Anatomy in the Digital Age

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The hand of Mrs. Wilhelm Roentgen: the first X-ray image, 1895, from Otto Glasser, *Wilhelm Conrad Röntgen and the Early History of the Roentgen Rays*, London, 1933

THE CHALLENGE FACED BY ANATOMICAL ILLUSTRATORS has shifted dramatically since the rise of modern medicine. The reader of this book can see immediately that the great anatomical illustrators from the Renaissance to the eighteenth century by and large thought of themselves as image makers as much or more than faithful recorders of what they saw. From Vesalius's skeleton pondering a human skull to Albinus's skeleton contemplating a rhinoceros is two hundred years of imagery full of visual elements that would be not only useless but positively distracting to a medical student or practicing doctor. To be taken seriously as educational or diagnostic tools, that is, to meet the needs of the growing medical establishment of modern times, anatomical illustrations would need to attain a higher degree of accuracy, a quality that can be measured in different ways. Certainly, scientific accuracy calls for greater precision in rendering and the sacrifice of such artistic values as composition and proportion; clarity, not expressiveness; and a sharp focus on the parts that needed to be mastered by the student, with distracting elements omitted. These factors explain the widespread popularity in the second half of the nineteenth century of anatomical atlases like Gray's, which an artist might see as being plain and uninspiring.

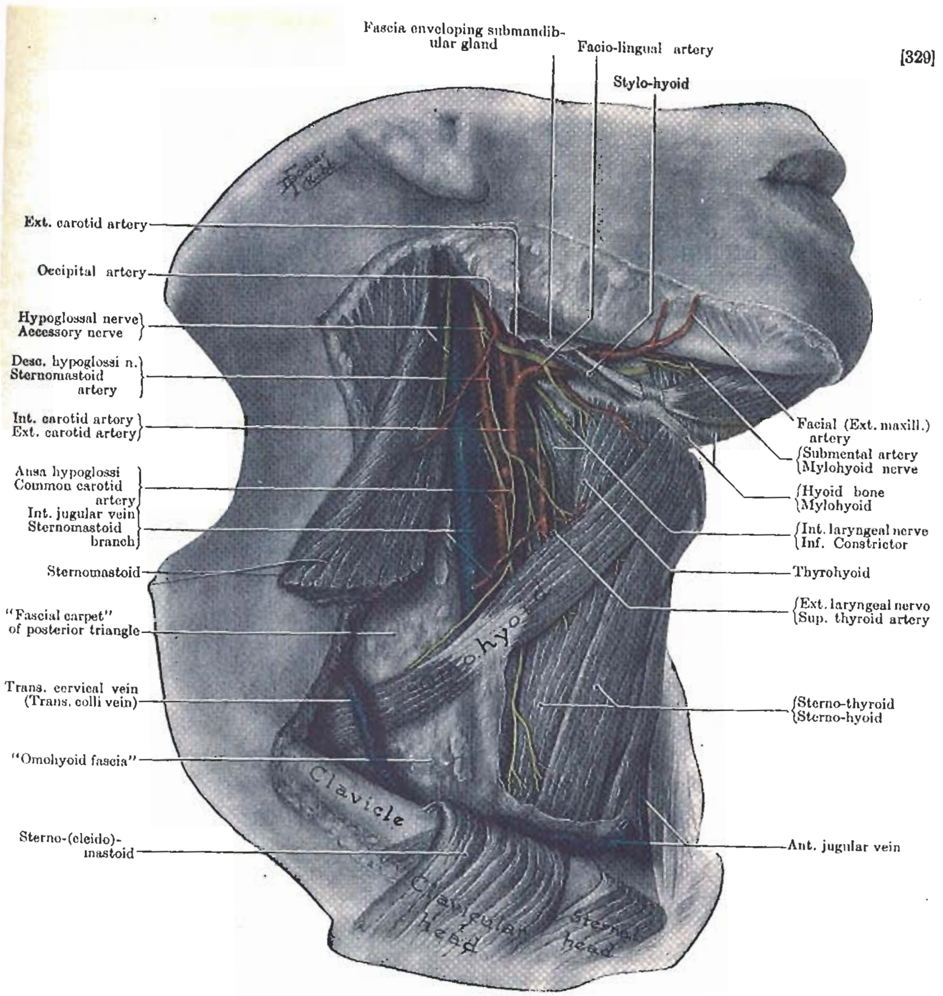
In a deeper sense, accuracy demanded a better mode of 3D visualization than had been attained by anatomists working with artists since the Renaissance. From the beginning of anatomical art, two-dimensional atlases of anatomy have been the mainstay for visualizing and identifying features of the human body and for understanding the relationships among these features. There is no question that enormous progress was made, from the primitive paper flaps used in the late Middle Ages to show that the organs were under the skin, to the remarkable axonometric perspectives of organs, systems, and body cavities mastered by nineteenth-century artists after demanding technical training. It was partly because each ensuing century brought more innovative rendering techniques that the understanding of human anatomy advanced as it did. Virtually every strategy that would later be used in the twentieth-first century world of digital imaging to portray a 3D image on a flat surface was developed by artists working before the twentieth century. (It is interesting to note in this regard that even the cross section view of the human body familiar now from CT scans and MRIs was anticipated by certain anatomical atlases that consisted of drawings of frozen cross sections of human cadavers. Serial sectioning of a specimen and viewing it with a microscope was the classic way of studying pathology.) Very few of the images reproduced thus far in this book, however, would be adequate for modern medical education, and, by definition, none would be a reliable guide to a doctor or surgeon caring for a specific patient.

The solution to this problem required that anatomical illustration, like so much else in the modern world, come under the control of machines rather than the subjective human hand and eye. In the nineteenth century, as a first step in this evolution, atlases based on photographs taken during cadaver dissection were introduced. The complex nature of the reality depicted in these photographs led to an interesting result—the photographs were often too cluttered with detail for students to be able to see their important features. Each photograph was often traced or accompanied by hand-drawn rendering of the same scene, in order to enhance or even to allow for understanding. The mid-twentieth-century anatomist J. C. Boileau Grant (opposite) described a common method in the preface to his *Atlas of Anatomy* (1943): "[E]ach specimen was posed and photographed; from the negative film so obtained an enlarged positive film was made; with the aid of a viewing box the outlines of the structures on the enlarged film were traced on tracing paper; and these outlines were scrutinized against the original specimen, in order to ensure that the shapes, positions and relative proportions of the various structures were correct. The outline tracing was then presented to the artist who transferred it to suitable paper and, having the original dissection beside her, proceeded to work up a plastic drawing in which the important features were brought out. Thus, little, if any, liberty has been taken with the anatomy; that is to say, the illustrations profess a considerable accuracy of detail."

For the purpose of teaching a student to identify an anatomical structure, a simplified tracing of the salient features in a photograph was probably preferable to an artist's freehand drawing of the same scene, even if a layman might find it duller to look at; but the necessary third dimension was still missing. This breakthrough would require the invention of mechanical visualization techniques that would render reality in 3D rather than 2D. The refinement of these was one of the many triumphs of medicine in the twentieth century.

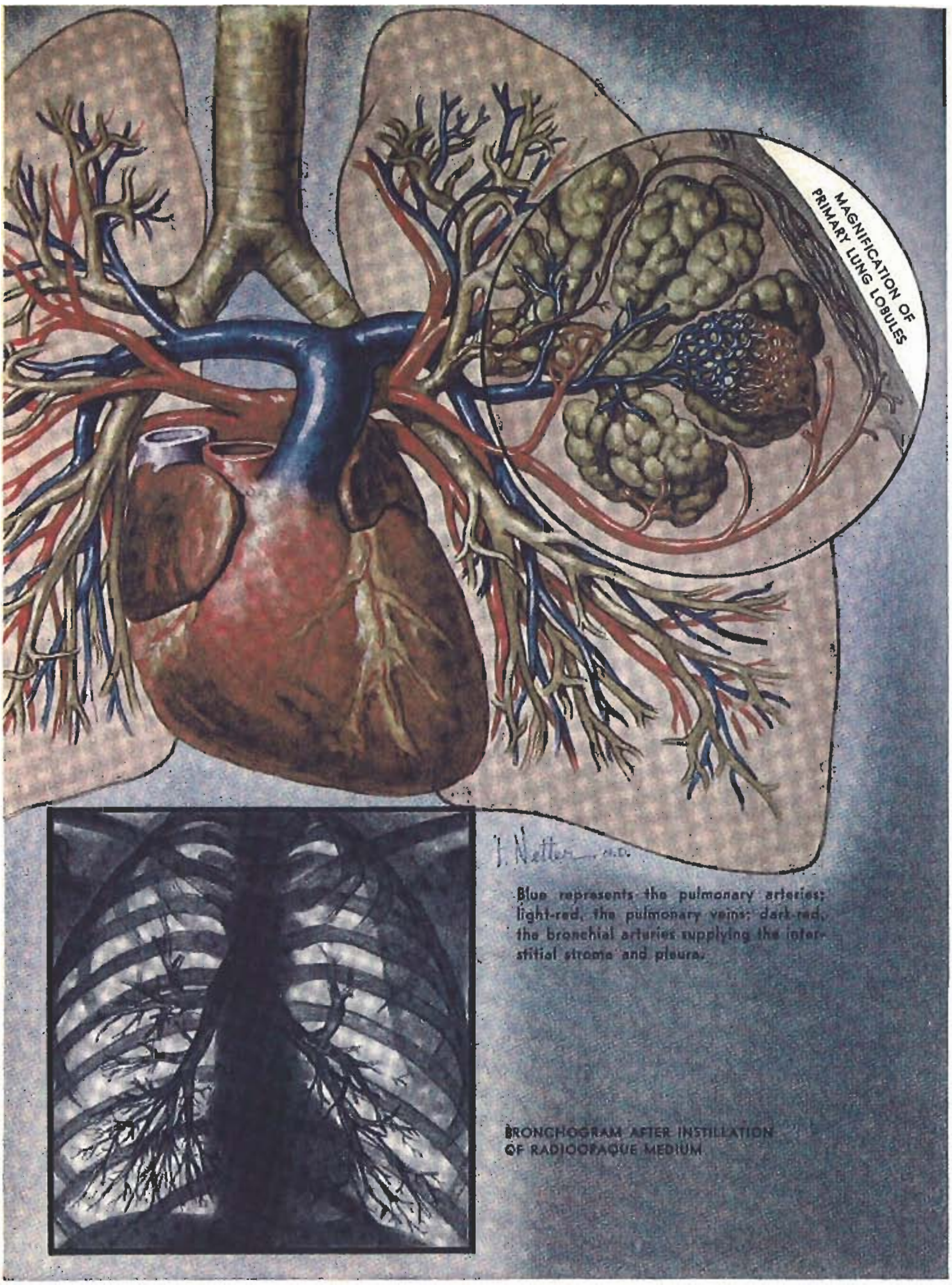
X-RAYS

A thorough grasp of the relationships between biological structure and function has been central to health care throughout recorded history, and providing a precise understanding of three-dimensional biological structure and its implications for therapy remains the gold standard for training in medical specialties such as surgery, neurology, and radiology today. To provide care, specialists in these areas require an intimate knowledge of the three-dimensional anatomy of the specific patient being treated, since the exact arrangement and



388. The Anterior Triangle of the Neck.

"The Anterior Triangle of the Neck," from J. C. Boileau Grant, *An Atlas of Anatomy* (Baltimore, 1943)



"Pulmonary Vessels and Bronchi," from Frank H. Netter, *The CIBA Collection of Medical Illustrations* (Summit, New Jersey, 1948) size of organs varies from individual to individual, and the exact form pathology may take is unique to each one of us. Enormous progress was made over the centuries, using cadavers, to map the interior of the average human body, but until the end of the nineteenth century, a doctor who wanted to know what was going on inside a specific patient's body would have to cut him open, often exposing him to more danger than he was in as a result of the condition that brought him to that doctor in the first place. It is probably not an exaggeration to say that the average doctor in the 1890s would have considered a noninvasive means of seeing under living human skin as unattainable as the ability to read someone else's thoughts.

That was about to change. In 1896, the German-born physicist Wilhelm Roentgen discovered the X-ray and invented X-ray photography, for which he was awarded the first Nobel Prize in Physics, in 1901. Now, for the first time, not without hazards to human health from radiation that it would take decades to understand and prevent, physicians could look inside the body noninvasively from the outside. But interpreting real anatomy from an X-ray is not as easy as it sounds.

The scene depicted in an X-ray is flat. There is no perspective. Everything appears to be located on the same plane. Look at an X-ray of the chest: the ribs, lungs, heart, and backbone appear as if they were all one structure. Furthermore, because the brightness of an object in an X-ray is determined by its physical density, not its relationship to a light source, X-rays don't even present the spatial relationships of objects as we are accustomed to seeing them. A dense object that is actually in the background of a scene may appear so bright in an X-ray that it obliterates objects that are actually in front of it. The correct interpretation of an X-ray image as a view of internal anatomical structure therefore requires a general knowledge of the anatomy in the region of interest, which was most likely obtained from cadaver dissection, the help of an anatomical atlas, and a little bit of imagination. In some of his well-known illustrations of anatomy and pathology, for example, doctor and artist Frank H. Netter juxtaposed X-rays and drawings to help practitioners better relate the one to the other (opposite).

Thus it came about that the availability of the X-ray as a diagnostic tool demanded the mastery of a new skill on the part of the physician: that of reading the X-ray, or rather, of reading a series of X-rays taken from different perspectives. Inevitably, some physicians were better at it than others. The attempt to convey three-dimensional content through a series of related two-dimensional images forces the viewer to imagine or build a third dimension, filling in the blank spaces. It is this self-constructed mental model that the student is asked to learn and understand. But because it is self-constructed, it may be inaccurate.

CT AND MRI

The detail of the anatomy visualized by X-ray technology was continuously improved in the course of the twentieth century. Real-time X-ray technology appeared very soon after the discovery of X-rays, in the form of fluoroscopy, and diagnostic-quality chest X-rays existed before 1910. Instant development Polaroid® film became available in 1951 and was used in order to greatly reduce the time and the facilities needed to develop conventional film. But the difficulty of interpreting a three-dimensional world from a two-dimensional impression continued to exist.

The problem of generating three-dimensional views of anatomy with X-rays was solved by a British engineer named Godfrey Hounsfield, who invented the computed tomography (CT) scanner. Hounsfield's work on the scanner began in 1967 and resulted in a clinically usable machine in 1972. CT scanning – also known as "CAT scanning" – produces an image through a cross-sectional anatomical plane ("tomography" was coined from the Greek word *tomos*, meaning "slice" or "section," and *graph*, meaning "drawing" or "writing"). It took nine days to scan the first object and twenty-one hours to process the data through what was considered, at the time, a large computer in order to produce the first picture. But soon the scanning time was reduced to eighteen seconds per image, and a tumor in a live human brain was visualized. Hounsfield was awarded the Nobel Prize in Medicine in 1979 for his work.

At about the same time the CT scanner was conceived and built, the idea of using magnetic resonance imaging (MRI) technology for visualizing internal anatomy was also conceived. At that time MRI technology was found in chemistry labs and was called nuclear magnetic resonance (NMR). This technology uses varying magnetic fields instead of X-rays to see inside the body. In 1969 Raymond Damadian conceived the idea of a whole-body MRI scanner, and he succeeded in producing the first MRI scan of a live human being in 1977. The ability to turn variations in magnetic fields into images was based on the previous independent work of Paul Lauterbur and of Peter Mansfield. Lauterbur and Mansfield were awarded the Nobel Prize in Medicine in 2003 for their work, causing a controversy in the scientific community because Damadian was not cited. In his Nobel Lecture, Lauterbur stated that the most gratifying emotional rewards of their invention came "when a stranger would volunteer 'you saved my daughter's life,' or 'your machine saved me from an unnecessary operation.'"

The introduction of the CT scanner and the MRI scanner literally introduced the missing dimension into anatomical imaging – the third dimension. Unlike X-ray pictures, which contain all the depth in the image merged into the same plane, CT and MRI images contain almost no depth at all, just a single plane through the object. If there is no depth in the image, where is the third dimension? Through the magic of computer processing, each of these thin depthless slices can be stacked on each other and aligned with its neighboring slice, thereby reconstructing the original object in three dimensions. Using the same computational techniques, the viewer can position himself or herself anywhere inside or outside the object, gaining a new prospective and understanding of the anatomy at hand.

THE VISIBLE HUMAN PROJECT

It is into this three-dimensional synthetic digital world that in 1987 I came upon the concept of providing a real anatomical dataset that could correspond to the CT and MRI datasets being used in clinical medicine – the Visible Human Project®. The goal of the anatomists and artists who created anatomical atlases throughout the centuries was generally two-fold: to portray anatomy realistically and to generate accurate schematic images showing anatomical structures and systems in relation to one another. Some excelled at one or the other of these purposes, and a few did both beautifully, but none was able to create fully three-dimensional images. CT and MRI images may be displayed three-dimensionally, but they don't look like real anatomy. The idea behind the Visible Human Project is to combine the realism and analytical skills of the great anatomical artists of the past with modern three-dimensional display technology provided by the CT and MRI. The problem is easily understood when one realizes that the student sees the CT and MRI images but must treat anatomy. CT and MRI, although three-dimensional and more life-like than X-ray images, are representations of anatomy; they are not true anatomy.

The Visible Human datasets are derived from consecutive digital images taken from real anatomical cross sections of a male and a female cadaver. Because the Visible Human Project was an initiative of the U.S. government, the data it generated would be publicly available, but someone needed to do the physical work of gathering it. The contract for this task was awarded to Victor Spitzer and David Whitlock of the University of Colorado School of Medicine. It wasn't until 1993 that the team acquired a suitable male cadaver; that of a man who had donated his body to science before being executed by lethal injection in Texas. The cross sections of the body were obtained in the following manner. The body was frozen, cross-sectioned into four parts, and embedded in a gelatin-ice mix. Beginning with the feet, the exposed surface of each cross section was sprayed with alcohol and then photographed with a digital camera. Then, a one-millimeter section was planed from each cross section, with a cutting device called a cryomacrotome, and the newly exposed surface was photographed. In this manner, 1,878 high-resolution digital images were obtained. A similar body of data was obtained from the body of an anonymous fifty-nine-year-old woman.

Thus, the Visible Human datasets are made up of consecutive digital images taken from real anatomical cross sections of a male and a female cadaver. Because the data is digital and the images are consecutive, 3D-modeling computer software can be used to reconstruct any aspect of anatomy in three dimensions. While the data does not change, enormous progress continues to be made in both the software and hardware used to convert it into 3D images. The data is presented in a way that corresponds to MRI and CT data, so that the correspondence between CT, MRI, and anatomic data can be learned and the three-dimensional nature of anatomy can be appreciated. The art of the past is combined with the technology of the present to provide a way to study and understand the full complexity of human anatomy in the future.

The Visible Human data has been used for a wide range of educational, diagnostic, and treatment purposes by researchers all over the world. For example, surgeons have used the data to "practice" surgery on the computer before operating on the real patient. Software has been developed that allows medical students to dissect virtual cadavers without destroying them: instead of cutting through muscle to view bone, the user can remove muscles one at a time by moving the cursor, revealing the skeleton with a series of mouse clicks. Environmental health experts are using the Visible Human data to devise computer models that predict the health risk of radiation exposure.

One consequence of the way the Visible Human datasets are

Opposite: These are five pictures using different imaging technologies of a cross section of the head of the male cadaver used for the Visible Human Project. The pictures across the top—a CT scan and three different modalities of MRI—are useful to diagnosticians who are experienced at reading them. They may reveal abnormalities in the density of tissues, for example, or the presence of fluids. The picture at the bottom is a digital photograph of the same cross section, showing the anatomy as it appears in visible light. In this picture, the very dark blue-green area indicates either a cavity or a place where material was lost when the body was sectioned.

CT

MRI
Proton Density

MRI
T1

MRI
T2

Visible Human cryosection

used is that the native format of the Visible Human images is in 3D, and when we look at them printed on the page, we are not seeing them to their best advantage. Because they are modeled in 3D in the virtual space of a computer, they are best viewed with a device like a computer, where they can be rotated in space and seen from different angles. There is a long history of anatomical teaching aids modeled in 3D in materials ranging from wax to plastic, but they always formed a minor tributary to the vast river of 2D imagery. Today, when every medical student has a computer and classrooms are equipped with multimedia equipment, we are probably reaching a turning point in the five-hundred-year history of anatomical illustration, when important new work for the medical community will have only a shadow presence on the page.

During the birth of the Visible Human project, some people predicted that the use of the Visible Human datasets on modern graphical computers would eliminate the need for artists in the field of anatomy. But just as happened in the past, students and teachers of anatomy quickly recognized that the images that resulted from an unedited stream of real-world data were too complex and too detailed for most purposes. Artists of the twenty-first century are now able to base their anatomical images on models generated in the computer from the Visible Human datasets, instead of real cadaver dissections. But it is still their interpretive and innovative renderings that help to make the human anatomy comprehensible.

Opposite: We can do a thought experiment to show how cross sections of a human cadaver might be used to create an accurate 3D model of human anatomy. Assume a stack of pages as high as a standing man. On each page is a drawing of the features you would see if you cross-sectioned the man at that precise spot. Now, let us say that you could cut away the paper on every page up to the edge of the particular anatomical structure that you wanted to reveal. You would end up with a 3D rendering of that structure, to a degree of accuracy controlled by the thickness of the paper. If you used cardboard, for example, your rendering would be much cruder than if you used tracing paper. This is similar to the process by which the digitally captured cross sections of the Visible Human Project have been used to generate 3D renderings of anatomical structures. Essentially, the digital images of the cross sections are manipulated in a 3D-rendering program so that they are arranged sequentially and in alignment, with the edges of any structure keyed so that they can be connected with lines to the edges of the same structure in an adjoining cross section. The contours of the 3D forms generated in this fashion are as accurate as the thickness of the cross sections used to generate them: in the case of the male cadaver used in the Visible Human project, this is one millimeter. The figures opposite were generated from the Visible Human dataset by the Center for Human Simulation at the University of Colorado, where the data was generated. But it is available to all, and researchers around the world have used it to develop virtual 3D models of human anatomy.