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Review

Leonardo da Vinci's studies of the heart

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ABSTRACT

Leonardo da Vinci's detailed drawings are justly celebrated; however, less well known are his accounts of the structures and functions of the organs. In this paper, we focus on his illustrations of the heart, his conjectures about heart and blood vessel function, his experiments on model systems to test those conjectures, and his unprecedented conclusions about the way in which the cardiovascular system operates. In particular, da Vinci seems to have been the first to recognize that the heart is a muscle and that systole is the active phase of the pump. He also seems to have understood the functions of the auricles and pulmonary veins, identified the relationship between the cardiac cycle and the pulse, and explained the hemodynamic mechanism of valve opening and closure. He also described anatomical variations and changes in structure and function that occurred with age. We outline da Vinci's varied career and suggest ways in which his personality, experience, skills and intellectual heritage contributed to these advances in understanding. We also consider his influence on later studies in anatomy and physiology.

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1. Introduction

Leonardo da Vinci (1452–1518 CE) is now regarded as "the most varied genius probably who ever lived" [1]. The life of this great artist and scholar was characterized by an itinerant existence, a unique career, and his interests – while being only formally trained in the fine arts – in various fields of science including engineering and human anatomy and physiology. Notably, and of interest from our point of view, da Vinci was intensely preoccupied with the issue of human morphology and function in the final period of his productive life. Combined with his talents, profound artistic ability, technical skills, creativity and immense pleasure in exploring new areas, this led to several remarkable discoveries in the history of medicine. Among approximately 800 anatomical illustrations made by da Vinci, a great number of drawings are devoted to the cardiovascular system [2]. Da Vinci claimed that he had dissected more than 10 human bodies in order to understand the blood vessels [2]. Doby attributed this drive to da Vinci's "irresistible attraction" toward mechanics and hydrodynamics.

Herein, we provide an account of da Vinci's life and his varied career and contributions that led to advances in understanding cardiovascular anatomy and physiology. Throughout the text, we outline ways in which his personality, experience, skills and intellectual heritage contributed to these advances, and ultimately, we consider his influence on later studies in anatomy and physiology. Owing to his significance in the history of art, medicine and engineering, da Vinci's life and work have been described in numerous sources [3–18], and the following biographical sketch is summarized from those sources.

2. Biography

Leonardo was born on April 15, 1452 in Italy; his father, Ser Piero di Antonio, was a wealthy notary [3–6]. His mother, Caterina, was a remarkably beautiful 16-year-old girl from a poor, lower-class family [6,7]. Sadly, Ser Piero and Caterina could not marry because of the difference in their social status [6,7]; his mother married another man just after Leonardo's birth [6]. Leonardo spent his earliest years in his mother's home in Anchiano [8]. At the age of five years, he entered his father's household in Vinci, Tuscany [8]. Therefore, he was known by the surname of "da Vinci" (literally meaning 'from Vinci'). The status of illegitimacy prohibited him from a formal education in the schools, so basic training had to be provided by his father, and for

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more than basic reading and writing he had to train himself in other subjects [6]. This probably led his childhood talents in art to promote.

When he was 14 years old, da Vinci was apprenticed to the eminent Florentine artist Verrocchio (Andrea di Cione), in whose workshop he was trained in art theory and a wide variety of technical skills [6,8,9]. Six years later, in 1472, he attained the status of master and joined of the Guild of St. Luke, a Florentine guild of artists, physicians and apothecaries, as a painter [8,9]. He continued to collaborate with Verrocchio, and was able to set up his own workshop in Florence [8,9]. It is not exactly clear when he left Verrocchio's studio, but in 1478 he had several independent commissions [9].

In 1482, Lorenzo de' Medici (also nicknamed Il Magnifico) commissioned da Vinci to give a gift, a silver lyre, to Ludovico il Moro, Duke of Milan [8], who was a patron of science and art. In 1485, da Vinci was appointed director of the Academy of Science and Art of Milan [10]. For the following 17 years he was largely based in Milan, working on a number of engineering, architectural and sculptural projects for Ludovico [3–5,8]. His mother, Caterina, came to live with da Vinci in Milan in 1493, and apparently he took care of her until her death in 1495 [6].

When Louis XI of France invaded Milan in 1499 and overthrew the dukedom, da Vinci (Fig. 1) – losing his patron – inevitably fled to Mantua and then to Venice [10–12]; in 1500, he returned to Florence [10] where he was welcomed by Filippino Lippi [13] and set up a new workshop in the monastery of Santissima Annunziata [8]. In 1502, he entered the service of Cesare Borgia, son of Pope Alexander VI, and developed his interests as a cartographer and military engineer [8]. He was issued a passport by Borgia to travel for six months in the region [14]. He spent the years 1503–1506 in Florence, and completed the Mona Lisa – "the most celebrated portrait of all time" [15]. Because of his fame as an artist, Louis XII welcomed him to the court and thus he returned to Milan [15]; he had to visit Florence several times to resolve difficulties arising from his father's estate; his father had died leaving his half-brothers to challenge him over his inheritance [6]. During his second stay in Milan, da Vinci performed most of his anatomical works [15]. The French rulers of Milan were defeated in 1513 [15], and da Vinci next moved to the Vatican. The circumstances in Rome, however, were not favorable; he was too obsessed with anatomy [16], and his relationship with Michelangelo did not go well [10]. His privacy was also violated by a German mirror-maker [17] who accused him before the Pope of evocation of the dead and necromancy [18] and he was subsequently prohibited from conducting his anatomical works at the hospital [18]. But fortunately, da Vinci met King Francis I in Italy, and in 1519 accompanied him to France where he was entitled to receive an annual salary of 700 crowns [10]. However, his health condition did not allow him to conduct genuine work in France [10]. At the end of his life, he was gifted a manor in France by the French king; his death in the arms of King Francis I was painted by Ménageot and Ingres [8].

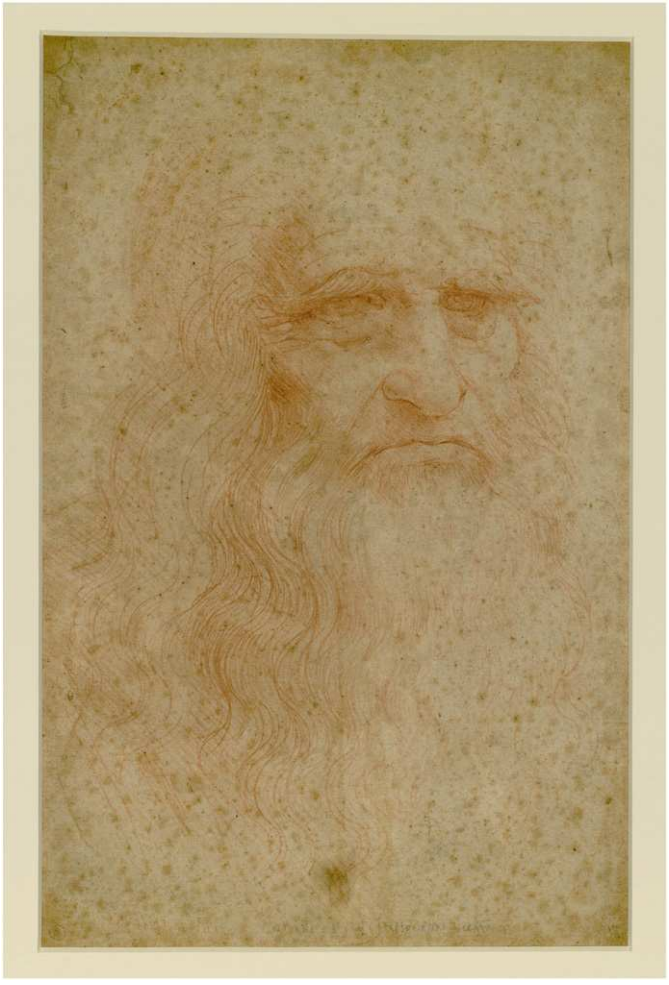


Fig. 1. A self-portrait of Leonardo da Vinci, reproduced with written permission ("Su concessione del Ministero per i Beni e le Attivita Culturali — Biblioteca Reale — Torino", Courtesy of the Ministry of Heritage and Culture — Royal Library — Turin, Italy).

Among the numerous published studies of da Vinci (Fig. 2), many have focused on his contributions to medicine and natural philosophy, later dubbed 'science' (e.g. [5,19–22].). His plans to publish his notebooks were not realized during his life or for fifty years after his death. His anatomical drawings were highly praised by William Hunter in 1784 and some were published in 1883 [23] and 1916 [24]. All the notebooks that survived were collected and meticulously edited by Keele (1979–81), who has published a number of scholarly accounts of da Vinci's contributions to anatomy, with particular emphasis on his studies of the heart and blood vessels [24–27].

In the subsequent sections, we review the motivation and significance of da Vinci's drawings and descriptions of the heart. We begin with an overview of the beliefs about the heart and blood vessels in medieval and early Renaissance Europe, and then summarize the new discoveries revealed by da Vinci's drawings and notes. In the succeeding section, we discuss the influences that led him to such a radical departure from accepted beliefs. In the final substantive section of the text, we consider the influence of da Vinci's discoveries about the heart and blood vessels on his contemporaries and successors, and the significance of his work for us today.

3. Da Vinci's intellectual heritage: beliefs about the heart in medieval Europe

The timeline of major historical discoveries in the anatomy and physiology of blood circulation is given in Table 1. Those closely relevant to the present article are discussed in some detail. Medieval Europe accepted Galen's teaching about the heart and the blood vessels. This had four major aspects [30]: First, venous and arterial blood differ and are separate; venous blood is created by the liver and nourishes the tissues, whereas arterial blood transports vital spirits to the body from the heart. Secondly, the pulmonary vein is not a blood vessel but supplies pneuma/spirits from the lungs to the arterial blood and evacuates its 'sooty vapours.' Thirdly, diastole is the active phase of the cardiac cycle, sucking blood out of the veins. Fourthly, venous blood passes from the right to the left heart through invisible pores in the interventricular septum. According to this view, the heart was the seat of the vital force and of the soul, so it could not be merely a muscle. The statement "All the arteries [emanate] from the heart, all the veins from the liver" is attributed to Nicolaus of Salerno [41], of whom little is known except that he flourished around the middle of the twelfth century CE.



Fig. 2. Leonardo da Vinci on a bronze medal signed by Baltazar. The reverse side of the medal reads "Italian Sculptor, painter, musician, engineer, physicist, writer and architect". da Vinci was an institution in himself.

Galen's anatomical work had become familiar in Europe through Avicenna's *Canon of Medicine*, first translated into Latin in its entirety in the 13th century, allegedly by Gerard of Cremona [31,33,42,43]. During the last 30 years of the 15th century, the *Canon* passed through 15 Latin editions [42]. Avicenna accepted the Galenist account of the circulation, including the idea of minute perforations in the ventricular septum; nevertheless, he had some grasp of the cardiac cycle and the function of the valves [32], and he also described vasovagal syncope and carotid sinus hypersensitivity [33]. The profusion of commentaries on the *Canon* available in Italy when da Vinci began his anatomical studies entrenched the Galenist account of anatomy and physiology [42].

Mondino de Luzzi (c. 1270–1326 CE) was noted for performing his own dissections, with Vatican approval, when he taught anatomy at the medical school of Bologna. He described the heart as comprising three ventricles: right, left and a middle ventricle within the septum. The right ventricle drew blood that originated in the liver, as taught by Galen, and conveyed it to the lungs. He recognized the tricuspid valve and also the link to what we now call the pulmonary vein, through which – again in accordance with Galenist teaching – vapor passed. Mondino's description of the vena cava ('vena chili') was more accurate than any earlier account [44].

Table 1
Contribution of some authorities to the anatomy and physiology of the heart and blood circulation from the ancient times to the 18th century A.D.

Authority	Discovery or contribution	Century	Reference(s)
Aristotle	He gave an accurate description of cardiovascular anatomy based on his observation on animals.	4th B.C.	[28]
Herophilus	He described the anatomy of the cardiac valves.	4th to 3rd B.C.	[29]
Erasistratus	He described how heart valves function to prevent retrograde flow of blood from the aorta.	3rd B.C.	[29]
Galen	His teachings were followed in medieval Europe. (see text)	2nd A.D.	[30]
Rhazes	He refuted the idea that a bony structure existed at the base of the heart.	9th to10th A.D.	[31]
Avicenna	He had an insight into blood circulation, cardiac valvular function, and systole and diastole.	11th A.D.	[32,33]
Ibn Nafis	He was the first to describe the pulmonary circulation.	13th A.D.	[34]
Leonardo da Vinci	He first described the moderator band of the right ventricle; he noted the importance of eddy currents in the aorta for valvular closure. (see text)	15th to early 16th A.D.	[23–27, 35]
Andreas Vesalius	He doubted the existence of pores in the interventricular septum, but did not clarify another route for transfer of blood between the ventricles.	16th A.D.	[36]
Michael Servetus	He refuted the notion that a communication exists between ventricles; noted that blood travels from the pulmonary artery to the pulmonary vein through small channels between them where mixing of blood with air (thus, spirit) takes place.	16th A.D.	[37–39]
William Harvey	He expounded upon blood circulation in its modern sense in his book, *De Motu Cordis* (On the Motion of the Heart and Blood).	Late 16th to mid-17th A.D.	[40]

4. Da Vinci's discoveries

Da Vinci considered the heart "an admirable instrument invented by the Supreme Being" [45]. Although da Vinci did not envisage a unified circulatory system as Harvey was to do more than a century later, his discoveries unsettled belief in the Galenist perspective. He began to investigate the heart and circulation during the 1490s and his studies culminated in the drawings and descriptions he produced in Milan (1508–1513) [46,47]. The Royal treasury of the Queen of England has a series of da Vinci's illustrations of the heart and vascular system, on ten bluish papers, with accompanying notes [48] (Fig. 3). These notes have been interpreted and translated by O'Malley and Saunder [49]. Da Vinci's earlier studies were conducted on pigs and oxen, but he subsequently dissected human cadavers (the number is uncertain but is variously reckoned at 19–30) [50,51]. In a nutshell, da Vinci believed that the heart had four chambers, one upper (atrium) and one lower (ventricle) on either side, and that the upper and lower chambers were separated by orifices and sinewy membranes, i.e. leaflets [49]. Interestingly, he noted the presence of a passage between the right and left atria in some cases; however, he erroneously followed Aristotle and Galen by attesting to the existence of a porous interventricular septum through which blood could pass between the ventricles. His most important findings were as follows.



Fig. 3. An illustration from da Vinci's collection showing the cardiac valves, chordae tendineae, and papillary muscles (Supplied by Royal Collection Trust/©HM Queen Elizabeth II 2012 — reproduced with written permission).

1. Da Vinci's notions of the cardiac cycle and asynchronous contraction and dilation of the atria and ventricles were original. He appears to have been the first investigator to recognize the functional significance of the auricles (though both Avicenna and Mondino had described them) and to declare that the heart has four chambers. He saw a clear functional distinction between the cardiac atria and ventricles: when the ventricle contracts, the atrium dilates and vice versa. He noted that the cardiac atria are more distensible and compliant than the ventricles. He mentioned the opening, contraction and closure of ventricles (diastole, systole and end-systole) as successive phases of cardiac motion culminating in the generation of heat. Although the latter represents the medieval concept of vital life energy (or intrinsic heat necessary for viability), it is interesting that da Vinci attempted to provide a mechanistic view of this concept. Therefore, da Vinci did not reject the Greek notion that the heart heats the blood. Instead, he attempted to reconcile his mechanical view with the traditional belief.
2. He showed that the heart is a muscle, and thereby challenged the Galenist view that it is the source of vital spirits; he showed that the fibers ran in different directions and could contract by themselves, stretching in proportion to the amount of blood entering the organ, almost anticipating Starling's law [52]. He showed that the heart exerts force by contraction, so the active part of the cycle is systole, not diastole. This alone was a radical departure from Galenism.
3. He also showed that the heart does not draw air into itself from the lungs, as Galen had taught, thereby contradicting Galen's opinion about the function of the pulmonary vein [24].
4. He was the first investigator to deduce the importance of eddy currents in the blood in the mechanism of valve closure [24]. He found that the open valve had a triangular orifice, and showed that the flow rate was highest at the center of the orifice. The valve shape generated three eddy currents in the aorta, running along what were later called the sinuses of Valsalva, forcing the valve to close [24]. These eddy currents are clearly illustrated in his drawings, which inspired more recent ideas about the mechanism of aortic valve closure after ventricular systole [53,54].
5. He gave us the earliest known drawings of the coronary arteries, following them in detail to the right and the left into the heart muscle and showing that they 'crowned' the heart [55]. His minute anatomical description of the aorta was wholly new [56].
6. He argued for a more unified view of blood vessels: "All the veins and arteries arise from the heart. The reason for this is that the maximum thickness found in the veins and arteries occurs at the junction which they make with the heart. The more removed they are from the heart, the thinner they become and divide into smaller branches" (quoted in [20]). It is widely believed that he recognized or at least predicted the evidence of capillaries, subsequently assumed by Harvey and confirmed by Malpighi's microscopic studies 150 years later [57].
7. His studies on old and young bodies provided an insight into arterial disease in the elderly. "The artery and the vein, which in the old extend between the spleen and the liver, acquire so great a thickness of skin that it contracts the passage of the blood …" (quoted in [19]). "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" (quoted in [51]). Martins e Silva speculates that in this section of his notes, da Vinci may have been referring to pulsatile blood flow [51].

8. Found among his notes is a description that according to O'Malley and Saunder reflects da Vinci's observation of a patent foramen ovale [49]: "I found from the left chamber to the right chamber a perforating channel, which I note here to see whether this occurs in other auricles [atria] of other hearts" (p. 244). This attention to the potential variability of morphological findings is unique for da Vinci's time. The concept of human anatomical variations remained to be elaborated upon by later European anatomists of the sixteenth and seventeenth centuries.
9. Da Vinci was the first to describe the trabecula septomarginalis or moderator band of the right ventricle. This intraventricular muscle trabecula is also known as Reil's band, but Sudhoff proposed the term "Leonardo's band" [35].

Nevertheless, da Vinci sustained the Galenic belief that blood was produced in the liver, cooled by the lungs and consumed by the muscles. He regarded the heart's primary function as heat production. In keeping with the Galenist account of blood movement, he attributed death due to atherosclerosis to the adhesion of nutrients to the walls of vessels leading from the digestive tract [58]; and he noted the increasing length and convoluted character of blood vessels in the elderly, which he explained in hemodynamic terms [58]. Notwithstanding his mechanistic view of the heart and his scientific approach to documenting his observations, the elements of the Aristotelian system of physiology recur in da Vinci's works. Typically, his mention that the lung functions as the coolant for the heart and blood recalls Aristotle's *Historia Animalium* and *De Partibus Animalium*.

5. Da Vinci's influences

5.1. Artistic ability

When he studied art in Verrocchio's bottega in Florence, the young da Vinci learned topographical anatomy [21]. Later, he pursued more detailed observation through dissection, using his precise artistic skill to record exactly what he saw. His descriptions were clear and succinct but he placed great reliance on his pictorial representations of anatomical structures: "With what words, O writer, can you with like perfection describe the whole arrangement of that of which the design is here? … How in words can you describe this heart without filling a whole book? Yet the more detail you write concerning it, the more you will confuse the mind of the hearer" (quoted in [55]).

5.2. Established beliefs and contemporaneous anatomical investigations

Da Vinci was influenced by the writings of Mondino and Albertus Magnus, who had commented on Avicenna [46,52]; his studies on the heart (1508–1513) were initially based on Mondino's, but were informed by collaboration with the anatomists at the Universities of Padua and Bologna, Marcantonio della Torre (1481–1511) and Jacopo Berengario da Carpi (1460–1530). Da Vinci's acquaintance and collaboration with Berengario and della Torre made him receptive to new ideas in anatomy [26]. The death of della Torre, with whom he collaborated closely, might have prevented the publication of these studies [59].

The late 15th century saw more frequent and more expert dissections by anatomists. These did not initially change the medieval viewpoint, but they raised questions about the relationship between arteries and veins. Berengario wrote[60]: 'There are many arteries and veins imperceptible to the senses.' Berengario suggested that the two systems were complementary [60]: 'There is no artery without its vein to accompany it. Thus, the artery may keep the vein alive, and the vein may give blood to the artery in its needs, the blood by which the vital spirit is made and the artery itself is nourished.' Berengario produced the first illustrated anatomical text and also published an edition of Mondino's book [60]. His interest in what we now term the cardiovascular system was evident, and da Vinci shared it.

5.3. Linguistic limitations

Da Vinci struggled to teach himself Latin and never mastered Greek or Arabic [55], which limited his reading of classical literature. As a result, he might have been less strongly influenced by the predominant ideas of the age: "I am fully aware that the fact of not being a man of letters may cause certain arrogant persons to think that they may with reason censure me, alleging that I am a man ignorant of book learning. They will say that because of my lack of book learning I cannot properly express what I desire to treat of. Do they not know that my subjects require for their exposition experience rather than the words of others?" (quoted in [21]).

5.4. Macrocosm and microcosm

He also exploited the analogy between macrocosm and microcosm: "Thus in fifteen entire figures you will have set before you the microcosm on the same plan as, before me, was adapted by Ptolemy in his Cosmography; and so I shall afterwards divide them into limbs as he divided the whole world into provinces; then I will speak of the function of each part in every direction, putting before your eyes a description of the whole form and substance of man, as regards his movements from place to place, by means of his different parts" (quoted in [50]).

This principle was applied particularly to an analogy between water flow in rivers and the flow of blood through the heart valves [22,24,61]: "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" (quoted in [51]).

5.5. Engineering skill

Da Vinci saw the world in terms of mechanical effects rather than occult influences: "Force with material movement and weight with percussion are the four accidental powers in which all works of mortals have their being and their end… I have drawn up the rules of the four powers of nature without which nothing through her can give local movement to these animals" (quoted in [24]). These principles underpinned his remarkable skill as an engineer, and he used them to expound rational relationships between anatomical structures and functions [62]. Around 1508, coinciding with the start of his anatomical studies of the heart and major blood vessels, he also began an intensive study of water flow [63], which provided an analogy for his account of the hydrodynamics of blood pumping [64]. For this purpose, he obtained wax casts of the heart and the aorta, and on the basis of their detailed structure he constructed a glass model of the aorta and its valve opening from the ventricle to study the functions of the parts, tracking the patterns of fluid movement with dyes or suspended grass seeds. Using this model, he described the vortices formed when blood is forced between the cusps of the valve, and

offered an explanation for the phenomenon based on his studies of water flow in rivers [27]. He acknowledged that his explanation was incomplete, but he established the importance of circular fluid motion for valve opening and closure, predicting that the inner walls of a valve would collapse if the vortices were not formed: "The time interval between two beats of the pulse is half of a musical tempo. Between one and the next beat of the pulse the heart closes twice and opens once, and between one and the next opening the heart opens twice and closes once… Accordingly in every harmonic or, we might say, musical tempo, the heart has three motions…" (quoted in [20]).

5.6. Did Ibn al-Nafis also influence da Vinci?

The remarkable work of Ibn al-Nafis in the 13th century has been described in a number of recent sources [33,65–68]. Nafis described the pulmonary and coronary circulations and gave the first correct description of the pulse [33,34,66]. Ghalioungui summarizes his departures from Galen and Avicenna [65]:

1. He denied the existence of pores in the interventricular septum.
2. He showed that blood flowed from the right ventricle to the lungs, and from there to the pulmonary vein 'to mix with air.' There may have been a premonition of the idea of capillaries in this observation.
3. The blood–air mixture passes from the lung into the left ventricle, not the other way around.
4. There are only two ventricles, not three as Avicenna claimed.
5. There are vessels that specifically supply nutrient to the heart; the heart is not nourished from blood in the right ventricle, as Avicenna and Galen had said.

In view of da Vinci's discovery of the coronary arteries, his anti-Galenist view of the pulmonary vein and the assertion that there are two not three ventricles, it may be supposed that he was influenced by Ibn al-Nafis. Indeed, Ghalioungui has argued cogently for the influence of Nafis on later Renaissance anatomists, notably Michael Servetus, whose description of the pulmonary circulation influenced Harvey [65]. However, there is no evidence that da Vinci was acquainted with Nafis, whose work was not available in Latin and would therefore not have been accessible to him. Certainly he did not advance any clear idea of a pulmonary circulation. We are therefore inclined to believe that he independently rediscovered much of what Nafis had described almost three centuries earlier.

6. The later influence of da Vinci's study of the heart and blood vessels

The Galenic theory of blood movement persisted after da Vinci's death. Vesalius continued to regard the arterial and venous systems as separate, though having refuted the idea that the septum was porous, he had started to wonder how venous blood was able to enter the arteries [36]. Nevertheless, it was da Vinci's recognition of the structure of cardiac muscle that inspired Vesalius's account of the *Machina Carnis* and the mechanistic model proposal of Descartes [69], and foreshadowed the perception of the heart as a rotary pump [45]. The mechanistic link between anatomy and physiology is rooted in da Vinci's work.

The importance of the eddy currents in the sinuses of Valsalva for closing the aortic valve has been confirmed during the past two decades [70]. Bellhouse and Bellhouse designed an artificial model of the aortic valve and examined its function in tubes with and without sinuses (external bulge above the valve cusp) [53]. With cyclic flow, high-energy vortices were generated around the valve with a sinus, and the valve closed with minimal regurgitation. In contrast, the valve without a sinus failed to close until 23% of the forward flow had been rapidly reversed. The authors gave due credit to da Vinci for the idea. Da Vinci's description of valve structure has subsequently provided inspiration for surgical repair and the design of prosthetic valves [71,72]. The glass model of da Vinci was reconstructed by Gharib et al. [73] and it functioned almost exactly as da Vinci had stated, and his hydrodynamic mechanism of valve closure and spiral blood flow in the aorta has been corroborated by magnetic resonance imaging and fluid dynamic studies [74–77]. More generally, his drawings have formed the basis for recent 3D virtual models of the heart and aorta [78]. Da Vinci's understanding of the importance of valve shape (notably the mitral valve) has proven valuable for modern cardiologists such as Francis Wells [79].

Notwithstanding his acceptance of Galenic anatomy, da Vinci might have had the correct insight into blood circulation [54]. However, Wells believes that the relevant information has probably been lost to us or da Vinci might have been "so busy with other things" that he was unable to elaborate upon all his discoveries; or perhaps his alleged discovery of the circulation "was withheld by the Church" [54]. In fact, the second conjecture may have some validity, because Klein gives us a vivid description of da Vinci's scientific attitude [48]: "Leonardo was pursuing so many interests that he could rarely take full advantage of his chance to solve any particular problem; he simply lacked the time to do so. In cases where an additional experiment would have given him more precise information, he was already moving on to the next unknown territory. And because he was working for himself, rather than for others, he did not devote much time to the issue of publishing his findings" (pp. 183–4).

Most of da Vinci's artistic and scientific works remained unfinished when he died; Solmi (as cited by [80], p. 17) also describes him as having an "unrequited desire to understand everything surrounding him, and with cold reflection to discover the deepest secret of everything." The elements of perfectionism and procrastination in da Vinci's life are more reminiscent of mood disorder, compulsive personality or passive–aggressiveness. Notably, Freud gave an interesting psychoanalytical account of da Vinci's personality, which now stands as one of the first examples of psychoanalysis based on childhood memory [80,81]. Freud perceived two phases in da Vinci's life, an early phase of productivity and a late phase of indifference and slowness, with his lack of desire for the opposite sex and obsession with the same sex. On the basis of da Vinci's childhood memories, Freud theorized that da Vinci's strong investigative impulses were rooted in his infantile sexual curiosities toward his young, single mother, which escaped the inhibitions of thought and compulsive reasoning and were completely transformed into a compulsion to investigate. So, perhaps da Vinci's psychiatric issues were the main barrier to his scientific activities.

Although da Vinci had insights into cardiac anatomy, physiology and blood circulation, which demonstrated differences from those of his predecessors, his writings do not depart radically from the belief that blood was made in the liver, cooled in the lungs, pumped by the heart and consumed in the muscles. Nevertheless, he made some other very important discoveries (as described earlier), which nowadays appear straightforward but were not at that time. Da Vinci had obtained evidence that could have led him to discovery of the blood circulation if he had continued his anatomical and physiological studies, but he left his investigations and writings unfinished.

7. Conclusions

Although da Vinci did not accept the modern (Harveyan) idea of blood circulation, his work was an essential step towards that idea [82]. He introduced visual images as a standard method for conveying knowledge, reasoning as an artist that 'true knowledge of the shape of any body will be attained by seeing it from different aspects' [83]. Model making played an essential part in this style of presentation. He pioneered a radically new approach to anatomical drawing, with his principles of layers, transparency, sections and cutaways, integrating our understanding of superficial and internal features [50,83]. By

applying the mechanical principles of engineering to the study of organs, he also pioneered a new approach to physiology, and he saw anatomy and physiology as intimately related. Nowhere are these fundamental departures from tradition more evident than in his studies of the heart.

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