Leonardo Da Vinci, the Great Innovator in Cardiovascular Biomechanics

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Abstract. Five hundred years after his death, the figure of Leonardo da Vinci continues transmitting his tireless desire to know and learn. *Leonardo* is the symbol of a century in which progress impacted, shattering the thickness of dogmas. In the *Quattrocento*, the doors were definitely opened, ideas spread and still feed us, clear our path and enlighten us. Florence, in Leonardo's time, was the Silicon Valley of the Renaissance. Leonardo studied the dynamics of water flow in rivers, using colors to show the flow patterns, thus defining the continuous stress on the side walls of the river. He determined, with different colors, the flow characteristics in the center and near the edges of the rivers and extrapolated those findings to the blood that flows in the arteries. Leonardo studied the coronary artery and veins, heart and bronchia in detail and made several assumptions about the cause of atherosclerosis, based on his previous hydrodynamic studies of water flow. Leonardo theorized that diseases were derived from some imperfection in the structure of the human body and addressed the issue of atherosclerosis and its correlation with aging. He accurately described a case of portal hypertension with liver cirrhosis as well as pulmonary circulation and chronic obstructive pulmonary disease. Leonardo was the great innovator in Biomechanics of the cardiovascular system: heart, lungs and circulation.

Keywords: Innovation · Biomechanics · Cardiovascular

1 Introduction

1.1 Brief History

Leonardo who was born on April 15, 1452 in his father's family property in An-chiano, in the small town of Vinci, embodied in the Renaissance atmosphere. He died in France in 1519 and was buried in the Château d'Amboise in the Loire Valley. The last three years of his life were spent in the service of the king of France, Francis I. Through his research and with the scarce resources available at that time, Leonardo anticipated and foresaw topical phenomena such as ecology, nuclear destruction, and the use of

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sciences for war purposes [1]. His focus, imagination and power of observation have left their mark on modern engineering. His most precious legacy is not the 21 paintings or the almost 100,000 drawings and sketches he left, but his creation of a new way of thinking. On the other hand, his ability to interconnect diverse fields of knowledge, increasing their cognitive potential tenfold when interwoven, is a good example of "interdisciplinarity" (to use a modern expression) that constitutes a fundamental basis for the bioengineers of the present [1].

Leonardo embodied the Renaissance ideal of the multi-talented sage—painter, sculptor, narrator, musician, scientist, mathematician, architect, engineer—with an insatiable curiosity and thirst for knowledge. Through his research and with the scarce resources available at that time, Leonardo anticipated and foresaw topical phenomena such as ecology, nuclear destruction, the use of sciences for war purposes [1]. His focus, imagination and power of observation have left their mark on modern engineering [2].

1.2 Leonardo and His Prophecies

In his modest house of Florence, Leonardo lived in the shadow of the palaces' splendor. In the heart of the night, he imagined the distant world to come, posing hypotheses that would take science many centuries to verify, intuitions that surprise us due to their conceptual power and prophetical precision [3]. Water is "the blood of the Earth", he wrote, "the main and essential element of the cycle where all forms of life articulate". It is Leonardo who stated that "the man is made of earth, water, air and fire, like the earthly body" [4]. That the whole cellular metabolism is based on aqueous exchanges was a completely unthinkable idea at that time. He was the pioneer of ecologists! He sensed that the water cycle, both in our whole planet and in the essence of any living organism, must be based on an inalterable balance; otherwise, we run the risk of a disaster. He foresaw a world where this essential cycle of vital water would be altered. From his 16th-century Florence, Leonardo foresaw the polluted big cities of our time. He sensed the poisoning of the air, the nauseating and dangerous substances that kill the oceans. And the war… a terrible war, of flame and steel, a war he speaks of in terms of "rupture of the matter in the most intimate elements…" Was he foreseeing the division of the atom? [5].

1.3 Leonardo the Innovator

Leonardo's greatest innovation was taking well-established concepts and bringing them under direct verification of phenomena, always using his great capacity of observation, equipped with his extraordinary ability to transform what he saw in a graphic schematization of processes [5]. Leonardo laid the foundations of new experimental sciences; he stepped away from mere empirism to precepts of applied science which was apt for the general application in the industrial world. In this regard, he was the first modern engineer. Leonardo was less influential because his writings did not have enough diffusion and some were lost. What if Galileo and Kepler had met him? The more his legacy is studied, the more that prodigious dimension of the great Florentine is understood [2].

In those days, being an innovator was not as simple as it is today. At the beginning of the 1500's, Inquisition became more and more strict to counteract the new thoughts and ideas coming from Germany, where intolerance was growing against the power of Rome: an intolerance that a few years later brought about Martin Luther's thesis against indulgences presented in Wittenberg, which officially sparked the Protestant Reform. Probably, Leonardo was not allowed to publish all his work even though he could have had time and support to do it. In his notes, next to the drawings of the heart and blood circulation, he wrote: "…I could say more if I were allowed to…" William Hunter (1718–1783) could observe and study Leonardo's drawings and notes on anatomy [6]. He defined Leonardo as the best anatomist of his time and, probably, of all times. He tried, unsuccessfully, to publish Leonardo's work. The interest in Leonardo in modern times has fascinated and it is still fascinating. It is an indefinable attraction. Most people place this attraction in the many intuitions, discoveries and ideas he had, looking to future horizons. In some way, Leonardo da Vinci is out of this world, his strange genius directs him to all the fields of knowledge and works that today we would call "engineering". Very early, he reveals himself as a universal spirit, his view of the world is that of a visionary in the real world [3].

2 Results

Leonardo was authorized to dissect corpses in the Santa Maria Nuova Hospital in Florence [6]. His diaries' notes include detailed studies of the human skull, human fetus, a woman's internal organs, muscles, tendons, skeleton, cardiovascular system, etcetera. During the Middle Age, human dissections were rare because of many reasons, among them was religion and the fear of disease transmission. To all those facts, we must add the "Ecclesia Abhorret a Sanguine" bull (1163) and the Papal bull entitled "De Sepolturis" (1299), which practically forbade touching corpses after death [8].

2.1 Leonardo and the Arteries

He studied the flow dynamics of water in rivers [6], using colors to show the flow patterns, defining the continuous stress on the lateral walls of the river, "… the water continuously bounces against the riverbank… And as time passes by, the course of "the river gets more tortuous…" He determined, with different colors, the flow characteristics in the center and near the edges of the rivers and extrapolated those findings to the blood that flows in the arteries [8].

2.2 Leonardo and the Heart

Leonardo stated that the heart is a muscle that spontaneously contracts and that the aorta supplies blood, calories and energy across the body through the arterial blood that comes up to the skin through the capillaries. Leonardo studied the anatomy of the coronary artery and the veins in detail, concluding that the heart is self-feeding. He noticed that both atria contract when the ventricles dilate, which explains the transport of blood from the atria to the ventricles. The left atria and ventricle are larger than their

right counterparts. In parallel, he made several wax moulds of bulls' hearts and, based on those, he built glass models to study the hydraulic characteristics of the blood flowing through the heart and its valves, an in vitro circulation model to imitate human circulation. Seeds were used to visualize the turbulences and blood flow [8].

2.3 Leonardo and the Bronchial Tubes

He examined the bronchial tubes in detail including their smallest branches, noticing that each of them is accompanied by a small branch of the pulmonary artery. Therefore, he posed the hypothesis that the bronchial arteries receive *freshness* from the bronchial tubes, filled with air, and that the venous blood receives *freshness* from the lungs, before returning to the heart [8].

2.4 Leonardo and the Valves

Having a special interest in hydraulic engineering, Leonardo studied the anatomy of the cardiac valves which "… are covered by the endocardium in the top part and the muscles in the lower part…". He concluded that the 4 valves must open and close completely; otherwise, the heart will not work properly, with blood regurgitation in the atria from the ventricles.

At that time, diseases were considered a punishment from God by the public at large, and a humor imbalance by the experts, who closely followed Galen's theories. The most common remedy for most diseases, regardless of their nature, was continuous venous bleeding. Leonardo theorized that diseases were the result of some kind of imperfection in the human body structure [8].

2.5 Leonardo and Atherosclerosis

Leonardo made several assumptions about the cause of atherosclerosis, based on his previous hydrodynamic studies on water flow in rivers, speaking of "… the continuous stress on the arterial walls" and "… the lack of nutrition of the media of the artery, far from the blood that nurtures it." In 1505, Leonardo met a man at Santa Maria Nuova, in Florence, who was more than 100 years old. Leonardo wrote: "… this man was wise, happy despite his old age." "I performed an autopsy to understand the causes of this pacific death and discovered that it was caused by the weak blood flow and a failure in the artery that feeds the heart and the other limbs". He clarified the concept of atherosclerosis and its correlation with old age "when vessels get old, they lose the straightness in their branches and become more tortuous or winding and stiff…" and "… one [can] ask why the vessels in old people become quite long and those which were previously straight become tortuous, and their skin becomes thicker in order to occlude and prevent blood flow…". Leonardo also performed an autopsy of a 2-year-old boy and found that "… all the arteries are soft and straight… different from those of an old man…" [9].

2.6 Leonardo, Cirrhosis and Portal Hypertension

He accurately described a case of portal hypertension with liver cirrhosis, possibly in the same autopsy in which he accurately described arteriosclerosis, "… the artery and the vein which extend from the spleen to the liver become so big that they block the blood coming from the mesenteric vein; the latter vein dilates so much and becomes so tortous as a snake that the liver dries and becomes like frozen bran, both in color and consistency…" [9].

2.7 Leonardo, Pulmonary Circulation and Chronic Obstructive Pulmonary Disease

When Leonardo was painting a fresco at the Santa Maria Novella church, a middle-aged man was preparing colors for his frescos. The man, breathing the vapors of the colors, developed a severe chronic obstructive pulmonary disease, with severe restrictive lung disease and the associated dyspnea at rest. Leonardo asked the man to be the model for Saint Jerome in the desert. The painting shows Saint Jerome, who lived the life of a hermit in the desert, in great suffering. The muscles of the neck, chest and face are shown in the spasmodic contraction. When the man died, Leonardo performed the autopsy in order to understand the reasons behind such suffering. He found lung emphysema and noted down the possibility of correcting those alterations. Based on his engineering knowledge, he stated the hypothesis that the lungs were dilated because the air could not be properly expelled [9].

2.8 Leonardo and the Mechanics of Venous Circulation in the Lower Limb

Leonardo was interested in the venous circulation of the lower limbs. Varicose veins have been described since the old days, but Leonardo had the intuition of understanding the importance of muscle contraction in facilitating the return of venous blood. He described the presence of collaterals in the superficial and deep venous system in the lower limb. In Italian anatomy, the perforator group of veins around and right below the knee are connected by the so-called Leonardo's vein [9].

3 Conclusions

Leonardo moved slowly among the accepted theories that he learned in books, but they were adapted to his new ideas and based on his own experiments. He wrote: "the heart is a muscle which contracts spontaneously". He understood that the aorta supplies blood, calories and energy across the body through arterial blood which comes up to the skin through the capillaries. He examined the bronchial tubes in detail up to their smaller branches, noticing that each of them is accompanied by a small branch of the pulmonary artery [8]. Interestingly, following his collaboration with scientists from Pavia, a series of new theories on blood circulation were proposed in the university by

Realdo Colombo and Andrea Cisalpino. Those theories were then reinforced by Fabrizio Acquapendente in the nearby University of Padua and were almost kept in secret.

Willian Harvey, a young student at Cambridge, studied in Padua as an assistant of Fabrizio Acquapendente. He graduated in 1602, before returning to London. In 1628, William Harvey published Exercitatio anatomica de motus cordis et sanguinis, which constitutes the foundation of modern cardiovascular physiology. The concept of oxigenation was defined by Marcello Malpighi, professor of theoretical medicine at the University of Bologna, when he published, in 1661, De Pulmonibus, anatomical observations where he described the concepts of venous blood oxigenation in the lungs before returning to the heart, thus completing William Harvey's previous theory [8].

Leonardo was a man in continuous psychological agitation who tried to understand the world that surrounded him and, above all, to get an understanding of himself. His desire to understand human nature is confirmed by the efforts he made to correlate psychological conditions with alterations in the human body and vice versa. He analyzed the condition of the heart in many dissections, trying to correlate the person's psychology with the general condition of the body. Leonardo understood the influence of the overt and the hidden psychological factors in heart diseases. Sigmund Freud, the father of psychoanalysis, was the first person to understand this aspect of Leonardo and tried to define Leonardo's personality. Freud found himself lost in a sea of sensations in his efforts. Leonardo seems so simple, but impossible to define. Scientists, whether consciously or not, find his message that science and art can work together attractive [1]. He possesses the unstoppable strength of the freedom that a man should always seek to conquer, persistently maintaining the creative fervor and the fierce need to know, not to leave the world as it is, but to change it [7]. It was not easy for Leonardo to express his daring ideas freely in the tumultuous environment of the Italian Renaissance and therefore his life continues to be a big puzzle which has not yet been completed, with many things still to be discovered [4]. A high level of erudition would be required. There are thousands of brochures written from right to left, blueprints, sketches, diagrams, which sleep in several large libraries around the world. Nobody has dared to gather them and make a vast summary of this huge amount of pending material and one cannot stop wondering how a man, who is one of the world's greatest painters, was able to accumulate such amount in a single lifetime. It is possible that Leonardo, due to the oneiric dimension of his research, still surpasses us.

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