Technical Milestone ■

The Visible Human Male: A Technical Report

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Abstract The National Library of Medicine's Visible Human Male data set consists of digital magnetic resonance (MR), computed tomography (CT), and anatomic images derived from a single male cadaver. The data set is 15 gigabytes in size and is available from the National Library of Medicine under a no-cost license agreement. The history of the Visible Human Male cadaver and the methods and technology to produce the data set are described.

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The 1987 Long Range Plan of the National Library of Medicine (NLM) Board of Regents recommended that the National Library of Medicine (NLM) should "... thoroughly and systematically investigate the technical requirements and feasibility of instituting a biomedical images library."[1] The NLM was encouraged to consider building and disseminating medical-image libraries much the same way as it acquires, indexes, and provides access to the biomedical literature.

Innovative research on computer-based representation of three-dimensional anatomic data was already under way in a number of medical centers in 1988 when the NLM convened a meeting of representatives from eight of these centers.[2] The consensus recommendation of the group was that the NLM could contribute substantially to the advancement of the field by supporting the development of an image data set of an entire human male and female, the Visible Human Project.

In 1989, the NLM Board of Regents convened the ad hoc Planning Panel on Electronic Imaging to explore in detail the proper position for the NLM in this rapidly changing field. The panel consisted of 33 members representing all medical specialties and relevant areas of computer science. In its report, adopted by the NLM Board of Regents in April 1990,[3] the panel stated, "[The] NLM should undertake a first project, building a digital image library of volumetric data representing a complete normal adult human male and female. This 'Visible Human' project would include digital images derived from computerized tomography, magnetic resonance imaging, and photographic images from cryosectioning of cadavers." The panel viewed this project as a cornerstone for future collections of related image data sets and a test platform for developing methods and standards for digital-image libraries.

In August 1991, the NLM contracted with two of us (VS and DW) of the University of Colorado School of Medicine to acquire the appropriate cadavers and capture the required images. On November 28, 1994, the NLM announced the availability of a digital data set of human male anatomy. The data set, about 15 gigabytes in size, consists of frontal radiographs, magnetic resonance (MR) images, computed tomography (CT) images, and images of anatomic serial sections from a single "normal" male cadaver.

Search for the Cadavers

Human bodies that become available for medical research and teaching are obtained in most states through gifts by their citizens to the State Anatomical Board (SAB). These boards have been established to consummate arrangements for donations and to over-

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see the handling and appropriate distribution of such material. To achieve the acquisition of cadavers that were as normal as possible for the Visible Human Project, a consortium of SABs of Colorado, Texas, and Maryland was established. Through the combined resources of these boards, a prospective inventory of around 3,000 anatomic gifts per year could be anticipated, which increased the likelihood of obtaining excellent material for the construction of the visible human.

Because the contract called for the acquisition of up to three cadavers of each sex to provide a sample group from which the final choice could be made, a screening process was established. This screening process initially reviewed the available medical records of each candidate for evidence of infectious or metastatic disease, surgery, or any other condition that might have altered or distorted the cadaver's anatomy or otherwise render it unsuitable for the project. The specimen's physical state was carefully examined for evidence of scars or distortion. The size and weight of the candidate were noted, and obese or emaciated cadavers were rejected. Because of the limitations imposed by the instruments to be used later in the preparation of the database, cadavers that were more than 6 feet tall also were eliminated from consideration.

After the history and physical condition of cadavers were evaluated, radiographs of the entire body were taken of those judged acceptable. If no abnormality was found in them, survey CT images were obtained of each region of the body. MR images were also acquired, initially of the head and neck and later through the entire body.

The total information thus collected for each sample-set cadaver was transmitted to the Visible Human Selection Panel established by the NLM, where, after review of these data, the cadavers for the Visible Human Project were selected.

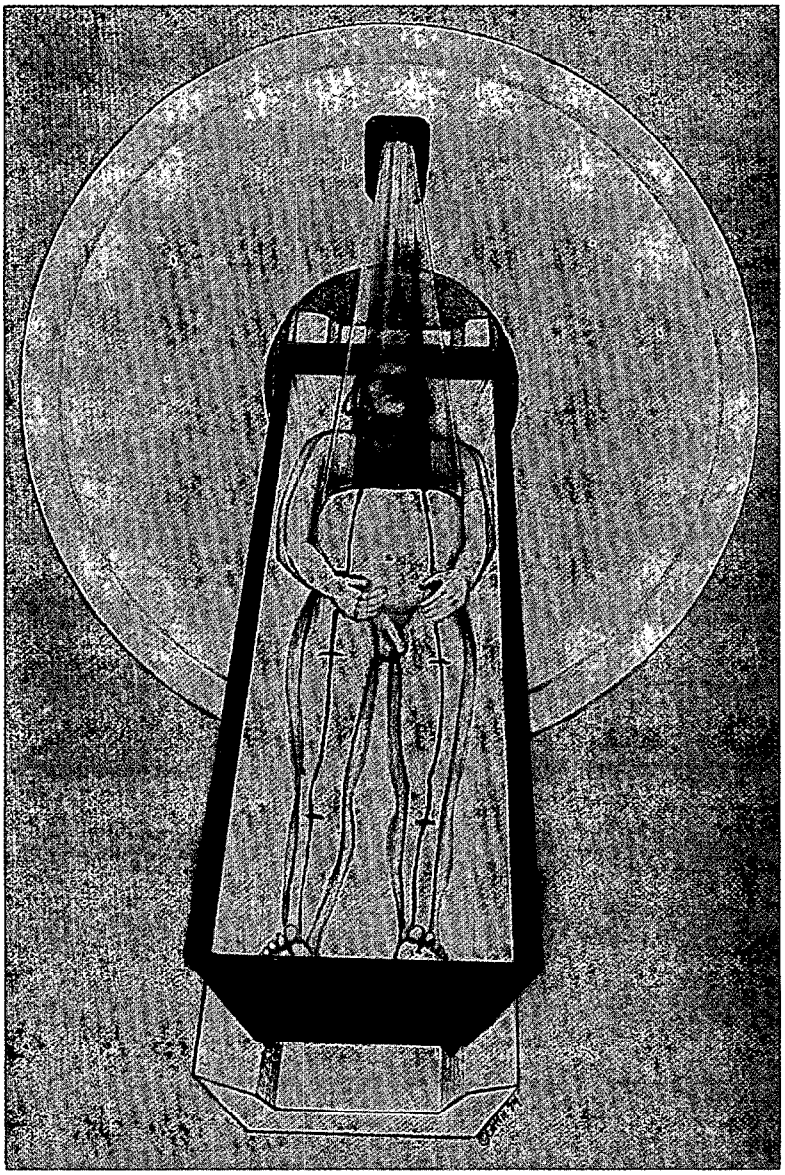
The Cadaver

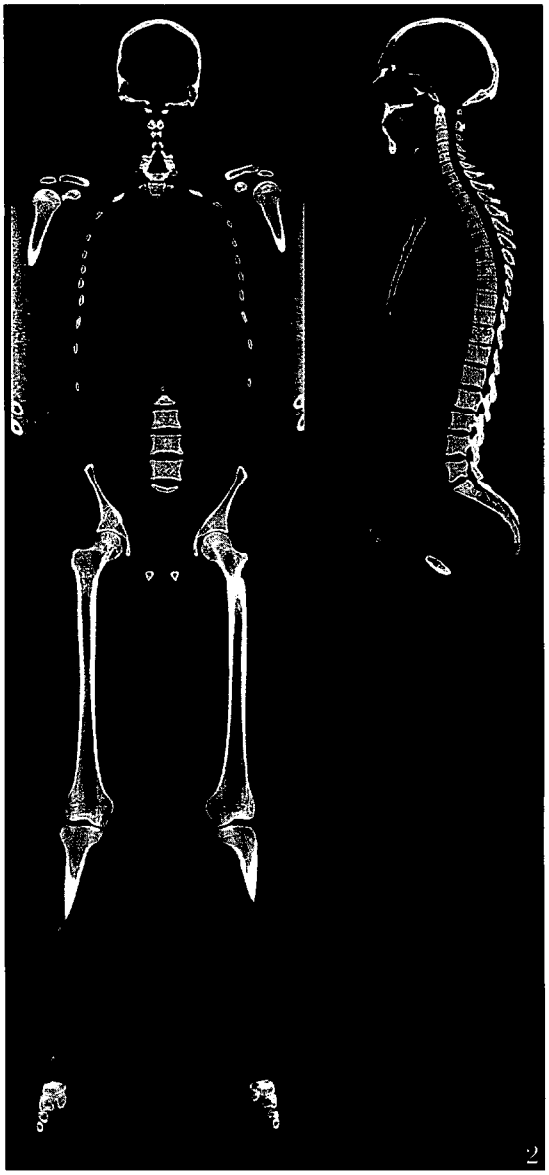
The man whose body was used as the Visible Human Male was 38 years old at the time of death. Before his demise, he had willed his body to the Texas SAB. A white male, he was 71 inches tall and weighed 199 lb. He died at 12:31 AM on August 5, 1993, of court-ordered lethal injection at the Texas Department of Corrections in Huntsville. The body was received by a representative of the Texas SAB about 1.5 hours later. The individual had undergone an appendectomy at age 21 and a left orchiectomy at age 15. Number 14 tooth had been extracted at age 38. No other major variation was noted in the medical record or on physical inspection.

Two tubes of blood were taken from the femoral vein for HIV and hepatitis B testing. Results of these tests were negative. Previous experience with willed cadavers who had died by court-ordered lethal injection had revealed that such remains may undergo massive deterioration within 24 hours of death. The cause of this change is unknown but may be a result of massive membrane depolarization resulting from chemicals employed in the lethal-injection mix. To delay this deterioration and to prepare the body for transfer to Colorado (and the anticipated 36-hour radiologic imaging), the cadaver was perfused with approximately 19 liters of 1% formalin and anticoagulant injection into the right femoral artery. Approximately 16 liters was injected into the vessel cranially, and 3 liters caudally. The dorsum of each forearm was also injected subcutaneously with approximately 60 ml. The right femoral vein was opened for drainage. The venous blood flow was regular, and an estimated 3 liters was drained. The femoral cut-down site was sutured, and the body was cleaned and packed for transfer to Colorado. The cadaver was shipped by air freight to Denver. The body was received at the Colorado SAB morgue at 8 hours after death and was then unpacked, inspected, and given the number 6022.

A fluoroscopy survey and anteroposterior (AP) film radiographs of the entire cadaver were taken at 12.5 hours after death, in the Department of Radiology Imaging Research Laboratory. Fifteen radiographs were obtained and later digitized as 2,048 × 2,048 × 14–bit images with a Leaf camera that was also used for imaging the cryosections. At 15.5 hours after death, the body was prepared for imaging and possible future sectioning for The Visible Human Project. Cotton gauze was placed both over the mouth and in the nose, and the head was wrapped. Two 1-mm ID, 3-mm OD Tygon tubes filled with a 4-millimolar solution of copper sulfate (for MR contrast) and 5% Omnipaque (an iodine solution for CT contrast) were attached with Liquid Nails to the skin surface of the anterior aspect of the body, from the head, down the trunk, and down each leg and foot. These tubes remained in place for the duration of processing, serving as fiducial markers (Fig. 1).

Because of the possibility of rapid massive deterioration of the cadaver, the time and condition of the cadaver were carefully monitored. Measureament of gas accumulation in tissues and bowel seen during the initial imaging was recorded, so that any evidence of early deterioration could be detected.





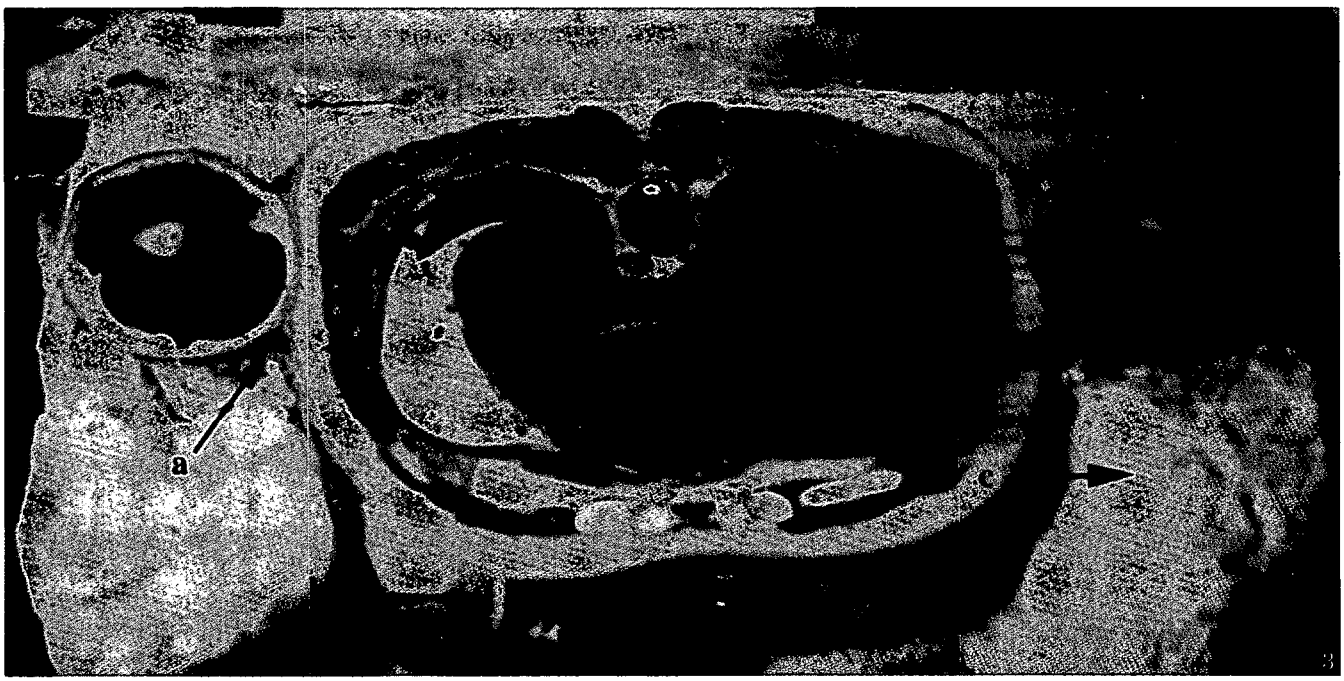

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Figure 1 (*Facing page, top left*) The lines up the anterior portion of the lower extremities and trunk that are continuous to the top of the head show the location of the Tygon fiducial tubing that was fixed to the body. These plastic tubes were filled with copper sulfate for registration of the MR, CT, and cryosection data. They were placed before MR imaging. The laser positioning light of the CT scanner is also indicated. This was used to mark the optimum location for sectioning the cadaver into four blocks. The wooden box and the surrounding, immobilizing "Alpha Cradle" were also included in the CT procedure.

Figure 2 (*Facing page, top right*) These coronal and sagittal views were reconstructed from the 1,878 transverse CT images. A bone window was used for the data.

Figure 3 (*Facing page, bottom*) A view of the inferior surface of the most superior block of the Visible Human Male. Notice the fiducial tubing on the anterior surface (b) and the blue gelatin between the surface of the abdomen and the upper extremities (a) used to "glue" the forearms to this and the second, or abdominopelvic, block. The alpha cradle foam (c) surrounds the body.

MR Imaging

Because pilot studies had shown that both CT and MR images of the human body were degraded by freezing, scans were captured, where possible, from the unfrozen specimen. To achieve that goal, the cadaver was transported to University of Colorado University Hospital MR CT Imaging Center and transferred to the imaging table of the General Electric 1.5 Tesla Signa Magnetic Resonance Imager. Imaging began at 18 hours after death and was completed 3.75 hours later. Images were acquired in the axial plane using the head coil. The remainder of the cadaver was imaged in the coronal plane with the body coil (Chart 1). All images were stored in General Electric Genesis format as 256 × 256 × 16-bit matrixes. The images were achieved to write-once optical disk from the MR console. The images were also transferred via ethernet to the Anatomical Visualization Laboratory in the University of Colorado School of Medicine and were stored on 4-mm DAT tape.

Immobilization

The Visible Human data set includes congruent sets of anatomic cross sections and CT images at 1-mm intervals from head to toes. This goal required that the CT scans be acquired mainly from the fresh, unfrozen cadaver, and later, that the specimen be cut so that each cross section would match its corresponding clinical image. This process was accomplished by first positioning the cadaver in a plywood mold designed for immobilizing the body. This immobilization provided a constant body configuration for both the subsequent CT scanning and the eventual 1-mm cryosectioning. The plywood mold was lined with two layers of plastic, one layer to protect the cadaver, another layer to protect the mold itself from the immobilizing foam. The cadaver was carefully positioned in the mold in the inner layer of plastic, with attention given to maintenance of the vertical plane of body symmetry. Three extra-large units of Alpha Cradle AC660 (Smithers Medical Products, Inc., Akron, OH), a foaming agent used in radiation therapy, were activated, and the solution was poured between the two layers of plastic that lined the mold. Within 15 minutes, the Alpha Cradle expanded and solidified around the cadaver, filling the mold and thus effectively immobilizing the cadaver.

Fresh Computed Tomography

The cadaver was taken to the University of Hospital CT suite 22.5 hours after death. The entire assembly of the cadaver, Alpha Cradle, and plywood mold was placed on the CT bed for scanning. Runners on the bottom of the mold aided in positioning it parallel to the long axis of the CT table. A General Electric High Speed Advantage scanner was used. Transverse images were collected every millimeter through the head and neck; every 3 mm in the thorax, abdomen, and pelvis; and every 5 mm in the lower extremities (Chart 2). The plywood box assembly was rotated 180 degrees on the CT bed for imaging the lower extremities.

The transverse colon was monitored for abdominal gas by imaging. The ratio of the diameter to the length of the colon had been noted on the radiographs to be 0.36 at 12.5 hours after death. At 23 hours after death, it was measured to be 0.45 on the CT table. This condition prompted the decision to space the imaging of the trunk and lower extremity at 3 and 5 mm as well as the decision not to image the section of the lower extremities, from just superior to the knees to superior to the ankles. CT imaging was completed at 25.5 hours after death.

Freezing

The plywood box assembly was removed from the CT scanner and returned to the SAB morgue, where it was covered with a thick plastic sheet. The entire assembly was lowered into a specially constructed freezing chamber at 26 hours after death. The chamber was constructed so that dry-ice cakes could be suspended above the cadaver and was insulated on all sides with 3 inches of Styrofoam. Body temperature was not monitored, but previous experience with thermocouples inserted to the core of cadavers of similar size yielded complete freezing in less than two days. Initially, 150 lb of dry ice was placed in the chamber, and another 175 lb was added 8 hours later. On August 8, 1993, 150 lb of dry ice was added to the chamber, and it was noted that approximately 100 lb remained from two days before. The cadaver was maintained in the dry-ice freezing chamber until October 15, 1993, when it was transferred to a walk-in freezer, where the temperature was maintained at or below −7°C.

Final Selection

On September 2, 1993, the NLM's Visible Human Selection Panel held its third meeting by conference call. The panel was made up of anatomists and radiologists. CT and MR images of two anonymous cadavers had been mailed to panel members the previous week. Based on these images and the known medical histories, the panel was to discuss whether one of these cadavers should become the Visible Human Male. Previous meetings had not resulted in a decision to proceed. The panel decided unanimously to

File Numbers	Region	Plane	TR (msec)	TE (msec)	Protocol	Thickness/ Spacing (mm)
m_vm0000.loc	Locator	Images				
2001-2012	Head	Sagittal			Locator	
3001-3010	Neck	Sagittal			Locator	
4001-4012	Thorax	Sagittal			Locator	
5001-5004	Pelvis	Sagittal			Locator	
6001-6010	Knees	Sagittal			Locator	
7001-7008	Feet	Sagittal			Locator	
m_vm0000.t1	T1	Weighted	Images			
1005-1165	Head	Axial	500	16	SE	
3392-3640	Neck	Coronal	600	16	SE	4/0
4392-4668	Thorax	Coronal	500	16	SE	4/0
5350-5672	Pelvis	Coronal	700	16	SE	4/0
6378-6598	Knees	Coronal	800	16	SE	4/1
7405-7625	Feet	Coronal	800	16	SE	4/0
m_vm0000.t2	T2	Weighted	Images			
1005-1165	Head	Axial	5,500	102	FSE/V	4/1
3392-3640	Neck	Coronal	5,000	102	FSE/V	4/0
4392-4668	Thorax	Coronal	3,000	102	FSE/V	4/0
5350-5672	Pelvis	Coronal	4,000	102	FSE/V	4/0
6378-6598	Knees	Coronal	3,600	102	FSE/V	4/1
7405-7625	Feet	Coronal	4,500	102	FSE/V	4/0
m_vm0000.pd	Proton	Density	Weighted	Images		
1005-1165	Head	Axial	5,500	17	FSE/V	4/1
3392-3640	Neck	Coronal	5,000	17	FSE/V	4/0
4392-4668	Thorax	Coronal	3,000	17	FSE/V	4/0
5350-5672	Pelvis	Coronal	4,000	17	FSE/V	4/0
6378-6598	Knees	Coronal	3,600	17	FSE/V	4/1
7405-7625	Feet	Coronal	4,500	17	FSE/V	4/0

Chart 1 MR chart. FSE = fast spin echo; SE = spin echo; V = variable bandwidth.

proceed with SAB number 6022 as the Visible Human Male.

Frozen Computed Tomography

With the cadaver placed in its plywood chamber, CT scanning in the frozen state was performed at 1-mm-slice thickness on 1-mm centers from head to midcalf on August 29, 1993, and from midcalf to toes (Fig. 2) on October 14, 1993 (Chart 3).

Sectioning of the Cadaver

The cutting system, or cryomacrotome, was developed at the University of Colorado Medical School in the former Department of Anatomy. The machine used in the Visible Human Project consisted of a milling device whose controls had been automated and drives upgraded to retain accuracy when subjected to the intense cold. The cutting blade was a specially constructed disk, 14 inches in diameter, with 20 specially hardened teeth mounted around its edge. For cutting, this blade remained in a fixed position above the block containing the specimen and was rotated at a speed of 300 rpm. The frozen-tissue block, which was bolted to the movable mill table, was passed under this spinning blade for each cut. After image capture, the block was returned to the cutting chamber, where it was raised to the next desired height.

This cutting system has successfully shaved blocks containing tissues to 0.1-mm intervals. To achieve that accuracy and those obtained in the Visible Human Project, the machine was maintained on a scheduled basis, and the overall system was calibrated before sectioning each block.

The physical limitations of the cutting system required that the cadaver be cut into four segments and that each block be no larger than 22 inches in height, 21 inches in width, and 14 inches in depth.

Blocking

On November 11, 1993, CT scanning of the cadaver in its plywood chamber was performed again to determine the optimal locations for the backsaw cuts necessary to section the cadaver into four blocks. This step was necessary so that each block's dimensions would be acceptable to the cryomacrotome. The cadaver was positioned so that the center of the vertebral body, yielding a block of less than 20.36 inches from the head, could be marked with the CT laser

File Numbers c_vm0000.fre	Spacing (mm)	FOV (mm)	kV	mA	Secs
1012-1019	1	250	120	170	2.0
1020-1078	1	460	120	150	2.0
1079-1161	1	345	120	170	2.0
1162-1288	3	450	120	170	2.0
1291-1957	3	460	120	170	2.0
1958-2263	5	480	120	170	2.0
2688-2893	5	480	120	170	2.0

Chart 2 Fresh CT chart. FOV = field of view.

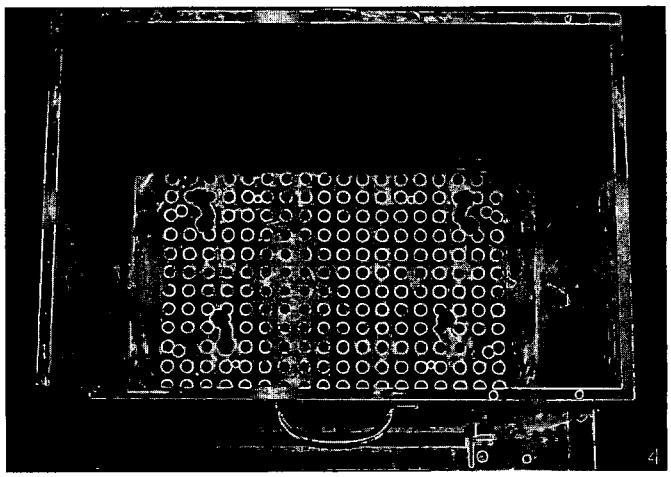
File Numbers c_vm0000.fro	Spacing (mm)	FOV (mm)	kV	mA	Secs
1006-1236	1	270	120	170	2.0
1237-1260	1	400	120	170	2.0
1261-2025	1	480	120	170	2.0
2026-2482	1	480	120	140	2.0
2483-2621	1	480	120	120	2.0
2621-2658	1	480	120	200	2.0
2659-2882	1	480	120	140	2.0

Chart 3 Frozen CT chart. FOV = field of view.

positioning light. Centering the saw kerf in this manner provided the flattest surface possible for cutting axially through the body. This point was marked on the skin for later alignment of the saw. Two other points were marked to yield blocks less than 20.36 inches, so that the two remaining saw kerfs were in the shaft of the femur and the shafts of the tibia and fibula. The cadaver was then returned to the walk-in freezer.

A high-tension backsaw (Denton Model 1624 Sectioning Saw) was specially constructed. The backsaw was designed to produce cuts congruent with the CT scans. To keep the cuts as planar as possible, the backsaw blade was put under extremely high tension and manually operated. A 1.3-mm-thick blade was used to obtain consistent planar cuts (Fig. 3).

On January 20, 1994, the cadaver was transferred from the walk-in freezer (−7°C) to the freezing chamber (−70°C), in which it was originally frozen with dry ice, in preparation for sectioning with the backsaw. Previous tests indicated that the most uniform saw cuts could be obtained with the specimen at this lower temperature. After 2 days, the cadaver was removed from the freezing chamber. The Alpha Cradle was re-



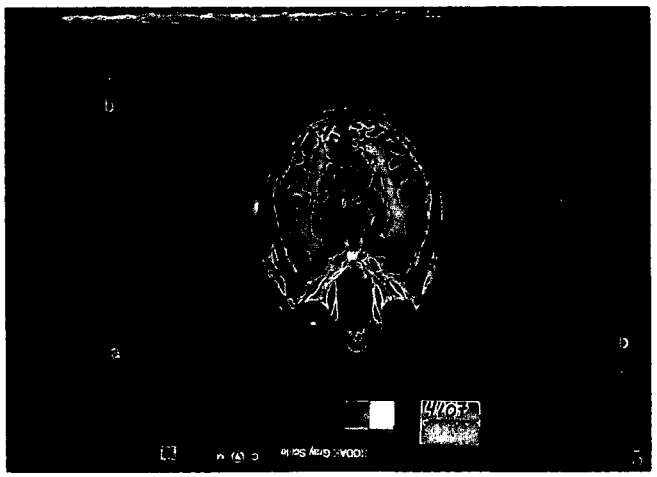


Figure 4 (*Top row, left*) Looking down into the aluminum-sided mold used to embed the blocks of the Visible Human Male. Notice the sieved baseplate whose holes were used to position vertical fiducial rods around the specimen.

Figure 5 (*Top row, right*) This image from the Visible Human data set has two fiducial I beams (b) in the field of view. The third fiducial rod is a round and uniform gray (a). These three fiducial rods are fixed in the baseplate and in a matched top plate. The gelatin surrounding the specimen filled the mold.

Figure 6 (*Middle row*) The congruence of the CT and anatomic images can be demonstrated by overlaying a coronal or sagittal slice derived from the registered image collection. Such nonoverlayed images are shown above.

Figure 7 (*Right*) Applications of the future for these data include surgical as well as other simulations. This electronic scalpel cut through the knee of the Visible Human Male was accomplished in real time (at video rate) on a Silicon Graphics Onyx Reality Engine. The inside texture was derived directly from the cross-sectional data.

moved from an area around the proximal portion of the forearms and hands. Gelatin (described later) was poured into the space between the cadaver's forearms and abdomen to stabilize and "glue" the forearms to the abdomen. Once frozen, this gelatin served to keep the forearms and hands in the same position relative to the abdomen, even after they were severed from the arms just above the elbows.

On January 24, 1994, the frozen cadaver, immobilized in its Alpha Cradle mold, was positioned and clamped to the bed of the backsaw. The blade was aligned at 90 degrees to the long axis with surface marks previously placed on the skin surface using the laser light of the CT. The four blocks obtained consisted of: 1) legs, ankles, and feet; 2) thighs and knees; 3) abdomen and pelvis; and 4) head, neck, and thorax. The kerf loss between them was approximately 1.5 mm. The cut surfaces were measured and were found to be uniform and flat.

Embedding

General Procedure

To cut the individual segments of the cadaver at 1-mm intervals, each block needed to be embedded in a suitable medium, which when frozen would provide stability for the cutting process. Embedding was accomplished by first constructing an aluminum mold of sufficient size and with break-apart sides, top, and bottom. The specimen was positioned in this assembled mold so that its cut surfaces retained alignment with the CT imaging plane, and the entire block was surrounded with a liquid medium. The mold and its contents were ultimately frozen to achieve a rock-hard block containing the tissue that could be removed from the mold and cut serially by the cryomacrotome. The general procedure consists of removing individual blocks from the Alpha Cradle and placing them in the aluminum mold. The inner dimensions of the aluminum mold were 22 inches mediolaterally, 14 inches anteroposteriorly, and 20.36 inches inferosuperiorly. The mold consisted of four removable aluminum sides mounted on an aluminum base plate. The dimensions of the base plate were 26.6 inches mediolaterally and 19.5 inches anteroposteriorly. The ends of the base plate were notched on the mediolateral sides for mounting to the cryomacrotome table. The base plate also had rows of 0.5-inch threaded holes. These holes served several purposes, as described below. The final piece of the mold was an aluminum registration plate that was mounted on the top. This top plate was pin-aligned with the base plate and was machined with the same pattern of 0.5-inch holes.

The embedding procedure began with the positioning of several large black Delran (plastic) screws on the base plate. These screws were 0.5 inch in diameter, so that they could be screwed directly into the threaded holes of the base plate. The head of each screw was a cylinder, 1.5 inches in diameter, 1 inch in height. These heads were positioned so that any exposed bones of the inferior surface of the block would rest on these cylinders to support and level the block. Once the optimum positions were determined, the screws were tightened in place, and the cryomacrotome was used to plane the screws level (Fig. 4).

At this point, the mold was assembled except for the top plate. The specimen was then positioned in the mold. The flat inferior surfaces of all the blocks, except the one containing the legs and feet, were set on the cylindric heads of the Delran screws. The flat posterior surface of the block, which was perpendicular to the inferior surface, was set against the posterior side of the mold. The specimen was then wedged in this position using a scissor jack to stabilize it during the addition of the gelatin solution. Three fiducial rods were positioned in the 0.5-inch holes of the base plate at the corners of the block. Two of these rods were plastic I beams measuring in cross section $^3/_8 \times ^3/_8$ inch. They were positioned in the registration holes in the base at corners on the cadaver's right posterior and left anterior sides. The third rod was a cylinder of gray resin designed to be of homogeneous color within 1% throughout its length. It was placed similarly in the corner at the cadaver's right anterior side. The pin-mounted alignment plate was affixed to the top of the aluminum mold to hold the tops of these rods in the same z-axis with their bottoms.

A 3% gelatin solution colored blue with food dye was used to fill this mold. The gelatin was siphoned into the mold, filling approximately 25% of it. The unit was packaged in dry ice to freeze this first gelatin layer. Once the gelatin was solid, the mold was transferred to the Ultra Freezer (−85°C) for at least 12 hours. The following day (or much later on the same day), the mold was removed from the freezer and partially disassembled. The scissor jack and any other materials used to wedge the specimen were removed. The mold was reassembled, and another layer of gelatin was siphoned into the mold, filling another 25% of it. That layer and each successive layer were frozen using dry ice. When the final layer was solid, the mold was again transferred to the Ultra Freezer for complete freezing and storage.

Before the cryomacrotoming process, the top plate and sides of the mold were removed, leaving the frozen specimen-gelatin block on the base plate. Ply-

wood sides were attached to the anterior and posterior edges of the base plate. The mediolateral sides were replaced with 0.75-inch-thick Styrofoam plates that were cut down as the cryomacrotoming proceeded. Because the base plate was larger than the mold (see dimensions above), there was a 2.75-inch space between the block and the plywood/Styrofoam sides. This space was frequently packed with dry ice during a cryomacrotoming session, when the block was not in the Ultra Freezer.

Block-specific Procedures

The general embedding process is described above. There were variations from that process, due to the anatomic uniqueness of each of the four blocks.

The first block cut, and the most difficult one to position, contained the legs and feet. In preparation for embedding, a transverse channel approximately 4 inches wide was cut into the Alpha Cradle mold in the middle of the legs. Blue gelatin was poured into the channel, creating a bridge between the cadaver's legs, to maintain them in their original position (January 25–26, 1994). After the gelatin bridge was frozen, the remaining Alpha Cradle was removed. The specimen was positioned and wedged against the back of the aluminum mold using the newly created posterior flat surface of the gelatin bridge. There was no flat inferior surface to rest on the screws, although one toe rested on a Delran screw, so the superior cut surface was leveled in relation to the cryomacrotome blade (January 27–28, 1994). Sufficient space remained at the top of the mold of the first block to embed a 2-inch-thick section of another cadaver's head. This was done to provide final test cuts before cutting into the legs of the Visible Human Male.

The second block embedded contained the thighs and knees. As in the first block, a gelatin bridge was created to maintain the original orientation of the thighs and knees. This bridge was created at the most inferior level of the block—the knees and below (March 14–15, 1994). The Delran screws were positioned so that the tibia and fibula of each leg would each rest on a screw. In this second block and in all subsequent blocks, 1-inch aluminum spacers were used to position the specimen away from the posterior side of the mold. The posterior flat surface of the gelatin bridge was positioned against these spacers (March 15, 1994). These spacers were used to ensure that the gelatin would surround the tissue. For several inches during the cryomacrotoming of the first block, the calves were at the posterior edge of the block with no gelatin behind them. The skin did not cut cleanly without surrounding gelatin as a heat sink. Once the specimen was locked in place in the first layers of frozen gelatin, the spacers were removed along with all wedging materials, and the remaining space was filled with gelatin. The embedding of the thighs was completed within one long day.

The third block contained the abdomen and pelvis. No bridge was required at the time of embedding (April 6–7, 1994), because the forearms had been previously "glued" in position with gelatin at the time of the sectioning of the cadaver into the four blocks. The Delran screws were positioned so that the femur of each thigh rested on a screw. The posterior surface used to position the specimen against the posterior side of the mold was the cadaver's body itself. The inevitable settling and flattening of tissue on which the prefrozen cadaver's weight rested were advantageous. The flatness of the cadaver's back and buttocks was used to position the specimen in the mold.

The fourth block contained the head, neck, and thorax and was embedded on May 3 and 4, 1994. No bridge was required. The Delran screws were positioned so that a vertebral body, the humeri, and various ribs all rested on screws. The posterior surface used to position the specimen against the posterior side of the mold was again the cadaver's own body. In this block, the flatness of the cadaver's upper back was used to position the cadaver in the mold.

Cryomacrotoming

Each day began with a 45- to 60-minute setup. A "beginning daily checklist" was created. Setup included removing the block from the Ultra Freezer, mounting the block to the cryomacrotome table, and filling the space between the block and the plywood/Styrofoam sides with dry ice. Plastic wrap was put in place to line the interior walls of the cutting chamber for easier cleanup. Thicker plastic lined the gutters on either side of the block to catch the bulk of the debris. Plexiglass plates were mounted to protect the body of the cryomacrotome. The photographic chamber was a wooden structure to which black butcher paper was stapled. This paper was in place as a nonreflective surface to contain debris. This wooden structure was fitted with a plexiglass protective lid, which was removed after each slice was planed to allow imaging of the slice. With debris containment and protective measures in place, the cryomacrotome table was moved to the height at which it ended during the previous cutting session. The new start point was then set. Once all of the cameras were turned on and the software programs on the personal computer (PC) and Macintosh computers (see Image Capture and

Photography) were initialized, the actual cutting began.

The cutting process required two operators, a mill operator and a computer operator. During the cutting process, the cryomacrotome operator routinely wore protective clothing, which included eye shields and mask, a dissection suit with boots and hood, and rubber gloves. The process was as follows. The mill operator switched on the cryomacrotome blade with a foot switch. Using a handheld computer controller, the mill operator moved the cryomacrotome table in the direction of the x-axis from its starting location in the cutting chamber under the spinning blade and into the photographic chamber. When the table reached its endpoint, the blade was turned off. The plexiglass lid was slid back to expose the newly cut surface. Compressed air was used to blow off loose debris from the surface. A scalpel was used to trim any uncut or poorly cut structure, such as tendons, which did not always cut cleanly. The scalpel was also used to remove any other debris, such as specks of blue gelatin or latex that may have become dislodged. Compressed air was used again to clear the surface.

The surface was sprayed with absolute ethyl alcohol. A black mask was placed on the surface to frame the specimen and to eliminate possible glare from the dry ice surrounding the block. A gray-scale strip remained attached to the black mask and appears anterior to the specimen in the images. A yellow post-it note with the original image number was placed next to the gray-scale strip. The numbering scheme for the original images of the first block started at 1,001, the second block at 2,001, the third block at 3,001, and the fourth block at 4,001. The mill operator called out the slice number to the computer, indicating that preparation for photography was complete. All imaging was performed under the control of the computer operator in the isolation booth. The computer operator confirmed the slice number and began the imaging process (Fig. 5).

The three-image photographic process was facilitated by a translation table interfaced to a PC. The first action of this system was to turn off the overhead light in the photographic chamber and move the translator table so that the Leaf digital camera was in the proper position to capture the image. When that camera was positioned, the PC presented a message prompting the computer operator to trigger the Leaf camera using the Leaf software on an Apple Macintosh computer. Once the picture was captured, the computer operator viewed the image to ensure that the preparation of the block surface was complete and optimum for photography. The computer operator then pressed the return key on the PC to continue with the program that would take two film pictures with the 3003 camera and 6008 camera (see Image Capture and Photography). The PC directed the translator table to the 3003 position, triggered the 3003, then moved to the 6008 position, triggered the 6008, turned the overhead light back on, and finally returned to the Leaf position, ready for the next cycle. Meanwhile, the computer operator assigned the Leaf digital image the proper slice name and saved it on the Macintosh computer's hard drive. The computer operator also recorded the x and z positions from a digital readout attached to the cryomacrotome table and the slice number, confirmed that the slice number was correct on the Post-it note in the image and that each camera triggered successfully, and made other notable comments.

Once the overhead light came back on in the photographic chamber, the mill operator placed a dry-ice tray on the block surface for 30 to 60 seconds of refreezing. The tray of dry ice was removed, and the cycle repeated. Every 30 cycles, the film was changed in the 3003 camera, and every 60 cycles, the film was changed in the 6008 camera. The average number of cycles, and hence slices per day, was about 50. The cycle times ranged from 3 to 15 minutes. The primary factor determining the cycle time was the amount of scalpel work required and whether latex fill was required (see below).

An occasional difficulty encountered was the ejection of small segments of tissue from the block. This problem occurred when 4 mm or less of a structure was not attached to anything inferior to it. At the end of each block, tissue was sucked away from the gelatin interface by the negative pressure caused by the spinning cryomacrotome blade. Also, internal structures that were not attached to anything inferior to them were ejected. Examples include the last few millimeters of the condyles of the femur, of some bones of the foot, of the temporal lobe of the brain, and of the cerebellum.

Blue latex was added to any cavity that was exposed during the cutting process, to stabilize the walls of that cavity and prevent debris from collecting in the cavity (the homogeneous color of the latex would be easier to subtract from the digital image than the nonhomogeneous colors of the debris). Examples of these cavities included the nasal sinuses, the trachea, the small intestines, and the colon. The cavities that were created when tissue was ejected (as described above) were also filled with latex.

On completion of a day's work, the block was removed from the cryomacrotome table and returned to

the Ultra Freezer (−85°C) until the next cutting session. Each day ended with another 30 to 45 minutes of cleanup. An "end-of-the-day checklist" was followed. The cadaver debris was collected, refrozen, and saved for cremation. The cryomacrotome blade was cleaned, and the entire cryomacrotome oiled. All of the removable plexiglass lids and shutters were removed and cleaned, as were the gutters. The plastic wrap lining the cutting chamber and the black paper lining the photographic chamber were replaced about once a week.

Cutting of the test specimen on top of the first Visible Human Male block began on February 17, 1994, and was finished on February 24, 1994. The 1-mm cutting of the Visible Human Male began on February 25, 1994, at the highest level of the first block, just inferior to the knees. Cutting of the first block (the legs and feet) was completed on March 21, 1994. Cutting of the second block (the thighs) was finished on April 4, 1994. Cutting of the third block (the abdomen and pelvis) was finished on April 30, 1994. Cutting of the fourth block (the head, neck, and thorax) was finished on May 19, 1994.

Image Capture and Photography

Photography of the Visible Human Male cryosectioning included production of a digital image for quality control as well as production of the digital database and two film records for redundancy and archival storage. The digital red, green, and blue images were acquired with a Leaf CCD camera back using a color filter wheel in front of the camera) under polarized strobe lighting from four heads. The Leaf camera back was attached to a Hasselblad 553 ELX camera body using a Carl Zeiss Distagon f4 50-mm lens (set at f6.8) with a polarizing filter. The resultant field of view was 25 square inches. Each of the three digital images (red, green, and blue) making up the full color image was captured in 2,048 × 2,048 × 14-bit TIFF format. The voxels in this database, therefore, were 0.32 × 0.32 × 1.0 mm. Each of these digital images was stored on the Apple Macintosh Quadra 840 AV as it was collected. Each image was also transferred, via ethernet, to a SUN 4/330 computer with a PIXAR image-processing computer. The image data on the SUN computer was archived to 4-mm DAT tape at the end of the day. Two 4-mm DAT tapes were individually written and verified and were then stored in separate locations. After the first tape was verified, the data were erased from the original image-capture disk on the Apple Macintosh Quadra 840 AV as space was needed.

Each digital image was inspected and archived while the two film images were acquired. The first film image was acquired with a Rolleiflex 3003 35-mm camera body using a Carl Zeiss Makro-planar f2.8 60-mm lens (set at f5.6) with a 1/3 ND filter and a polarizing filter. Thirty-six-exposure rolls of Ektar 25 film (all of the same stock number) were used in this camera. The second camera was a Rolleiflex 6008 70-mm camera body using a Carl Zeiss Makro-planar f4 120-mm lens (set at f8) with a polarizing filter and an 85B filter. Seventy-exposure rolls of Ektachrome 64T tungsten (all of the same stock number) were used in this camera. All film was removed from its refrigerator storage at least one day before use. After exposure, the film was returned to the refrigerator. On completion of the Visible Human Male project, all of the film was processed at the same time.

Digital Image Processing

All digital images were reduced from 42-bit (14 bits of red, green, and blue) to 24-bit images by independently and logarithmically compressing the 14 bits of each channel to 8 bits. Each pixel value in each image was raised to the 0.57143 power for this compression: byte image (*,*) = byte [integer image (*,*) ^ 0.57143 + .5]. The images were cropped in the anteroposterior (AP) dimension of the anatomy from 2,048 to 1,216 pixels. Frame alignment was accomplished by aligning two of the most convenient fiducial rods. The cross-sectional I-beam shape of two of the rods helped facilitate their alignment. Because the specimen base plate was pin-registered to the cryomacrotome table, no image rotation and little translation were required to register the images in a block.

Interblock spacing was determined by comparison of the stacked anatomic slices with the frozen-state CT scans. The cryosection and CT scans were compared for anatomic detail on either side of each kerf loss. The closest alignment of anatomic detail of these neighboring slices was achieved through visual comparison of anatomic landmarks, to establish the correspondence between anatomic and CT slices throughout the block and to provide alignment and spacing for the slices lost in kerf. Note that not all losses in the gaps of the data are due to the kerf loss from the saw. Partial slices are included in the 42-bit "raw" images that were eliminated from the "processed" 24-bit images due to their having little anatomic content or because the tissue was permeated with the blue gelatin. These partial slices can be attributed to the opposing cut surfaces of the second and third blocks' not being perfectly parallel, or from

the inferior surfaces of the second through fourth blocks' not being perfectly flat. Other losses include actual loss of tissue during the cutting of the last few slices of a block.

When the alignment of CT scans and anatomic slices was finalized and the anatomic kerf spaces were determined, the anatomic and CT slices were renumbered to reflect the correspondence. Numbering was started at 1,001 and proceeded to 2,878. Anatomic slices missing due to kerf loss were indicated by the use of empty files as place holders. CT slices were numbered as c_vmXXXX, and the anatomic slices were numbered as a_vmXXXX. The resultant digital data set consisted of anatomic slices in 24-bit "raw" file format and CT slices numbered correspondingly, still containing their original General Electric format headers.

The MR images were numbered to reflect some anatomic correspondence to the CT and anatomic slices. The head images were transverse but not necessarily in planes parallel to the CT and anatomic slices. The best possible visual alignment was established between the anatomic and MR images, and the images were numbered accordingly. Consequently, the MR images are numbered as m_vmXXXX from 1,001 to 1,165 in the head, with an average slice spacing of 4 mm. For the coronal MR images of the body, each set of images is numbered at the next 1,000, and the numbers within the series are an index of the MR table position. This arrangement allows some alignment in the AP direction based on the three-digit file number for these coronal slices (Fig. 6).

Data Set Access

Sample scaled-down Joint Photographic Experts Group (JPEG) versions of images from the Visible Human Male data set can be found through the NLM's World Wide Web home page (*http://www.nlm.nih.gov*) in the Visible Human Project section. The complete data set is 15 gigabytes in size and is available from the NLM under a no-cost license agreement. The data set is being distributed over the Internet via FTP or on 4-mm or 8-mm tapes. All inquiries should be addressed to The Visible Human Project at the NLM.

Discussion

Atlases of anatomy have long been the mainstay for visualizing and identifying features of the human body. Many are constructed of idealized illustrations rendered so that structures are presented as three-dimensional pictures of an organ or region. Others have employed photographs of actual dissections, either labeled or coupled with drawings in which features of interest are identified. Still others are composed of collections of illustrations made of dissections in which the artists have faithfully depicted individual structures in considerable detail. All rely on graphic display of the human form to allow better understanding of its structure.

Since the introduction of powerful clinical imaging systems, notably CT scanning and MR imaging, several atlases devoted to cross-sectional human anatomy have appeared. Structures are shown as photographs, clinical images, drawings, or illustrations in transverse, coronal, or sagittal planes, often designed to aid in the interpretation of clinical images. Cross-sectional planes shown in these atlases, however, have been obtained from different cadavers; thus, translation from one plane to another is sometimes difficult. The cross sections shown usually have been derived from material cut at thicknesses of 1 cm or more. Because clinical images can be obtained with modern CT or MR machines at intervals as small as 1 to 3 mm in thickness, existing atlases do not allow examination of the anatomy at that level of resolution.

The Visible Human Male data set provides solutions to both of these problems. Because the cross sections of the male were cut at 1-mm intervals, the anatomic detail available exceeds that currently seen in clinical images. Also, because the Visible Human Male data set can be compiled as a volume of data, it can be reformatted, even warped, and displayed in any desired plane through that volume. The resultant images are obtained from the same specimen and are directly comparable from one plane to another. The Visible Human Male data set, therefore, is not only an atlas of cross sections for the entire human male body, but also one of high resolution and manipulative ability, so that any part can be viewed through different planes.

As of December 1995, the data set was being used by more than 350 research, academic, and industrial groups in 25 countries. The images are being used for the teaching of anatomy and other health subjects from high school through medical school. They are also being used as the basis for models of radiation absorption and therapy, crash injury, ergometric design, and surgical planning. A virtual colonoscopy has been demonstrated,[4] and a virtual laparoscopic simulator is expected shortly. The data set is providing the visual basis for surgical simulation. It is being used as a starting point by medical illustrators and is serving as a common source of images for the development and testing of rendering algorithms. The

value of this national resource in the public domain increases through its applications. Its utility will continue to grow as related databases are attached to it, and as more attributes are given to its image elements.

The segmentation, classification, and three-dimensional rendering of the data set are under way at several locations. This work has resulted in international recognition for the University of Colorado as the recipient of the 1995 Nicograph Grand Prize Award. Some of the most exciting applications of this tissue classification is the ability it provides for interaction with the data in virtual space as demonstrated by the University of Colorado in a celiac plexus block simulator at the October 1995 meeting of the American Society of Anesthesiologists (Fig. 7).

Quite possibly the greatest value that this work may have is in providing a complete body of human anatomy that not only will be developed by specialists but will also be available and used by generalists at any and all educational levels. As such, the Visible Human Project will serve its role as a visual communications language for medicine.

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