]

Inicialmente, Leonardo acreditava que o calor do Sol estaria na origem de todos os fenómenos que ocorriam no Mundo. Nessa perspectiva os fluxos líquidos dependeriam de variações térmicas; tal como na terra e nas plantas, o calor seria responsável pela elevação do sangue até aos locais em que arrefece, para se condensar e descer novamente até ao coração:

"The waters return with constant motion from the lowest depths of the sea to the utmost height of the mountains, not obeying the nature of heavier bodies; and in this they resemble the blood of animated beings which always moves from the sea of the heart and flows towards the top of the head; and here it may burst a vein, as may be seen when a vein bursts in

"At one and the same time in one and the same subject two opposite motions cannot take place, that is repentance and desire. Therefore, if the right upper [auricle] and lower ventricles are one and the same, it is necessary that the whole should cause at the same time one and the same effect, and not two effects arising from two diametrically opposite purposes."[25]

Around 1513, he observed that contraction and pulsation were linked, and compared them to the ebb and flow of the tides and to perfusion in plants:

"... the beating of the heart... generates a wave of blood through all of the vessels, which continually dilate, and contract. The dilatation occurs on the reception of the superabundant blood, and the contraction is due to the departure of the superabundance of the blood received, and the pulse teaches this to us when we touch the aforesaid vessels in any part of the living body with the fingers".[26]

These observations fitted in with Leonardo's view that the human body (the microcosm) and the Earth (the macrocosm) were governed by universal mechanical laws[1,3,11]. This explained why the tides and waterways on one hand, and the blood and the vasculature on the other, were functionally equivalent in the Earth and in the body respectively, as he noted at the beginning of his anatomical studies:

"By the ancients man has been called the world in miniature; and certainly this name is well bestowed, because, inasmuch as man is composed of earth, water, air and fire, his body resembles that of the earth; and as man has in him bones the supports and framework of his flesh, the world has its rocks the supports of the earth; as man has in him a pool of blood in which the lungs rise and fall in breathing, so the body of the earth has its ocean tide which likewise rises and falls every six hours, as if the world breathed; as in that pool of blood veins have their origin, which ramify all over the human body, so likewise the ocean sea fills the body of the earth with infinite springs of water."[27]

Leonardo initially believed that the heat of the Sun was the origin of all phenomena in the world. In this theory, flows of liquids would depend on thermal variations; as in the Earth and in plants, heat would be responsible for raising the blood to parts where it cooled, condensed and returned to the heart:

the nose; all the blood rises from below to the level of the burst vein. When the water rushes out from the burst vein in the earth, it obeys the law of other bodies that are heavier than the air since it always seeks low places".[28]

Ao interrogar-se por que razão, naquela perspectiva, a água no alto das montanhas não era tão abundante como ao nível do mar, Leonardo alterou os anteriores pontos de vista, considerando que o calor teria origem no centro da Terra, a partir do qual irradiaria para o exterior, pela água. A existência de fontes de água e de vapor nas montanhas apoiariam aquela ideia:

"Where there is life there is heat, and where vital heat is, there is movement of vapour. This is proved, inasmuch as we see that the element of fire by its heat always draws to itself damp vapours and thick mists as opaque clouds, which it raises from seas as well as lakes and rivers and damp valleys."[29]

Convicto da analogia entre o microcosmo do corpo humano e o macrocosmo Terra[12], Leonardo propunha que o calor essencial à vida resultaria do coração, o qual se comportaria como uma fornalha geradora de calor corporal[30]. Através da via da entrada, que funcionaria como chaminé, o ar chegaria aos pulmões para ser aquecido pelo coração e, depois, transportado pelos vasos sanguíneos a todo o corpo (*Fig. 6*). Em suporte desta difusão Leonardo defendia que todos os vasos provinham do coração e ramificavam-se como uma árvore (*Fig. 7*). Numa fase posterior, ao verificar a constituição muscular do coração, alterou a sua concepção de uma fonte estática de calor para um mecanismo dinâmico. Nesta perspectiva, o calor seria gerado pelo coração através da fricção do sangue em movimento:

"As the heat of the heart is generated by the swift and continuous motions made by the blood with the intrinsic friction caused by its churnings and also with the friction which it produces with the cellular wall…these frictions caused by the velocity of the viscous blood proceed to heat, subtilize and cause the blood to pass through…giving life and spirit to all the members into which it is infused"[31]

Ainda conforme os ensinamentos de Galeno, Leonardo admitia que o sangue era produzido no fígado, arrefecido nos pulmões, impulsionado pelo coração e consumido nos músculos; distinguiu-se de Galeno ao afirmar que o sangue não atravessava o septo interventricular e que todos os vasos

"The waters return with constant motion from the lowest depths of the sea to the utmost height of the mountains, not obeying the nature of heavier bodies; and in this they resemble the blood of animated beings which always moves from the sea of the heart and flows towards the top of the head; and here it may burst a vein, as may be seen when a vein bursts in the nose; all the blood rises from below to the level of the burst vein. When the water rushes out from the burst vein in the earth, it obeys the law of other bodies that are heavier than the air since it always seeks low places."[28]

Leonardo then wondered why, if this were true, the water at the top of the mountains was not as abundant as at sea level. This caused him to change his views and to propose that heat originated at the center of the Earth, from where it radiated outwards via water. The existence of springs and mists in the mountains supported this theory:

"Where there is life there is heat, and where vital heat is, there is movement of vapour. This is proved, inasmuch as we see that the element of fire by its heat always draws to itself damp vapours and thick mists as opaque clouds, which it raises from seas as well as lakes and rivers and damp valleys..."[29]

Firm in his belief in the parallel between the microcosm of the human body and the macrocosm of the Earth[12], Leonardo proposed that the heat essential to life comes from the heart, which acts as a furnace that generates the body's heat[30]. Entering by the airway, which functions as a chimney, air reaches the lungs and is then heated by the heart, from where it is carried via the blood vessels throughout the body (*Fig. 6*). To support this hypothesis, Leonardo argued that all the vessels originated from the heart, branching out like a tree (*Fig. 7*). Later, after discovering the muscular composition of the heart, he changed from the idea of a static heat source to a dynamic mechanism. In this view, heat would be generated by the heart through the friction of moving blood:

"As the heat of the heart is generated by the swift and continuous motions made by the blood with the intrinsic friction caused by its churnings and also with the friction which it produces with the cellular wall... these frictions caused by the velocity of the viscous blood proceed to heat, subtilize and cause the blood to pass through... giving life and spirit to all the members into which it is infused."[31]

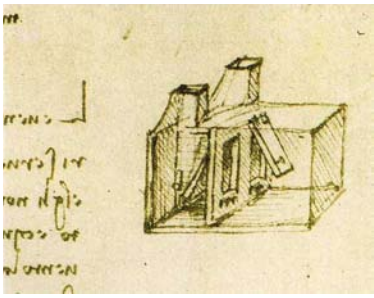


Fig. 6
Desenho de Leonardo, em que o coração é comparado a uma fornalha que aquece o ar proveniente dos pulmões, antes de o enviar para o resto do corpo. A entrada de ar nos pulmões e a sua saída do coração seriam reguladas por válvulas cardíacas. A traqueia e os pulmões funcionariam como uma espécie de chaminé para remoção dos fumos resultantes do aquecimento do ar pelos pulmões. (In Codex Arundel, fol. 24r; Courtesy of British Library)
Fig. 6
This drawing compares the heart to a furnace that heats the air coming from the lungs before sending it to the rest of the body. The entry of air to the lungs and its exit from the heart would be regulated by the cardiac valves. The trachea would act as a chimney to remove the fumes resulting from the heating of the air by the lungs. (In Codex Arundel, fol. 24r; courtesy of the British Library)

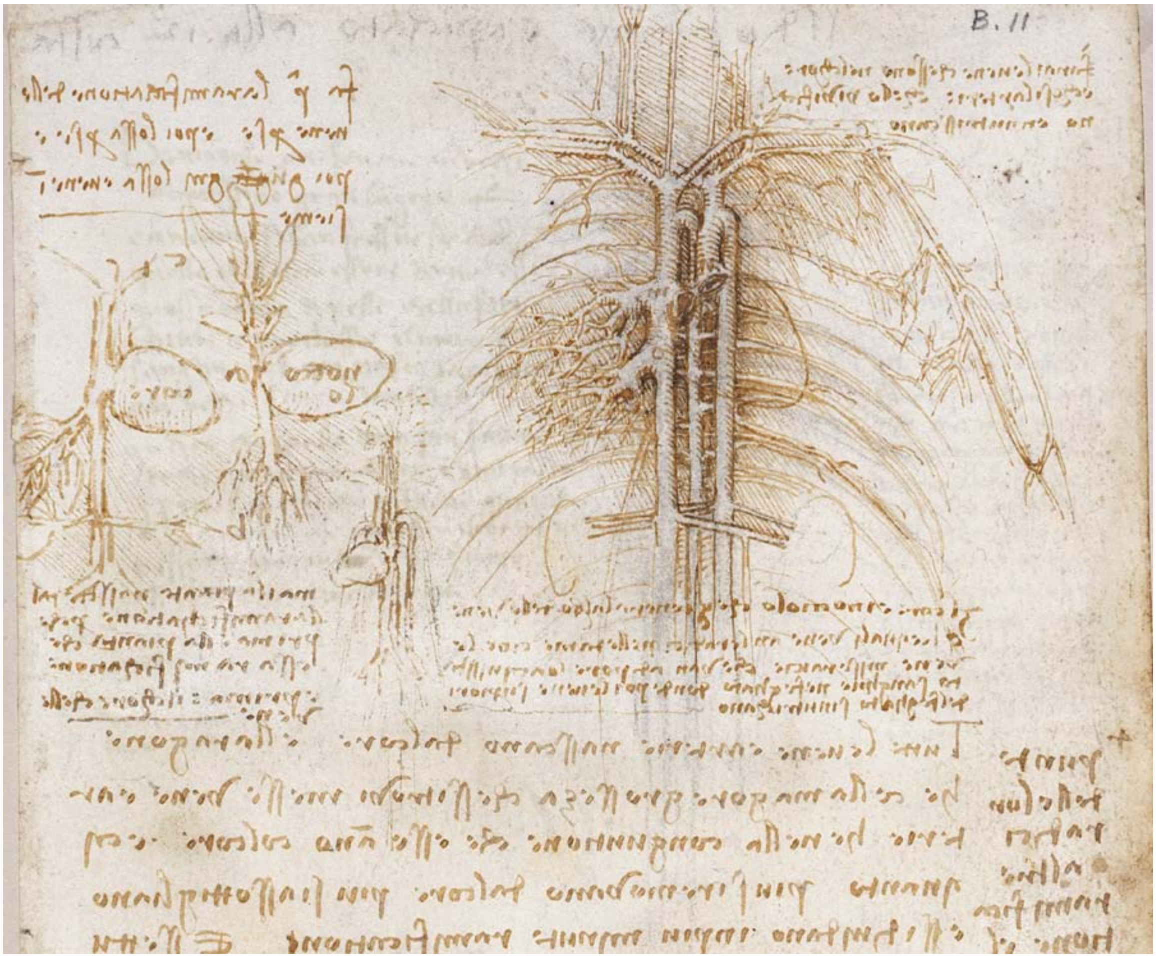


Fig. 7
Representação dos principais vasos do tórax em que o coração é comparado (no esquema da esquerda) a uma semente que, ao germinar, origina ramificações. Desenho a giz preto coberto à pena com tinta castanha (cerca de 1508; The Royal Collection 919028r). A parte inferior da mesma página contém as explicações que Leonardo redigiu com a mão esquerda, utilizando uma escrita de tipo oriental (da direita para a esquerda), codificada, sem pontuação nem acentos. Nessa anotação é explicada a dissecção do centenário (*del vecchio*), em que Leonardo observara a forma e posicionamento relativos do coração e dos principais vasos. Paradoxalmente, à medida que a meticulosidade das suas observações anatómicas se reflectiam no apuro das imagens desenhadas, Leonardo tende a completar os seus desenhos com descrições pormenorizadas e conceitos sobre o assunto. É o que sucede na página reproduzida, em que o desenho ocupa menos de metade da parte superior, sendo o espaço restante utilizado para explicações. Até então, em quase todos os assuntos, uma das características de Leonardo era a se expressar através dos desenhos, usando o mínimo de palavras. (Courtesy of The Royal Collection ©2007, Her Majesty Queen Elizabeth II).
Fig. 7
Representation of the main vessels of the chest, in which (on the left) the heart is compared to a seed that germinates and produces branches. Brown ink over black chalk, c. 1508 (Royal Collection, Windsor, 919028r).
In the lower part of the drawing are Leonardo's notes on the dissection of the old man, describing the shape and relative positions of the heart and the main vessels. Like all his notes, these are written from right to left (Leonardo wrote left-handed), in code, without punctuation or accents. Perhaps surprisingly, given the care with which Leonardo reproduced his meticulous anatomical observations in his drawings, he usually filled up the page with detailed descriptions and hypotheses on their subject-matter. This can be clearly seen in this page, in which the drawing occupies less than half of the upper part, the rest being taken up with notes. Until this time, Leonardo had usually expressed himself mainly through drawings, using a minimum of words, on almost all subjects.
(Courtesy of The Royal Collection ©2007, Her Majesty Queen Elizabeth II)

nasceriam do coração e não do fígado. Para acentuar esta última particularidade sustentava que o calibre (espessura) dos vasos diminuía do coração para a periferia, à medida que se ramificavam:

"All vessels arise from the heart. The reason for this is that the maximum thickness found in the veins and arteries occurs at the junction with the heart. The more removed they are from the heart the thinner they become and divide into smaller branches"[32].

Embora não chegasse a formular uma teoria para a circulação, Leonardo, pelo modo como relacionava o fluxo das águas e do sangue, teria uma concepção elaborada do sistema circulatório[32]. A favor desta hipótese referem-se ainda as seguintes anotações num dos seus cadernos:

"The artery and vein which in the old extend between the spleen and the liver acquire so thick a coat that it contracts the passage of the blood which comes from the mesenteric vessels, which blood passes through the liver to the heart and two great vessels (veia cava e aorta) and consequently through the whole body".[12]

Mecanismos cardíacos e observações hemodinâmicas - Leonardo conferia grande importância à aorta, a qual teria domínio sobre a vida de cada animal. O seu principal objectivo seria o de relacionar o funcionamento do coração e o das suas válvulas com o fluxo turbulento do sangue, a ser bombeado para a aorta; o sangue, depois de ultrapassar às válvulas aórticas, originava redemoínhos semelhantes aos observados nas correntes de água (*Fig. 8*):

"Observe the motion of the surface of the water which resembles that of hair, and has two motions, of which one goes on with the flow of the surface, the other forms the lines of the eddies; thus the water forms eddying whirlpools one part of which are due to the impetus of the principal current and the other to the incidental motion and return flow".[34]

Para interpretar o mecanismo de formação daqueles vórtices pós-valvulares, e apesar de considerar essa interpretação complexa e de difícil demonstração, Leonardo estabeleceu que os redemoínhos eram essenciais para o re-encerramento das válvulas, as quais actuariam passivamente no processo (*Fig. 8a*):

Although, in agreement with the teachings of Galen, Leonardo still believed that the blood was produced in the liver, cooled by the lungs, pumped by the heart and consumed in the muscles, he differed from Galen in claiming that the blood did not cross the ventricular septum and that all blood vessels arose in the heart and not in the liver. In support of this theory, he pointed out that the caliber or thickness of the vessels progressively diminished as they branched out from the heart towards the periphery:

"All vessels arise from the heart. The reason for this is that the maximum thickness found in the veins and arteries occurs at the junction with the heart. The more removed they are from the heart the thinner they become and divide into smaller branches."[32]

He never actually formulated a theory of circulation, but Leonardo's linking of the flow of water and of blood meant that he had a well-developed concept of the circulatory system[32]. The following extract from one of his notebooks backs this up:

"The artery and vein which in the old extend between the spleen and the liver acquire so thick a coat that it contracts the passage of the blood which comes from the mesenteric vessels, which blood passes through the liver to the heart and two great vessels [the vena cava and the aorta] and consequently through the whole body."[12]

Cardiac mechanisms and hemodynamic observations - Leonardo considered the aorta to be of great importance and to govern the life of all animals. His main objective was to relate the workings of the heart and its valves to the turbulent flow of blood being pumped to the aorta, and realized that after it passed through the aortic valves, it produced eddies similar to those seen in currents of water (*Fig. 8*):

"Observe the motion of the surface of the water which resembles that of hair, and has two motions, of which one goes on with the flow of the surface, the other forms the lines of the eddies; thus the water forms eddying whirlpools one part of which are due to the impetus of the principal current and the other to the incidental motion and return flow."[34]

Setting out to uncover the mechanism by which these postvalvular vortices were formed, a task he knew would be complex and difficult to

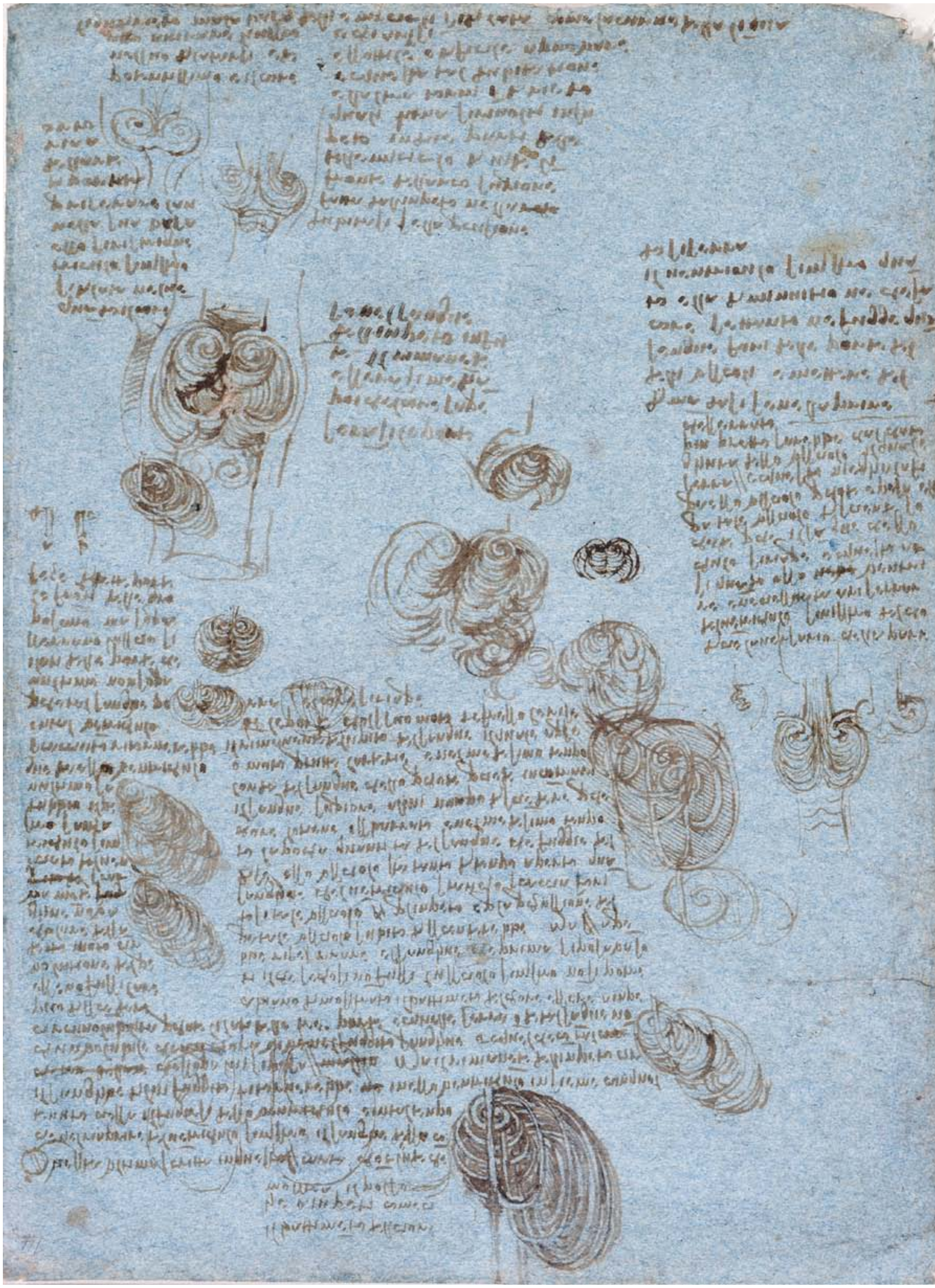


Fig. 8
Estudo dos redomínhos de sangue intracardíacos e na aorta ascendente. Desenho a tinta com pena, em papel preparado com coloração azul (cerca de 1516; The Royal Collection 919083v). No centro destacam-se diversos tipos de "ondas" sanguíneas direccionadas e redemoinhos com orientações opostas. Em aambos os lados, parece haver uma tentativa de explicar o encerramento da válvula aórtica pelo redemoinho pós-valvular (Fig. 8a). (Courtesy of The Royal Collection ©2007, Her Majesty Queen Elizabeth II).

Fig. 8
Study of vortices in blood flow inside the heart and in the ascending aorta. Pen and ink on blue prepared paper, c. 1516 (Royal Collection, Windsor, 919083v). In the center of the page various types of waves of blood flow can be seen, with eddies in the opposite direction. On the sides there appears to be an attempt to explain the closure of the aortic valve by postvalvular vortices.
(Courtesy of The Royal Collection ©2007, Her Majesty Queen Elizabeth II).

"This occurs so that the blood in the middle of the triangle directs (abertura aórtica) its impetus straight upwards and that which surges along the sides distributes its impetus by lateral motion, and percusses against the front of the arches of the hemicycles (aortic sinus), and follows the concavity of this hemicycle, constantly passing downwards, until it percusses against the concavity at the base of this hemicycle (concavidade das cúspidas) and then by reflected motion turns upward and continues to revolve upon itself with a circular motion until it expands its impetus..."[35]

Leonardo também observou que o fluxo do sangue ejectado para a aorta pela contracção cardíaca apresentava diferenças: a fracção mais central percorria uma maior distância na aorta ascendente do que a fracção adjacente às paredes, a qual, por seu lado, tendia a refluir até ao anel valvular. O sangue que refluía originaria uma especial turbulência junto das cúspides, que provocava o encerramento valvular antes da contracção ventricular seguinte. Sem aqueles redemoínhos ocorreria o colapso da paredes internas valvulares, o orifício de entrada não poderia encerrar e o refluxo de sangue, da aorta para o ventrículo, não teria força suficiente para encerrar a válvula (*Fig. 8a*):

"That the blood which returns when the heart opens again is not the same as that which closes the valves of the heart"[22]

Leonardo também verificou que as pregas valvulares da aorta faziam parte da parede aórtica, representando uma unidade funcional com capacidade para resistir duradouramente ao refluxo da onda sanguínea:

"the valves are constructed in association with the vessels immediately at the termination of the heart. … so that the reflected blood with its momentum might not tear away the membranes of which these valves are composed"[36]

Aquela unidade anatomo-funcional seria suficientemente elástica para se adaptar à contracção e distensão local:

"…this momentum…must expand in the membranes at the base of the vessels, does no damage to these valves, but is cast horizontally to beat against and expand with ease the tunics (paredes vasculares) in which the aforesaid momentum is expanded".[36]

demonstrate, Leonardo established that the eddies were essential for the valves to close, which only had a passive role in the process (*Fig. 8a*):

"This occurs so that the blood in the middle of the triangle [the aortic aperture] directs its impetus straight upwards and that which surges along the sides distributes its impetus by lateral motion, and percusses against the front of the arches of the hemicycles [the aortic sinus], and follows the concavity of this hemicycle, constantly passing downwards, until it percusses against the concavity at the base of this hemicycle [the concavity of the cusps] and then by reflected motion turns upward and continues to revolve upon itself with a circular motion until it expands its impetus..."[35]

Leonardo also observed that the flow of blood ejected into the aorta by the heart's contraction was not uniform: the more central portion traveled further up the ascending aorta than the portion moving along the walls, which tended to flow back to the valve annulus, where it gave rise to marked turbulence at the cusps that caused the valve to close before the next contraction of the ventricle. Without these eddies, the internal walls of the valve would collapse, the orifice would fail to close and the reflux of blood from aorta to ventricle would have insufficient force to close the valve (*Fig. 8a*):

"That the blood which returns when the heart opens again is not the same as that which closes the valves of the heart."[22]

Leonardo also discovered that the folds of the aortic valve were part of the aortic wall, which together made up a single functional unit that was strong enough to resist the force of the returning blood wave:

"the valves are constructed in association with the vessels immediately at the termination of the heart. ... so that the reflected blood with its momentum might not tear away the membranes of which these valves are composed."[36]

This anatomical and functional unit would have to be sufficiently elastic to adapt to local contraction and expansion:

"... this momentum... must expand in the membranes at the base of the vessels, does no damage to these valves, but is cast horizontally to beat against and expand with ease the tunics [vessel walls] in which the aforesaid momentum is expanded."[36]

Fig. 8a
Pormenor dos redemoínhos de sangue na aorta ascendente (referente a desenho 919083r). Leonardo terá visualizado a formação de redemoínhos na raiz da aorta e a configuração das cúspides valvulares nas fases de abertura e encerramento. Porém, não terá podido observar pormenorizadamente a situação, pelo que grande parte das conclusões obtidas (em especial a participação do refluxo aórtico no encerramento das válvulas aórticas, referida na mesma folha do original), terão sido baseadas em observações hemodinâmicas prévias sobre movimento. (Courtesy of The Royal Collection ©2007, Her Majesty Queen Elizabeth II).

Fig. 8a
Detail of drawing 919083r (Fig. 8), showing eddies in blood flow in the ascending aorta. Leonardo probably observed the formation of eddies in the aortic root, as well as the configuration of the valve cusps during opening and closure. However, he could not have examined them in detail, and so most of his conclusions, particularly the role of aortic reflux in closure of the aortic valve (which is mentioned on the same page), must have been based on his previous observations on hemodynamics. (Courtesy of The Royal Collection ©2007, Her Majesty Queen Elizabeth II).

Leonardo não terá observado *in vivo* os mecanismos descritos, pelo menos em pormenor suficiente, limitando-se a extrapolar os seus conhecimentos de hidrodinâmica para o que ocorreria no coração e, em especial, junto das suas válvulas. Porém, não se pode excluir que aquelas observações tenham sido realizadas em animais e, inclusivamente, fossem completadas em modelos especialmente concebidos para o efeito. Há a convicção de que Leonardo estudou o fluxo da água em tubos de vidro sob diferentes forças e resistências, na tentativa de reproduzir

Leonardo could not have observed these mechanisms in vivo, at least not in sufficient detail; he was merely extrapolating his knowledge of hydrodynamics to what went on in the heart, particularly around the valves. However, we cannot exclude the possibility that he made such observations in animals, as well as constructing models specially designed to illustrate the mechanisms. It is thought that he studied the flow of water in glass tubes subjected to different forces and resistances in his attempts to reproduce experimentally what he observed in rivers, with their bends, slopes, differing rates of flow, eddies, and surges[1,12].

In the margin of one of his drawings (*Fig. 9*), Leonardo sketched a glass model of the aorta (*Fig. 9b*), depicted the aortic valve in various positions, and drew the formation of postvalvular vortices (*Fig. 9a*). These eddies (and the closing of the valve) were equivalent to those that he described having observed produced by grass seed and other objects in currents of water:

"Make this test in the glass [this is thought to refer to a specially made model] and move inside it water and panic grass seed."[22]

Gharib et al. recently demonstrated that Leonardo's observations were correct[37]. They constructed a glass model (*Fig. 10*) similar to the one Leonardo drew, representing the left ventricular outflow tract, the valve annulus and the ascending aorta (*Fig. 9b*), and recorded the flow patterns generated (*Fig. 11*), with and without the valve, and showed them to be remarkably similar to Leonardo's predictions (or possibly observations)[37]. In the opinion of Kemp[3], Leonardo's diagram of the aortic root, recreated and tested by Gharib, is an astonishing example of a 'theory machine' that was based on anatomical observations, studies of moving water, and geometric concepts.

Leonardo's hypotheses concerning the characteristics of blood flow and reflow in the aorta and their contribution to the mechanism for opening and closing the valve have recently been confirmed by magnetic resonance imaging studies[38,40]. The complexity of flow in the aortic arch affects the endothelium and is associated with the sites at which atherosclerosis develops[41], while the blood does indeed move in a spiral in the aorta and great vessels[42].

Fig. 9
Estudos da válvula aórtica e do fluxo sanguíneo na aorta ascendente. Desenho a tinta com pena, em papel especialmente preparado com coloração azul (cerca de 1516; The Royal Collection, 919028r). Na metade esquerda da página (e Fig. 9a) são representados os esquemas do que sugere ser um estudo sobre o mecanismo da válvula aórtica ou de uma prótese válvular. De facto, no canto superior direito (e Fig. 9b) é representado o que parece ser um modelo da aorta ascendente e do anel valvular, que Leonardo se proporia a executar em vidro. Na metade inferior direita é esquematizado o fluxo sanguíneo através de válvulas aórticas, o trajecto de saída do ventrículo esquerdo e a formação de vórtices na aorta ascendente, junto do anel valvular. No topo da página, a meio, é novamente esboçada a raiz da aorta e, aparentemente, a disposição das paredes valvulares durante a abertura da válvula aórtica. A meio, à direita, é ainda representada a válvula mitral, com os músculos papilares e respectivos cordões tendinosos. (Courtesy of The Royal Collection ©2007, Her Majesty Queen Elizabeth II).

Fig. 9
Studies of the aortic valve and blood flow in the ascending aorta. Pen and ink on blue prepared paper, c. 1516 (Royal Collection, Windsor, 919028r). On the left half of the page (see Fig. 9a) are what appear to be studies of the mechanism of the aortic valve or an artificial valve. In the upper right corner (see Fig. 9b) is what appears to be a model of the ascending aorta and the valve annulus, which Leonardo planned to make in glass. At the bottom on the right, there is a diagram of blood flow through the aortic valve, the trajectory of the left ventricular outflow and the formation of vortices in the ascending aorta near the valve ring. At the top of the page, in the middle, there is another drawing of the aortic root and what appears to be the position of the valve cusps during opening of the aortic valve. In the middle, on the right, the mitral valve is also represented, with the papillary muscles and chordae tendineae. (Courtesy of The Royal Collection ©2007, Her Majesty Queen Elizabeth II)

experimentalmente o que observava nos rios, com as suas curvas, declives, diferenças de velocidades, redemoinhos e aluviões[1,12].

Nas margens de um dos esquemas (*Fig. 9*) Leonardo propôs um esquema em vidro representativo da aorta (*Fig. 9b*), desenhou a válvula aórtica em várias posições e esquematizou a formação de vórtices pós-valvulares (*Fig. 9a*). Estes redemoínhos, bem como o encerramento da válvula, seriam equivalentes aos que observara, segundo as suas palavras, pela trajectória de sementes de erva e outros objectos em correntes de água.

"Made this test is the glass (pensa-se que seja um modelo criado para o efeito) and move inside it water and panic grass seed"[22].

Mory Gharib demonstrou, recentemente, que as observações de Leonardo estavam correctas[37]. Para o efeito construiu um modelo em vidro (*Fig. 10*) semelhante ao que Leonardo desenhara, representando a via de saída do ventrículo esquerdo, o anel valvular e a aorta ascendente (*Fig. 9b*). Utilizando aquele modelo, Gharib e Cols registaram os perfis de fluxo gerado (*Fig. 11*), com e sem válvula, comprovando a sua extraordinária semelhança com as previsões (ou observações) de Leonardo[37]. Kemp manifestou a opinião de que o esquema da raiz da aorta esquematizado por Leonardo, recriado e testado por Gharib representa uma concretização espantosa de uma "máquina teórica", que seria baseado em observações anatómicas, estudos da água em movimento e conceitos geométricos[3].

As características do fluxo e refluxo sanguíneos na aorta, e a sua contribuição para o mecanismo de abertura e encerramento valvular, foram confirmados recentemente por ressonância magnética[38-40] A complexidade do fluxo no arco aórtico repercute-se no endotélio e estará associada à localização e desenvolvimento da aterosclerose[41]. Na aorta e nos grandes vasos o sangue movimenta-se sob a forma de um fluxo em espiral[42].

O padrão helicoidal (com tendência para uma rotação direita nos indivíduos normais) do fluxo sanguíneo sistólico observado na aorta (desde a raiz até à posição descendente), seria atribuível à curvatura da aorta. Porém, os redemoínhos pós-sistólicos localizados junto dos seios de Valsalva dependeriam mais das características hemodinâmicas do fluxo aórtico do que das suas

Fig. 9a
Representação esquemática da válvula aórtica (referente a desenho 919082r). (Courtesy of The Royal Collection ©2007, Her Majesty Queen Elizabeth II)
Fig. 9a
Diagram of the aortic valve (from drawing 919082r). (Courtesy of The Royal Collection ©2007, Her Majesty Queen Elizabeth II)

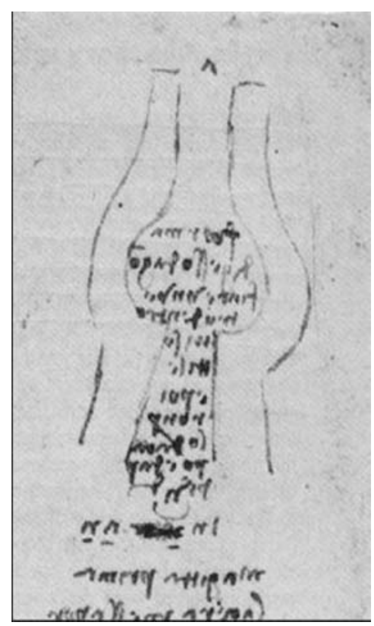
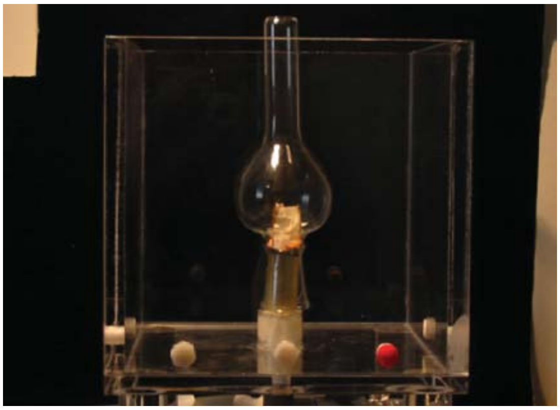
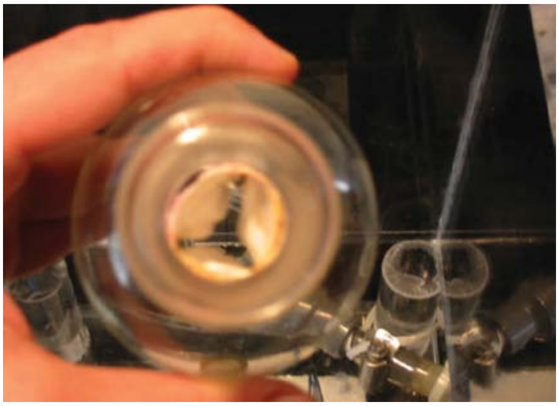


Fig. 9b
Pormenor em que é representado um modelo em vidro da saída do ventrículo esquerdo e aorta ascendente (referente a desenho 919028r). (Courtesy of The Royal Collection ©2007, Her Majesty Queen Elizabeth II)
Fig. 9b
Detail of drawing 919028r, showing the design for a glass model of the left ventricular outflow tract and ascending aorta. (Courtesy of The Royal Collection ©2007, Her Majesty Queen Elizabeth II)

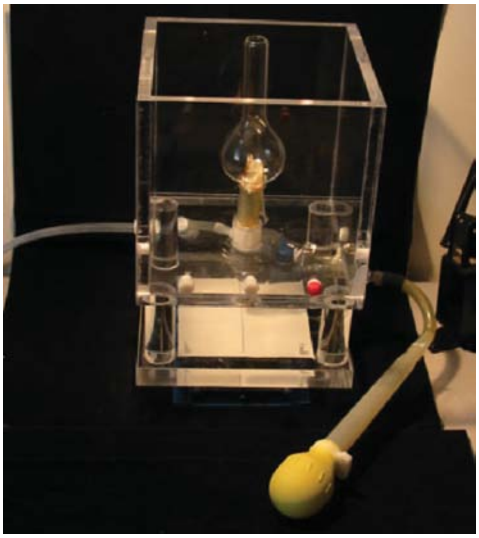
The helicoidal pattern of systolic blood flow in the aorta from the root to the descending portion, which tends to rotate to the right in normal individuals, is due to the curvature of the vessel.



(a)



(b)



(c)

Fig. 10
(a) Modelo em vidro que reproduz a raiz e o segmento ascendente da aorta, sendo a localização da válvula na base de ampola. Este modelo, concebido por Mory Gharib e Cols, reproduz o esquema de Leonardo descrito na Fig. 9b.
(b) Modelo da válvula aórtica do esquema anterior
(c) Aspecto global do sistema

(Courtesy of Dr. Mory Gharib, Hans W. Liepmann Professor of Aeronautics and Professor of Bioengineering, Garib Res Group, California Institute of Technology, USA).

Fig. 10
Glass model of the aortic root and ascending aorta, with the valve located at the base. This model, designed by Gharib et al., is based on the drawing by Leonardo in Fig. 9b.
(b) The aortic valve from the above model.
(c) Overall view of the system.

(Courtesy of Dr. Mory Gharib, Hans W. Liepmann Professor of Aeronautics and Professor of Bioengineering, Gharib Research Group, California Institute of Technology, USA).

propriedades geométricas ou mecânicas[40]. Nos indivíduos mais jovens o fluxo muda de direcção à medida que progride na aorta ascendente, ao mesmo tempo que origina um breve redemoínho e algum refluxo até junto da válvula aórtica. Este refluxo poderá contribuir para a perfusão das coronárias e ou reverter novamente para a onda sistólica que se desloca para a aorta descendente. Nos indivíduos normais a onda sistólica atinge a crossa da aorta num batimento, chegando à aorta descendente no seguinte. Nos indivíduos com doença aterosclerótica, ou durante o envelhecimento, as condições de fluxo são substancialmente diferentes[39]. Em ambos os casos há aumento do tempo de progressão do fluxo sanguíneo até à aorta descendente, sendo também mais rápido o fluxo retrógrado (*Figs. 12 e 13*), por vezes extensivo a todo o lume arterial, originando uma trajectória muito variável ou caótica no segmento proximal ou junto aos seios aórticos[39,43]. Estas modificações resultariam da perda de elasticidade da parede arterial[38,39], junto com a

However, the postsystolic vortices that occur at the sinus of Valsalva are due more to the hemodynamics of aortic flow than to the aorta's geometric or mechanical properties[40]. In younger individuals the flow changes direction as it travels up the ascending aorta, and gives rise to a short-lived vortex and some reflux to the aortic valve. This reflux may contribute to coronary perfusion and/or return to the systolic wave which is moving towards the descending aorta. In normal individuals the systolic wave reaches the transverse arch in a single beat and reaches the descending aorta on the following beat. However, flow conditions are significantly different in those with atherosclerotic disease and in old age[39]. In these cases the blood flow takes longer to reach the descending aorta, while retrograde flow is faster (*Figs. 12 and 13*) and can fill the entire arterial lumen, which causes highly variable or even chaotic flow in the proximal segment or at the aortic sinuses[39,43]. These changes result from loss of elasticity in the arterial wall[38,39], together with a

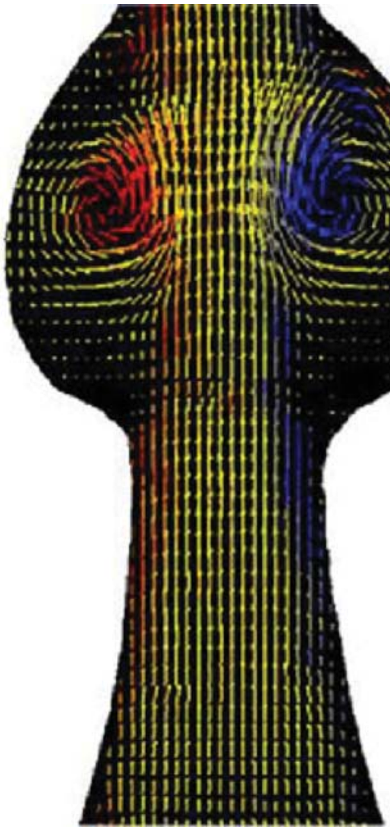


Fig. 11
Fluxo líquido com redemoínhos gerados pela técnica de imagem laser num modelo de vidro desenvolvido por M. Gharib e Cols, com base num esquema de Leonardo (Fig. 9b). O fluxo provém de um reservatório inferior que simula o coração, sendo impulsionado por bomba pulsátil conectada ao modelo de vidro. Utilizando iluminação laser laminar visualiza-se o traçado de partículas e correspondente padrão de fluxo. (Courtesy of Dr. Mory Gharib, Hans W. Liepmann Professor of Aeronautics and Professor of Bioengineering, Gharib Res Group, California Institute of Technology, USA).

Fig. 11
Liquid flow with eddies generated by laser imaging in a glass model developed by Gharib et al. based on a diagram by Leonardo (Fig. 9b). The flow comes from a reservoir positioned at a lower level that simulates the heart and is propelled by a pulsatile pump connected to the model. Laser sheet illumination is used to reveal the path of the particles, and thus the flow pattern. (Courtesy of Dr. Mory Gharib, Hans W. Liepmann Professor of Aeronautics and Professor of Bioengineering, Gharib Research Group, California Institute of Technology, USA)

tendência para alargamento da aorta e diminuição do débito cardíaco na cardiopatia aterosclerótica e com a idade[44]. Uma consequência importante das anomalias referidas no fluxo sanguíneo ao longo da aorta seria a redução da perfusão coronária, com a possibilidade acrescida da isquémia do miocárdio[39].

CONCLUSÕES

Leonardo, mais de um século antes da definição da circulação sanguínea por Harvey, esclareceu algumas questões fundamentais sobre a estrutura e funcionamento cardíacos, ao mesmo tempo que arredava um conjunto de ideias erradas ou míticas que persistiam desde a Antiguidade.

Designadamente, clarificou as seguintes questões:

- O coração não é a origem da "força vital (ou alma)";
- O coração é um músculo;
- O coração subdivide-se em quatro câmaras;
- A pulsação periférica é síncrona com a contracção do ventrículo esquerdo;

tendency for the aorta to widen, and with the reduced cardiac output in atherosclerotic heart disease and ageing[44]. An important consequence of these problems with blood flow along the aortic is a reduction in coronary perfusion, which increases the risk of myocardial ischemia[39].

CONCLUSIONS

More than a century before William Harvey demonstrated the circulation of the blood, Leonardo answered some fundamental questions about the structure and workings of the heart, while at the same time refuting a series of errors and myths that had persisted since antiquity.

Specifically, he showed that:

- The heart is not the seat of the "vital force" or soul;
- The heart is a muscle;
- The heart is divided into four chambers;
- The peripheral pulse is synchronous with the contraction of the left ventricle;
- The closure of the aortic valve results from the formation of vortices and currents generated as the blood passes through the structure of the aorta;

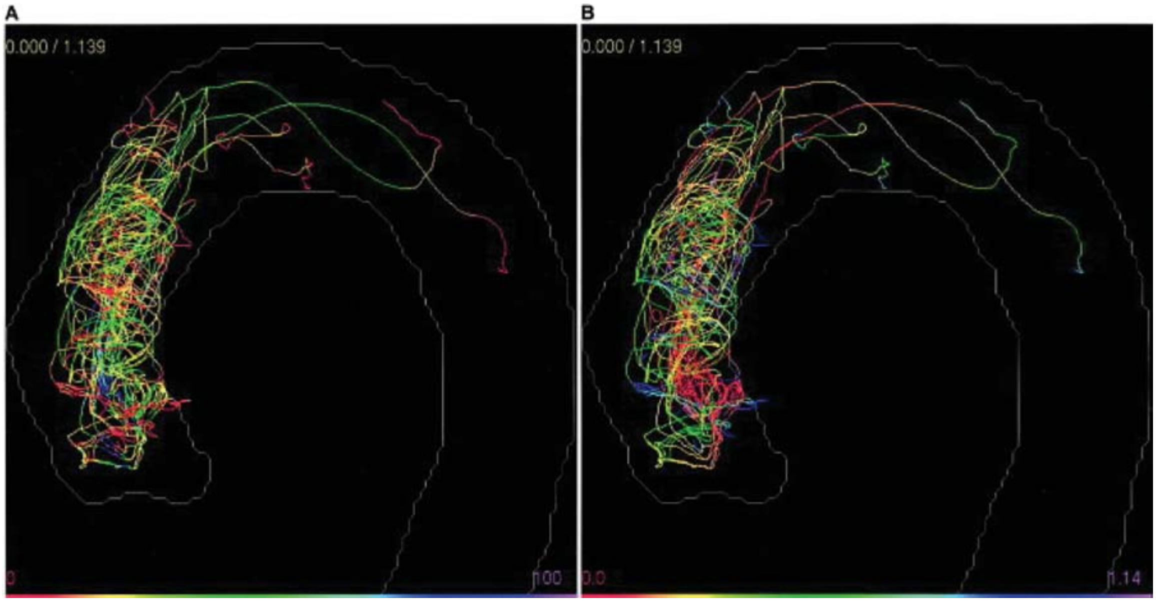


Fig. 12
Fluxo caórtico observado na aorta ascendente e seio aórtico de mulher com 62 anos. As particulas sanguíneas fluem da válvula aórtica para a aorta ascendente durante a sístole, após o que refluem em contra-rotação, divergindo em todas as direcções na aorta proximal e início da ascendente no fim da sístole e início da diástole. A: velocidade do fluxo é de cerca de 0,65 cm/segundo. B: Duração do intervalo RR, que evidencia fluxo desorganizado durante a diástole. In: Bogren HG, Buonocore MH, Valente RJ - Four - dimensional magnetic resonance velocity mapping of blood flow patterns in the aorta in patients with atherosclerotic coronary artery disease compared to age-matched normal subjects. J Magn Reson Imaging. 2004; 19:417-427 (Fig. 3). @2004 Wiley-Liss, Inc. "Reprinted with permission of Wiley-Liss, Inc., a subsidiary of John Wiley & Sons, Inc.

Fig. 12
A 62-year-old woman with chaotic flow in the ascending aorta and aortic sinus. Blood particles flow from the aortic valve to the mid ascending aorta in systole, then flow counterclockwise and diverge in all directions within the proximal and mid ascending aorta in late systole and early diastole. A: Speed image shows flow in range of 0-65 cm/second. B: Time-in-RR interval image shows disorganized flow throughout diastole. In Bogren HG, Buonocore MH, Valente RJ. Four-dimensional magnetic resonance velocity mapping of blood flow patterns in the aorta in patients with atherosclerotic coronary artery disease compared to age-matched normal subjects. J Magn Reson Imaging. 2004; 19:417-427 (Fig. 3). 2004 Wiley-Liss, Inc. (Reprinted with permission of Wiley-Liss, Inc., a subsidiary of John Wiley & Sons, Inc.)

- O encerramento das válvulas da aorta decorre da formação de redomoínhos e correntes geradas pela passagem de sangue pela estrutura da aorta;

- O revestimento interno das artérias aumenta de espessura com a idade, constituindo um risco para a saúde.

Leonardo também antecipou (em quase meio milénio) alguns dos conceitos tidos por fundamentais para a compreensão da fisiopatologia cardiovascular. A relação estabelecida entre a evolução da aterosclerose com a idade é um marco na epidemiologia das doenças cardiovasculares que, desde há cerca de oitenta anos, constitui uma preocupação constante das sociedades industrializadas. Igualmente, as suas conclusões sobre o fluxo sanguíneo na aorta ser consideradas referências pioneiras da hemodinâmica.

Entre outros exemplos dessa actualidade merece referência o trabalho de Francis Wells, cirurgião cardíaco do Papworth Hospital de

- The lining of the arteries thickens with age, which has an adverse effect on health.

Leonardo also anticipated, by nearly half a millennium, some of the concepts now accepted as fundamental to our understanding of cardiovascular pathophysiology. The relationship between the development of atherosclerosis and advancing age, one of the key concepts in the epidemiology of cardiovascular disease, has been a major concern in the industrialized world for the last eighty years. As a result of his deductions on blood flow in the aorta, Leonardo should also be considered a pioneer of hemodynamics.

Among other examples of his relevance to current knowledge is the work of Francis Wells, a heart surgeon at Papworth Hospital near Cambridge, UK, and co-author of an interesting article on Leonardo's cardiovascular research[45]. In a recent interview on the BBC, Wells revealed that Leonardo's drawings of the heart had inspired him and had helped him improve his surgical technique in repairing damaged mitral valves[46].

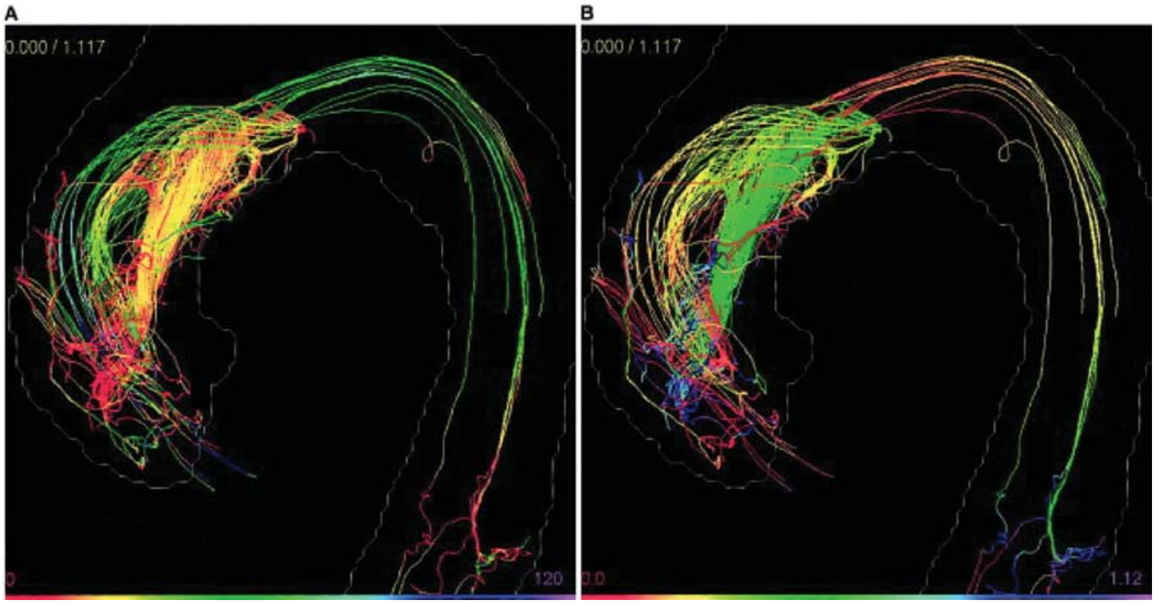


Fig. 13
Fluxo e refluxo sanguíneo na aorta ascendente de uma mulher de 69 anos com doença coronária. A: A velocidade máxima do fluxo é de 120 cm/segundo, sendo relativamente lento até meio da aorta ascendente (70 cm/segundo). O refluxo é de 25 cm/segundo ao aproximar-se da válvula aórtica. B: O trajecto das partículas sanguíneas revela rotação em sentido horário à medida que o fluxo progride na aorta ascendente, emtre o fim da sistole e o início da diástole. In: Bogren HG, Buonocore MH, Valente RJ - Four - dimensional magnetic resonance velocity mapping of blood flow patterns in the aorta in patients with atherosclerotic coronary artery disease compared to age-matched normal subjects. J Magn Reson Imaging. 2004; 19:417-427 (Fig. 2). @2004 Wiley-Liss, Inc. "Reprinted with permission of Wiley-Liss, Inc., a subsidiary of John Wiley & Sons, Inc.

Fig. 13
A 69-year-old woman with CAD. A: Speed image with maximum speed of 120 cm/second and color map shown at the base of the image. In the mid ascending aorta, the antegrade flow has a relatively slow speed (70 cm/second), while the retrograde flow has a relatively high speed (25 cm/second). B: Time-in-RR interval image (1 RR interval) with RR interval of 1.12 seconds and color map shown at the base of the image. The particle paths show antegrade flow of blood particles from the aortic valve to the distal ascending aorta, followed by a clockwise rotation and retrograde flow throughout late systole and early diastole in the mid ascending aorta. In Bogren HG, Buonocore MH, Valente RJ. Four-dimensional magnetic resonance velocity mapping of blood flow patterns in the aorta in patients with atherosclerotic coronary artery disease compared to age-matched normal subjects. J Magn Reson Imaging. 2004; 19:417-427 (Fig. 2). 2004 Wiley-Liss, Inc. (Reprinted with permission of Wiley-Liss, Inc., a subsidiary of John Wiley & Sons, Inc.)

Cambridge e co-autor de um notável artigo sobre as investigações cardiovasculares de Leonardo[45]. Em entrevista recente (largamente divulgada pela BBC News), Wells revelou que os desenhos do coração por Leonardo da Vinci haviam constituído para si uma fonte de inspiração, que o conduzira a melhorar a sua abordagem operatória na reparação de válvulas mitrais lesadas[46].

Alguns anos antes, Jean-Raoul Monties, presidente da International Society of Rotary Blood Pumps, sugerira que Leonardo da Vinci havia sido um membro precursor daquela Sociedade e dos seus objectivos primordiais[47]. Tendo em conta que as modificações do fluxo sanguíneo podem ser influenciadas pela viscosidade sanguínea total e/ou pelos parâmetros que a determinam[48-50], poder-se-á afirmar que Leonardo foi também um precursor da Hemorreologia.

Some years before, Jean-Raoul Monties, president of the International Society of Rotary Blood Pumps, suggested that Leonardo had been a "precursor member" of the society in his understanding of what became its basic aims. Bearing in mind that blood flow can be affected by whole blood viscosity and/or the factors that determine it[48-50], Leonardo could also be said to be a pioneer of hemorheology.

In such ways, the ancient continues to be modern, and it is no surprise that Leonardo's visionary genius continues is still alive in our times.

Neste contexto, em que o antigo continua a ser moderno, não surpreende que o génio visionário de Leonardo continue a fazer-se sentir nos nossos dias.

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