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TEACHING ANATOMY THROUGH IMAGES: THE POWER OF ANATOMICAL DRAWINGS

ABSTRACT: How medical educators taught anatomy in the past changed throughout the centuries, ranging from dissection to wax modelling. More recently, imaging for teaching purposes has become increasingly crucial to anatomy education.

The main focus of this contribution is to present the history of anatomical illustrations from the Middle Ages to our age.

Anatomical illustrations are to a certain extent the ancestors of diagnostic images: Guido da Vigevano (c. 1280-1350) was the first anatomical illustrator who introduced the systematic use of anatomical drawings. Renaissance artists performed their dissections, inextricably binding anatomy and the arts in a crescendo that reached its peak in the work of Leonardo da Vinci (1452-1519) and Andreas Vesalius (1514-1564).

Leonardo presented the human body in more than 750 anatomical illustrations that included sketches of muscles, bones, brain, blood vessels, and viscera. He discovered the frontal and maxillary sinuses and described the structure and function of the cardiac valves in great detail. Although the anatomical accuracy of the drawings is open to debate, the methods and techniques Leonardo used are undeniably impressive and genuinely pioneering. Over Five hundred years after Leonardo's death, the purpose of this study is to offer a review of the medical literature on the history of anatomical illustrations and Leonardo's anatomical drawings offering a glimpse into the history of anatomical illustrations, the forerunners of today's imaging techniques.

KEY WORDS: Anatomy education - Anatomical drawings - Imaging - History of medicine - Leonardo da Vinci

"We are like dwarfs on the shoulders of the giants of the past, and our discoveries and knowledge are indissolubly tied to those of the men who lived before us".

Berengario da Carpi (c. 1460-1530) (Stahnisch *et al.* 2019)

"To develop a complete mind: study the science of art; study the art of science. Learn how to see. Realize that everything connects to everything else".

Leonardo da Vinci (1452-1519)

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1. INTRODUCTION

Which is the best way to teach anatomy? Until recently the obvious answer has been dissection.

Human anatomy has always been a mainstay of medical education. Although cadaveric dissection has been the primary method of teaching anatomy for centuries, new trends in medical education have modified the role of dissection in the teaching of anatomy in modern-day medical schools (Papa, Vaccarezza 2013, Papa, *et al.* 2019a). Dissection is indeed a time-consuming and expensive procedure. It also involves issues concerning ethical beliefs and legal restrictions; moreover, the colour, texture, and smell of cadavers can sometimes have a negative impact on students, who may end up finding the dissection process extremely stressful (McLachlan 2004, Vaccarezza, Papa 2015).

Increasing evidence has demonstrated that radiology should play a significant role in anatomy teaching, which has made many medical schools integrate this subject in anatomy education. Moreover, X-rays of cadavers, as well as ultrasonography of living individuals have been used to enhance students' understanding of sectional and 3D anatomical structures (Bohl *et al.* 2011, Griksaitis *et al.* 2012, Knobe *et al.* 2012, Kotzé *et al.* 2012, Lufler *et al.* 2010, Rengier *et al.* 2009). Altogether, these studies have demonstrated moderate to positive effects on students' perspectives and academic performances (Lufler *et al.* 2010). The *liaison* between anatomy and art began in the Middle Ages, despite the myth of medieval resistance to dissection. In 1300 Pope Boniface VIII (c. 1235–1303) issued a bull, *De Sepolturis*, threatening excommunication for anyone carrying out the practice of boiling corpses in order to obtain clean bones, particularly Crusaders, to make their storage and transport easier for burial at home (Di Ieva *et al.* 2007, Mavrodi, Paraskevas 2014, Papa *et al.* 2019a, 2019b). The first open mention of dissection was one performed on a victim of pestilence in Italy in 1286, even if it was more of a *post-mortem* examination rather than a scientific procedure, merely aimed at finding that individual's cause of death. As the sources report, in that year "*there was in Cremona, Piacenza, Parma, Reggio, and many other Italian cities, great mortality between humans and hens [...]. A certain physician had some of the hens opened and found that there was a vesicular apotome on the tip of each hen's heart. He also had a man opened and found the same thing [...]*" (Park 1994). Indeed, in 1302 Azzolino Degli Onesti was autopsied at the judge's request by

a commission of two physicians and two surgeons who concluded from their examination that "*the said Azzolino had not died of poison, but rather and more certainly from a large quantity of blood that had gathered around the great vein and the nearby veins of the liver*" (Park 1994). Moreover, the widely known author of the *Decameron*, Giovanni Boccaccio (1313–1375), in the sixth story of the Fourth Day of his famous novel, tells us that certain doctors on the order of the *Podestà* (chief magistrate) are believed to have performed a rudimentary forensic examination on Gabriotto's body to certify the nature of his death and deliver their verdict of cardiac failure (Toscano *et al.* 2016). It therefore seems evident, that these first attempts at dissection involved forensic examination. The first public dissection took place in 1315 by Mondino de' Liuzzi (1275–1326), the "Restorer of Anatomy" (Rengachary *et al.* 2009), who is considered the first to have performed a public dissection after Herophilus and Erasistratus. In 1316 Mondino completed his masterpiece, *Anothomia*, and the book quickly became the main textbook in nearly all European medical schools. Anatomists in Mondino's day were incapable of substantially contributing to the advancement of human anatomical science as dissection was not performed to broaden knowledge or make discoveries.

Although the barber-surgeons were the only ones allowed to dissect while the professors read aloud from Galen's works, they were considered to be little more than butchers and did not have the chance to illustrate their findings (Calkins *et al.* 1999, Davison 1969).

Mondino's text was therefore primarily based on descriptive information, and no illustrations or descriptions were provided.

1.1 History of the anatomical illustrations:

Guido da Vigevano

The illustration of medical subjects took place before the advent of papyrus, paper, and similar materials (Allbutt 1921); in Greek history, the most influential and significant scientific figure was Aristotle of Stagira (384–322 BC), who was the first scholar of record to illustrate human anatomy based on a legitimated scientific study (Calkins *et al.* 1999, Singer 1921).

Moreover, although the first appearance of anatomical illustration is thought to date back to the era of Aristotle, who believed that the teaching of anatomy should include "*paradigms, schemata, and diagrams*" (Da Vinci 1983), the systematic use of drawings or illustrations was first introduced by Guido

da Vigevano (1280–1349), one of Mondino de Liuzzi's students in the late 14th century.

Guido da Vigevano (c. 1280–1350) (Di Ieva *et al.* 2007, Nanda *et al.* 2016) was an anatomist who served as the personal physician of three monarchs: Emperor Henry VII of Luxembourg (c. 1269/74–1313), Jeanne de Bourgogne of France (1293–1348) and Philip VI of France (1293–1350), and dedicated his work to the latter. *Anathomia Designata per Figures*, originally included 24 anatomical plates, 18 of which have been lost; these plates illustrated structures such as cerebrum, spinal cord, meninges, ventricles, and cortical convolutions making the manuscript the first to show a close relationship between drawings and anatomical descriptions, forming a new trend in the field of anatomy that gained terrain in later centuries.

Although it was based on empirical and observational concepts, Guido da Vigevano's work set a milestone for the further development of anatomical sciences, especially in the Renaissance.

1.2 Vesalius' *De Humani Corporis Fabrica*

During the Renaissance, the affair between science and arts reached an apex with the publication in 1543 of *De Humani Corporis Fabrica* by Andrea Vesalius (1514–1564). This legendary work blended the study of human anatomy with the beauty of artistic drawings.

In 1537 Andreas Vesalius became a professor of anatomy and surgery, and six years later, he finished his masterpiece. Vesalius transferred the 3D form of the human body onto paper, setting the standard for subsequent generations of anatomical publications, research, and training (Garrison Hast 2013, Mazzotti *et al.* 2010, McLachlan 2004). He illustrated the human body in different poses and various stages of the dissection process eschewing the Galenic theologically-inspired theories; he was also the first author to classify the organs into seven organ systems, as well as to use anatomical terminology.

The illustrations were mainly in the form of handmade drawings, even if the production of anatomical texts with illustrations or figures became more manageable thanks to the invention of the printing press (Ghosh 2015).

It was not until the 16th century, however, that anatomical drawings acquired a role in teaching and training. Up to this time, the use of any figures, that could distract the reader from the text itself was condemned, even if miniatures illustrating anatomical dissection scenes without any scientific or teaching purpose could be found in manuscripts from the 14th century.

During the Renaissance, on the other hand, the increasing popularity of anatomy was not confined to physicians or medical students but also involved contemporary artists: Italian Renaissance artists started to perform their dissections fusing the science of anatomy and the world of art in a *crescendo* that reached its peak with the work of Leonardo da Vinci (1452–1519).

By attending dissection sessions the aim of the painter was to enhance his knowledge of nature rather than anatomy: Luca Signorelli (c. 1450–1523) is said to have visited burial grounds searching for body parts, and Giotto's assistant, Stefano, was called the "echo-of nature," because of the skills he acquired in the drawing of superficial veins (Da Vinci 1983, Singer, 1921).

1.3 Leonardo: the "anatomical artist"

"If you find from your own experience that something is a fact and it contradicts what some authority has written down, then you must abandon the authority and base your reasoning on your own findings."

Leonardo da Vinci (Tarshis 1969)

Frank Netter (1906–1991) heralds Leonardo as the "founder of physiologic anatomy", but for other scientists and historians, da Vinci is principally regarded as an artist and thinker who dabbled briefly in the study of human anatomy (Netter, Friedlaender 2014).

Leonardo was born in Vinci in the River Arno valley on April 15, 1452; he was the youngest and the illegitimate son of a wealthy notary, Pietro, and of Caterina, a young commoner from Archiano, a nearby village.

At some time in the late 15th century, Leonardo's father showed his son's drawings to the famous painter Andrea del Verrocchio (1435–1488), who then became his mentor, and in 1472, Leonardo enrolled in the *Compagnia di San Luca*, the painters' guild (Jose 2001). Verrocchio in his *Treatise on Painting* explained why painters should learn anatomy: "*It is a necessary thing for the painter, to be good at arranging parts of the body in attitudes and gestures which can be represented in the nude, to know the anatomy of the sinews, bones, muscles, and tendons*" (McMahon 1956, Pevsner 2019). It therefore seems likely that under the guidance of his master, Leonardo studied the superficial layers of the human body to improve his drawings.

Leonardo portrayed the human body in more than 750 anatomical illustrations, now preserved at Windsor

Castle, including sketches of muscles, bones, cerebrum, blood vessels, and viscera (Ose 2008).

His objective was to reveal structure through the imaging of dissected material: for this reason, Leonardo should be considered the first artist-anatomist.

He dissected more than 30 bodies, discovered the frontal and maxillary sinuses, and described the structure and function of heart valves (Ose 2008). Moreover, in an era when the heart was dogmatically described as a two-chambered structure, he was the first to accurately describe the heart as having a four-chambered muscular organization (Netter, Friedlaender 2014, Ose 2008). Leonardo also studied the anatomical changes involved in the pathophysiology of atherosclerosis, cirrhosis, and portal hypertension. At the beginning of his anatomical experience, Leonardo was still under the influence of his study of the works of Galen, Avicenna, and Mondino, and his first drawings are mainly based on text reading and animal rather than human dissection. Nevertheless, he later used methods such as a cross-sectional technique or his method of injecting wax into the brain's ventricles to study their morphology, which still today is impressive (Jose 2001, Singer 1921).

The earliest group drawings are a set of seven sheets drawn when he was in Milan working on *The Virgin of the Rocks* (1485–1487) painting. In Milan, Leonardo met the mathematician Luca Pacioli (1477–1517) whose work *De Divina proportione*, published in 1509, displayed some of da Vinci's illustrations with geometric figures; one figure in particular represents the proportions of the human body.

According to Pevsner (Pevsner 2019), on one sheet, Leonardo described pithing a frog. He wrote: "*The frog retains life for some hours when deprived of its head and heart and all its bowels. And if you puncture the said nerve [spinal medulla], it immediately twitches and dies.*" On the verso, he further notes: "*Here, therefore, it appears, lies the foundation of movement and life.*" *The spinal column in Leonardo's drawing is labelled "virtu gienjtua"* (generative power), and he writes: "*All the nerves of animals derive from here.*" He erroneously indicates that the vertebrae included a pair of nerves, a mistake that persisted across many of his drawings (Da Vinci 1983, Keele, Pedretti 1978–80).

During the first years of the 16th century, due to the political situation after the First Italian War (1494–1498), Leonardo was forced to leave Milan and, together with Luca Pacioli, moved to Mantua in 1499 (Splavski *et al.* 2019).

On their way to Mantua, they visited Venice, where Leonardo lived from March 1500. In Venice, he had the opportunity to attend Alessandro Benedetti's (c. 1450–1512) anatomy class, as attested by a notebook dated 1508. Back in Florence, Leonardo continued his anatomical training, dissecting material available at the Florentine Hospital Santa Maria Nova. Thus in the group of drawing dated c. 1504–1505, he represents an imaginary vein on the grounds that each artery has a corresponding vein; the arm of "Francesco the miniaturist" still attests to the fact that Leonardo was observing living subjects, this is consistent with the shortage of cadavers available.

He acquired his first human skull in 1489, and the works displayed were impeccably curated and beautiful. He discovered that the humors did not reside in three cerebral ventricles, that the heart, not the liver, was at the core of the blood system. He also described the coronary sinuses almost 200 years before Valsalva gave them his name, and, 120 years before Harvey, was surely only one step away from grasping the idea of the circulation of blood (Jones 2012).

Leonardo was elderly when he met the famous anatomist Marco Antonio Della Torre (1481–1511), the founder of the "Anatomical School" of the University of Pavia, who was Professor of Theoretical Medicine at the University of Padua. According to the historian Giorgio Vasari (1511–1574), while Della Torre performed his dissections, Leonardo traced red-pen drawings of the muscular system. In 1513, soon after Della Torre's death, this book of drawings became the property of the English Crown and is preserved at Windsor Castle (Picardi *et al.* 2019).

Unfortunately, it is not possible to estimate the precise faith of Leonardo's drawings and manuscripts, probably because some of them went missing while Leonardo was traveling across Italy (Splavski *et al.* 2019). Leonardo's contributions to anatomical knowledge came just before the development of the printing press, and da Vinci's remarkable anatomical illustrations were not published in his lifetime (McMurrich 1930).

His chalk drawings remained buried for over 200 years until discovered by William Hunter in 1784.

1.4 Henry Gray and Frank Netter the Contemporary Age

During the Modern and contemporary ages, medical teaching, and the teaching of anatomy, became institutionalized with established courses of regimented learning (McMurrich 1930).

In August 1858, the London publishing firm John Parker & Son published a new medical treatise entitled *Anatomy. Descriptive and Surgical*. The book was written by a young English surgeon, Henry Gray (1827–1861), and Henry Vandyke Carter (1831–1897), his colleague on the medical staff of St George Hospital in London, drew the illustrations (Hansen 2006).

In the Preface to his book, Gray wrote: "One of the chief objects of the author has been to induce the student to apply his anatomical knowledge to the more practical point in surgery, by introducing, in small type under each subdivision of the work, such observations as show the necessity of accurate knowledge of the part under examination". Still today, 150 years on, the volume continues to sell, and Gray's anatomy is considered one of the standard textbooks of anatomy, especially for medical studies.

Netter, in the Preface to his *Atlas of the Human Anatomy*, wrote, "Anatomy, of course, does not change, but our understanding of anatomy and its clinical significance does change as do anatomical terminology and nomenclature" (Hansen 2006, Netter, Friedlaender 2014, Niekrash *et al.* 2015).

Frank Netter was born in New York and was both a physician and an artist. He studied at the National Academy of Design and the Art Students League and attended the New York University Medical College.

As a child, he displayed "*an uncanny knack for making pictures*" (Hansen 2006) and preferred visiting the Metropolitan Museum of Art rather than playing football with friends. Although his mother had hoped he would pursue a more respectable career, Netter became a successful commercial artist and only after her demise did he enrol in medical school.

Studying his class notes and the sketches of embryology and anatomy that he drew alongside his lectures and laboratory notes, he realized it was easier to learn from his drafts rather than to memorize the textbook.

Having obtained his degree, he decided to join a private surgical practice; soon afterwards, however, due to the Great Depression, he discovered that there was "*more demand for my pictures than for my practice*" (Netter, Friedlaender 2014). He embarked on a career as a medical illustrator and never practiced medicine again. Netter put his predecessors' knowledge of art and medicine to good use and although he neither created his specimens nor theorized about the anatomy he drew, he was the most prolific of medical illustrators.

Netter painted over 4,000 medical illustrations, including not only normal anatomy, histology, and embryology, but also pathology, diagnostic procedures, surgical techniques, and the clinical manifestations of many diseases. His painting became the centerpiece of over 250 issues of *Clinical Symposia* and later formed the 13 volume set of *The CIBA Collection of Medical Illustrations*.

The persistent demand, from both practitioners and students, for a gross anatomy atlas, finally, resulted in the publication in 1989 of the *Atlas of Human Anatomy*, Netter's masterpiece.

The Atlas, often referred to as Netter's "personal Sistine Chapel," rapidly became the most widely used atlas of anatomy in American medical schools (Netter, Colacino 1989, 1997, Netter, Hansen 2003).

2. DISCUSSION AND CONCLUSIONS

Anatomy has always been at the heart of medical education despite variations in nation, religion, ethnicity, or instructional systems. Learning gross anatomy remains essential to preparing medical students for their future clinical practice, as it forms the basis for the understanding of disease and treatment strategies. In-depth knowledge of the three-dimensional (3D) anatomy of human structures is essential for safe clinical practice especially considering the increasing involvement of high-definition computed tomography (CT) in diagnosis and surgery, either endoscopic or robotic (Murakami *et al.* 2014).

Furthermore, familiarity with imaging also supports the appreciation of both pathology encountered during clinical education and anatomical variations (Bohl *et al.* 2011).

How best to deliver anatomy to students has been a core debate for many years, and it still represents a moot point. A further unresolved question in modern anatomy teaching is the validity of different anatomical pedagogies and the supposed superiority of dissection versus other tools that are now extensively utilized in biomedical education (McMenamin *et al.* 2018, Murakami *et al.* 2014). Despite these pedagogical variations, however, comprehensive knowledge and anatomical skills still underlie high-quality medical practice (Petriceks *et al.* 2018, Vaccarezza 2017).

Recent findings by Wilson and coworkers (Wilson *et al.* 2018), clearly demonstrates that dissection is not superior to other teaching tools when it comes to learning anatomy.

The use of radiology in the teaching of anatomy to medical students is gaining popularity; However, although the importance of radiological instruction during medical school is acknowledged, there is wide variation in how and when radiology is introduced into the curriculum.

The radiology boom for anatomy teaching is probably due to the improved quality of imaging technology and its ability to represent anatomy, particularly spatial and sectional anatomy (Lufler *et al.* 2010). Reduced cadaveric donations and possibly reduced availability of anatomists should also be taken into account.

Indeed, modern imaging methods offer examinations of the internal structures of living patients during medical procedures, allowing the range of anatomical variations present in real human materials to be observed. According to Davy and colleagues (Davy *et al.* 2017), radiology has become main-stream in North American, Australian, and New Zealand medical schools, where anatomy is delivered via integrated curricula involving radiological imaging as part of the undergraduate curriculum (Craig *et al.* 2010, Grignon *et al.* 2012, Jack, Burbridge 2012). In this scenario, anatomical illustrations stand as the harbinger of diagnostic images whose interpretation requires an in-depth knowledge of anatomy and its normal variants (Jack, Burbridge 2012).

Anatomical illustrations are the first attempt to study anatomy through imaging. As Benjamin Rifkin explains (Rifkin, Ackerman 2006): "Physician and artist worked to preserve life, but an artist could even revive the dead, an idea that took on particularly witty form in Renaissance anatomy books that show animated cadavers strutting across the landscape" [...] "These pictures were often about the nature of anatomy, the cadaver, and the moral condition of being dead and dissected. Above all, they show the dead as living embodiments of our form and fate" (Slipp *et al.* 1815).

Leonardo da Vinci was the most significant figure in this regard, even if he cannot be considered an anatomist since he never obtained his medical degree, and the anatomical accuracy of his drawings is still a matter of debate. His approach to anatomy was more scientific than artistic, and he truly should be the apogee of the artist-anatomist.

Finally, photogrammetry is worth mentioning: it might be considered a "merged" tool able to combine 2D illustration with 3D reconstruction.

Photogrammetry, snapping objects from different angles, combines the advantages of photographs while avoiding most of the pitfalls. A specific software then overlaps the images of the object to generate a 3D reconstruction.

In a recent pilot study, Petriceks and colleagues (Petriceks *et al.* 2018) used a photogrammetric setup and rendering software developed to produce digital 3D models of dissected specimens of regional anatomy. These models were identical to their original specimens. Faculty members who did not participate in the study were asked to provide feedback on photogrammetrically generated 3D models. All the interviewed faculty members were instructors in ongoing anatomy courses and used the physical dissections regularly in teaching; they gave positive feedback, being truly impressed with the models' simultaneous provision of representative surface anatomy, interactivity, kinesthetic learning, and potential for annotation and self-examination. Although the study is limited by the type of organ considered (dissections featuring muscles or bones were not documented), it demonstrates photogrammetry's power for creating digital, interactive resources for anatomy education. Citing Calkins "With respect to the development of human anatomic illustration, three elements were essential: the recognition of anatomy as a distinct branch of medical science, the acceptance of human dissection as a scientific method to advance understanding of the anatomical structure, and the advancement in printing such that illustrations could be included alongside descriptive text" (Calkins *et al.* 1999).

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