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CT Analysis of Bowed Stringed Instruments[1]

PURPOSE: To determine the utility of computed tomography (CT) for the noninvasive evaluation of bowed stringed instruments.

MATERIALS AND METHODS: Thirty-seven instruments that ranged in quality from student instruments to exquisite Stradivarius violins were analyzed with CT. Accuracy of thickness measurements was determined from 24 measurements of cross-sectional pieces sawed from a student violin. Accuracy of density measurements was determined from 328 CT attenuation measurements of 16 woods used in stringed instruments.

RESULTS: Substantial differences of normal structure were noted between the masterpieces crafted in Cremona, Italy, and factory-produced student instruments. Unexpected defects were detected in nine of 14 instruments older than 100 years and ranged from a few wormholes (eight instruments) to many wormholes and extensive repair (one violin). CT thickness and attenuation measurements correlated well to the line of identity with actual measurements ($P < .0001$). Two cellos and a viola have been constructed from CT-derived information. The viola was awarded a gold medal at a recent international competition.

CONCLUSION: CT provides the modern luthier and acoustic scientist with a unique tool for characterization of normal structure, defects, and repair and for accurate measurements of wood thickness and density. CT-derived information aids in the replication of original masterpieces. CT evaluation may have an important role in the valuation, insurance, and identification of valuable stringed instruments.

Several unique applications of computed tomography (CT) have been reported since the introduction of CT in the early 1970s. These include CT evaluation of Egyptian mummies and cats (1–4), antique sword hilts (5), and a 1730 cello scroll (6). In 1981, Fairbairn (7) used CT to scan an 1840 Neuner and Hornstainer violin and a student violin. Transaxial CT images of these violins helped establish some of the normal structure of the violin, and Fairbairn concluded that CT is a safe, noninvasive procedure for imaging all portions of the intact instrument.

It is generally agreed that Andrea Amati (1520–1578, Cremona, Italy) originated the form of modern bowed stringed instruments (8). Nicolò Amati (1596–1684, Cremona, Italy), the grandson of Andrea, found himself the only surviving violin maker, or luthier, of any consequence within the entire world after a bubonic plague decimated Cremona, Italy, in 1630 (9). Antonio Stradivari (1644–1737), universally regarded as the greatest violin maker of all time, drew his early inspiration from Nicolò Amati's work (10).

Stradivarius instruments are famous for their brilliant tone and have an extraordinary capacity to perform well (11). Sacconi (12), who has systematically studied many Stradivarius violins, believed that Stradivari's ingenuousness was in his ability to use the precise principles of acoustic physics and chemistry. Of the approximately 1,200 stringed instruments crafted by Stradivari from 1686 to 1737, only 602 instruments (540 violins, 12 violas, 50 cellos) could be identified at the beginning of this century (10). Today, many Stradivarius violins are valued in excess of $1,000,000 (13).

The bowed stringed instruments constructed by Stradivari and other Cremona masters are extremely valuable and therefore highly safeguarded. These masterpieces are handled by several world-class professional musicians and master luthiers. A major function of the modern luthier is determining the market value of stringed instruments. When asked to give an appraisal, the luthier carefully inspects the external surfaces and, with dental mirrors, the internal surfaces of the instrument for evidence of defects or previous repair. The value of the instrument may decrease considerably if a defect or repair is discovered. For example, a violin with a crack in the sound post region of the back plate is traditionally valued at only 50% of the instrument without the crack. It is well known that many serious abnormal conditions may be concealed with glue, filler material, retouch, or varnish (14). Abnormal conditions that affect old bowed stringed instruments include cracking, warping, and wormholes (caused by the infestation of larvae from the beetle, *Anobium domesticum*).

Over the past 250 years, many luthiers have attempted to improve on the quality of the violin originated by the Cremona masters. Despite these efforts, only a few minor structural changes have been adopted. It is the

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intent of almost every modern luthier to construct accurate copies of a few original masterpieces. The quality of modern workmanship is judged by how well the instrument copies the components of the original masterpiece. Much of the normal structural details of these valuable stringed instruments, crucial to the tonal quality that a modern copy will ultimately possess, are often difficult to access.

The process of copying a bowed stringed instrument involves many stages, and each stage is associated with error. When constructing an instrument, the luthier must have an accurate outline of the instrument's edges from which a top and back plate are created. The outlines are traditionally created with a sharp tool carefully traced around the perimeter of the plate The tracing is then placed on a metal plate, and a template is produced. The metal template is then positioned on wood, and a tracing is etched into the wood. The luthier then carves the front and back plates. This traditional method of producing an outline introduces compounding errors, initially caused from the finite thickness of the tracing tool and becoming compounded.

One weekend afternoon in 1988, as I (S.A.S.) was monitoring radiology residents and occupying my free time by practicing my violin, a young man involved in a motor vehicle accident was referred for CT. I inadvertently carried my violin into the CT room, and after scanning was completed, I found my violin next to the scanner. Out of curiosity, I scanned the violin. I presented the CT scan to John R. Waddle. He became very excited about the potential use of CT for the evaluation of violins. This began our investigation. Because of John's international customer base and the very close association of professional luthiers throughout the world, John has had access to many of the world's rare and valuable instruments.

A schematic diagram of a typical stringed instrument is illustrated in Figure 1. The body comprises a spruce front plate, a maple back plate, and maple sides (ribs). Figure 2 illustrates a typical cross section through the maple bridge. A spruce sound post (Fig 3), 5.5 mm in diameter, is carefully wedged between the front and back plates. The spruce bass bar, parallel to the long axis, is attached to the inner surface of the front plate on the side opposite the sound post.

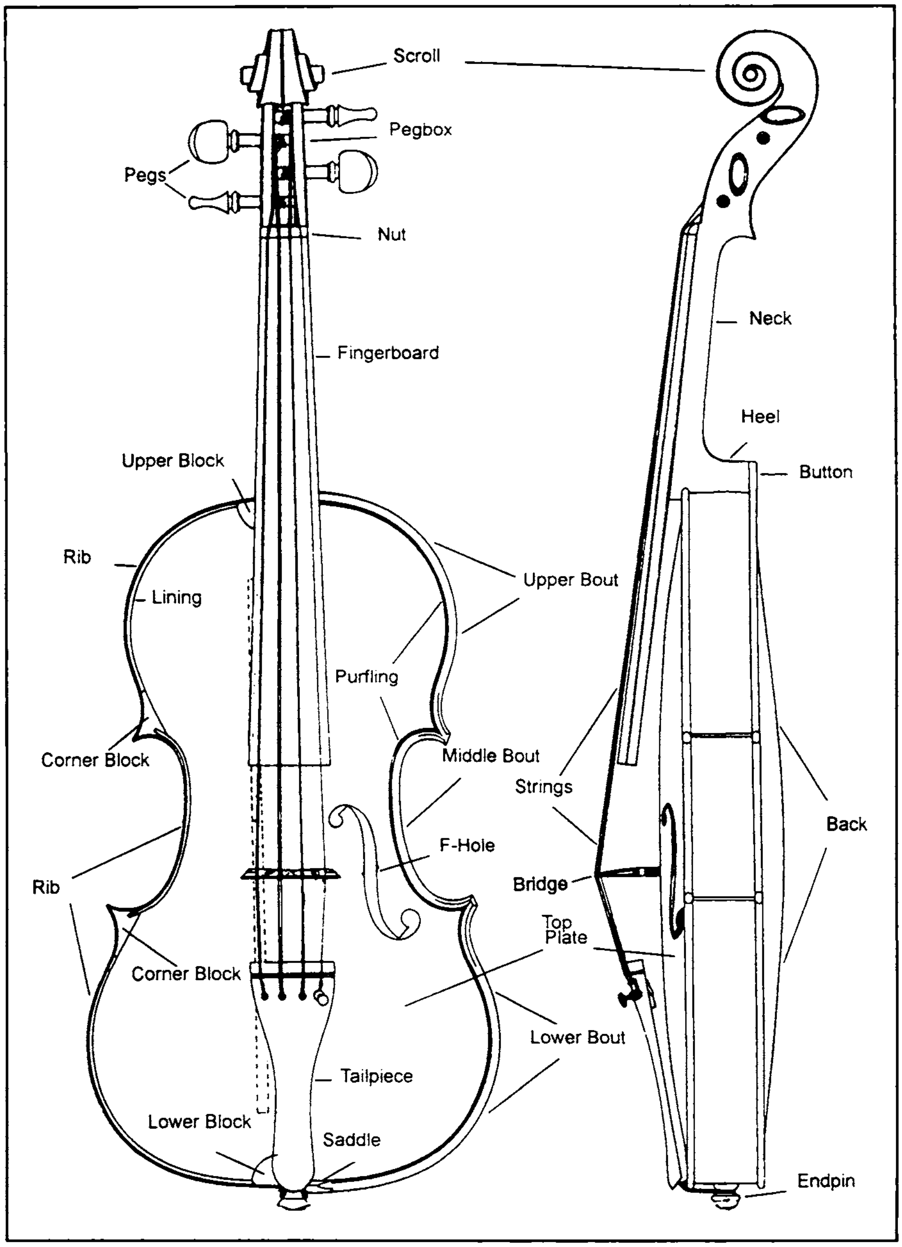


Figure 1. Schematic frontal and side views of a typical violin illustrate normal structure. The front plate on the bass side of the instrument has been removed exposing the blocks, the linings, and the ribs. The spruce sound post would be carefully positioned between the front and back plate, near the foot on the treble side of the bridge. The spruce bass bar (dashed line) is attached on the inner surface of the front plate directly beneath the foot on the bass side of the bridge.

MATERIALS AND METHODS

Since 1988, we have performed CT of 37 bowed stringed instruments with a wide range in quality, from the poor quality mass-produced stringed instruments used by students to soloist quality stringed instruments played by the world's most accomplished musicians (Table). Fourteen of these instruments (11 violins and three cellos) were older than 100 years. Because many of the student instruments had forged labels (many ascribing to Stradivari or other eminent luthiers), the precise ages of the student instruments were indeterminate. The oldest violin scanned was a 363-year-old violin crafted by Andrea Guarneri in Cremona, Italy.

Several CT scanners were used: models DR and RD, Siemens Medical Systems, Iselin, NJ; and models HiSpeed Advantage, 8800, and 9800, GE Medical Systems, Milwaukee, Wis. The following CT technique was used to image the bowed stringed instruments. For transaxial imaging, the instrument was carefully positioned on its back in the middle of the table, with the long axis of the instrument parallel to the long axis of the table. The CT table was advanced into the scanning position, and a localization scan was obtained. As a standard imaging routine, we obtained 1-mm-collimated transaxial scans through the scroll, peg box, upper bout, middle bout, lower bout, sound post, and the bridge. In general, we found the CT head algorithm with 120 kV, 120 mA, and 4-second scanning time optimal for

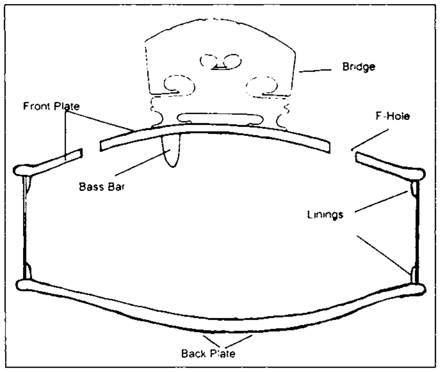
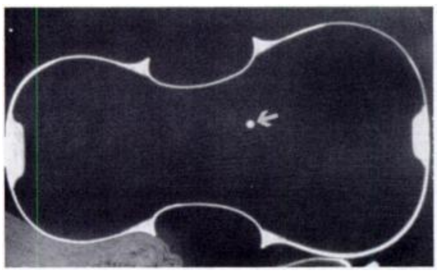


Figure 2. Schematic transaxial section though the middle bout, at the level of the bridge. Note the two "f" holes located between the foot of the bridge and the edge of the front plate. The linings attach the front and back plates to the ribs.



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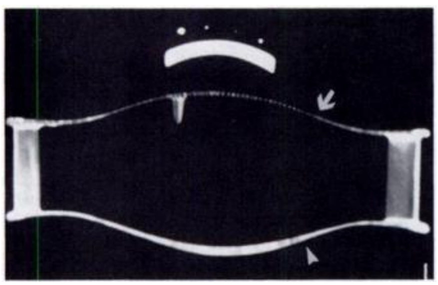

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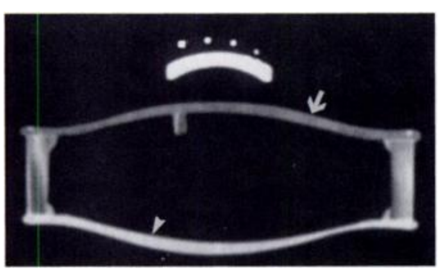


4b.

Figure 3, 4. **(3)** Coronal CT scan of an exquisite violin crafted by Antonio Stradivari demonstrates the rib outline. This outline provides the modern luthier with an exact copy of the edges. Note the round sound post (arrow), a 5.5-mm-diameter spruce rod that establishes a connection between the front and back plates. **(4)** Transaxial CT scans through the middle bout of **(a)** a violin crafted by Nicolò Amati in 1654 and **(b)** an inexpensive German student violin. Note the exquisite archings and changes in thickness of the anterior front plate (arrow) and posterior back plate (arrowhead) of the 1654 Amati violin compared with the front and back plates of the student violin. All the student violins had very thick and poorly arched plates.

List of 37 Bowed Stringed Instruments Scanned with CT Since 1988

Instrument	Date Constructed
Violins	
Andrea Guarneri (Cremona, Italy)	1633
Nicolò Amati (Cremona, Italy)	1654
Antonio Stradivari, "Lord Borwick" (Cremona, Italy)	1702
Antonio Stradivari (Cremona, Italy)	1672
Antonio Stradivari, "The Lark" (Cremona, Italy)	1698
Antonio Stradivari (Cremona, Italy)	1720–1725
Attributed to Giuseppe Guarneri (Cremona, Italy)	1734
Attributed to Jacob Stainer (Absam, Germany)	1659
Attributed to Guidantus (Bologna, Italy)	1720
Pietro Antonio Dalla Costa (Treviso, Italy)	1752
Giovanni Grancino (Milan, Italy)	1708
Vincenzo Sannino (Naples, Italy)	1910
Guy Rabut (New York, NY)	1989
David Rubio (Cambridge, England)	1996
William Fulton (Idyllwild, Calif)	1994 and 1995
George Yu (Salt Lake City, Utah)	1996
Fourteen mass-produced student violins	?[*]
Cellos	
Domenico Montagnana (Venice, Italy)	1730
Anselmo Bellosio (Venice, Italy)	1770–1780
Attributed to Thomas Dodd (London, England)	1800
John Waddle (St Paul, Minn) and William Scott (Minneapolis, Minn)	1990[†]
Two mass-produced student cellos	1975–1993

[*] Forged labels made ages indeterminate.
[†] This instrument was crafted from details revealed on the CT scan of the 1730 Montagnana cello.

imaging. The window settings were centered at approximately −500 HU with a width of approximately 800 HU. For coronal imaging, violins were also carefully positioned on their side, allowing for imaging of the front plate, back plate, purfling, and the ribs. If a defect was visualized during routine CT scanning, additional images were obtained to characterize the nature and extent of the defect.

CT analysis of the premier stringed instruments (four Stradivarius violins, the Amati violin, the Guarneri violin, and the Montagnana cello) was very comprehensive. These instruments were scanned in numerous transaxial and coronal positions.

The accuracy of CT measurements of wood thickness was determined in the following manner. With a high-speed band saw, an inexpensive student violin was transversely cut into 22 individual cross-sectional pieces. A high-quality micrometer was used to obtain 24 thickness measurements of the front and back plates, ribs, and bass bar. At the precise point of each thickness measurement, a droplet of melted paraffin was carefully positioned. The individual violin pieces were then transaxially scanned with window settings centered at −400 HU and a width of 1,800 HU. Images were magnified to include the paraffin droplets. CT thickness measurements were obtained at the precise position of each paraffin droplet.

The accuracy of CT attenuation measurements of woods commonly used to construct stringed instruments was determined in the following manner. CT scans with 8-mm collimation were obtained of 16 varieties of instrument-quality wood. Each piece of wood was positioned on the CT table with the long axis of the wood parallel to the long axis of the table. A small volume of water was also placed into the imaging field. Each piece of wood was scanned at three different positions with window settings centered at −400 HU and a width of 1,800 HU. CT attenuation measurements of the wood and water were then obtained. All CT wood attenuation measurements were normalized to the measured water attenuation. A total of 328 CT attenuation measurements were obtained.

The actual wood density was measured in the standard fashion. Each piece of wood was weighed with a high-quality scale. The wood was then completely immersed into water, and the volume of displaced water was measured. To avoid artificially high CT wood attenuation measurements caused from water absorption into wood, all of the CT wood attenuation measurements were obtained before measuring the actual density.

To determine the possible effect of collimator thickness on CT wood attenuation measurements, three pieces of instrument-quality Sitka spruce were scanned using 2-, 4-, and 8-mm collimation. Window settings were centered at −400 HU with a width of 1,800 HU. Every piece of Sitka spruce was imaged at three positions separated by 10–15 cm. A 1.0 cm^2 region of interest was used for all CT attenuation measurements. A total of 171 CT wood attenuation measurements were obtained.

RESULTS

High-resolution, 1-mm-collimated CT scans were obtained in both transaxial and coronal planes. A coronal CT scan obtained through the ribs of a Stradivarius violin demonstrated the rib outline (Fig 3); this provides the modern luthier with an exact copy of the rib edges.

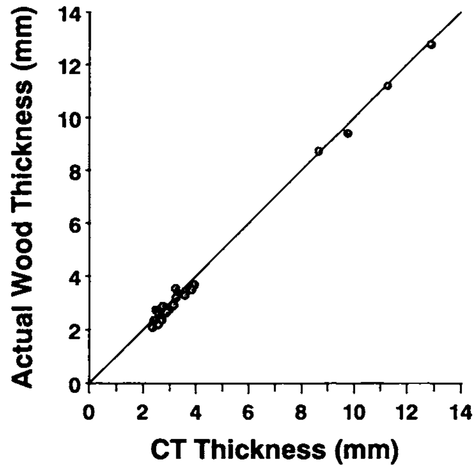
The archings of the front plates of the student instruments were generally less pronounced than the archings of the premier instruments. Also, the maximum thickness was greater and the change in thickness of the plate (graduations) much less in all 16 student instruments. This is illustrated in a transaxial scan obtained through the middle bout of a violin crafted by Nicolò Amati in 1654 (Fig 4a) compared with a scan obtained through the same position in a typical student violin (Fig 4b).

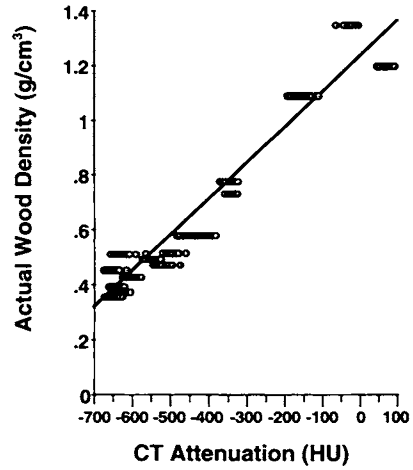
CT thickness measurements (in millimeters) of wood showed an excellent degree of correlation to the line of identity with the actual thickness measurements (in millimeters): actual thickness = 1.018 × CT thickness − 0.105 (*P* < .0001, simple regression analysis) (Fig 5).

CT wood attenuation measurements (in Hounsfield units) also showed an excellent degree of correlation to the line of identity with actual wood density measurements (in grams per cubic centimeter): actual wood density = 1.000 × CT attenuation + 1.254 (*P* < .0001, simple regression analysis) (Fig 6).

CT wood attenuation measurements of Sitka spruce piece 1 had a mean attenuation of 649.2 HU with standard deviations of 8.2, 6.7, and 8.4 for 2-, 4-, and 8-mm collimation, respectively. Mean attenuation measurement for spruce piece 2 was 537.1 HU with standard deviations of 8.0, 5.9, and 6.5 for 2-, 4-, and 8-mm collimation. Mean attenuation measurement for spruce piece 3 was 654.1 HU with standard deviation of 9.7, 8.9, and 9.0 for 2-, 4-, and 8-mm collimation. Therefore, CT wood attenuation measurements were not dependent on collimator thickness.

Unexpected internal defects were detected in nine of 14 bowed stringed instruments older than 100 years. The severity of the defects of instruments older than 100 years ranged from only a few wormholes and limited repair in eight instruments (Fig 7) to very extensive wormholes and repair in an Italian violin (Fig 8). Wormholes or glue repair most commonly involved only the scroll; however, wormholes also involved the peg box and blocks of three stringed instruments more than 100 years old (Fig 9). Glue lines from repair were detected in the front or back plates in 100% of the stringed instruments greater than 100 years old.





Figures 5, 6. **(5)** Regression analysis compares 24 CT thickness measurements with actual wood thicknesses in a dissected student violin. **(6)** Regression analysis of CT attenuation of wood versus actual density for 16 types of wood commonly used to construct bowed stringed instruments. Ebony, a wood with an actual density greater than that of water, has an average CT attenuation of +55 HU.

DISCUSSION

CT provides the modern luthier and acoustic scientist with a unique, noninvasive imaging tool for evaluating normal instrument structure and abnormal conditions that may affect the instrument. A direct relationship exists between the structure of the instrument and the quality of sound produced by the instrument. Critical portions of the body, including the front and back plates, play an important functional role in sound production. The archings and variation of thickness (graduations) of the plates determine, to a large extent, the tonal quality of the instrument and are a good predictor for the long-term health of the instrument. For example, if a violin's front plate is too thin, deformity or cracking may occur. If the front plate is too thick (a common problem associated with student instruments), the tonal quality produced by the instrument is considerably diminished. CT also provides the modern luthier with an accurate measuring tool for determining wood thickness and density. We demonstrated that collimator thickness has no effect on CT attenuation measurements of wood.

With the violin positioned on its side, outlines of the front plate, back plate, purfling, and the ribs were easily obtained. A CT-derived outline provides the modern luthier with an exact copy of the edges of the instrument, thereby avoiding the compounding errors intrinsic to mechanical tracing techniques traditionally used to create outlines. One of the authors (J.R.W.) used features revealed with CT examination to reproduce two cellos and one viola. The cello crafted by Domenico Montag-

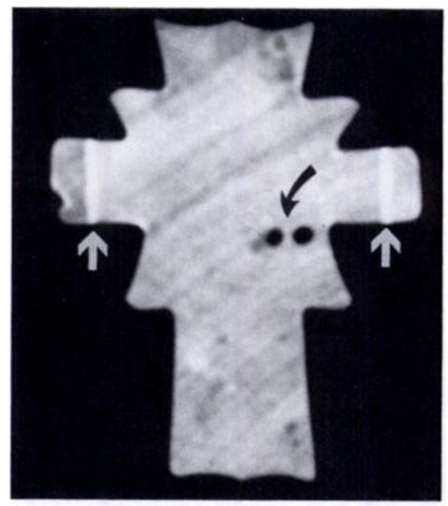


Figure 7. Transaxial CT scan obtained through the scroll of a 1730 Domenico Montagnana cello. Note the hyperattenuating glue lines (straight arrows) from previous repair and wormholes (curved arrow) caused by infestation from the larvae of the beetle, *A domesticum*.

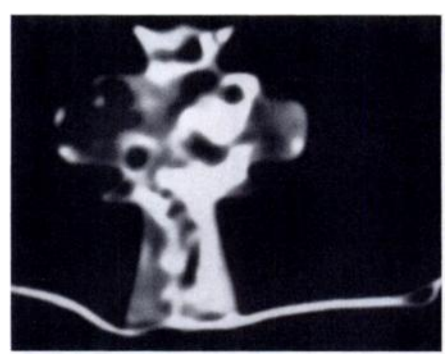


Figure 8. Transaxial CT scan obtained through the scroll of a solo-quality violin. Note the extensive repair with hyperattenuating filler material and associated wormhole damage. The massive extent of repair was not suspected before this CT scan.

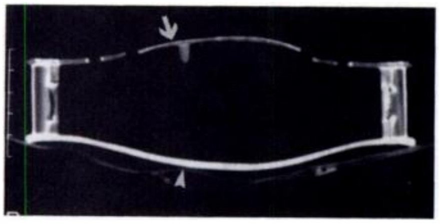


Figure 9. Transaxial CT scan obtained through the two "f" holes of a Stradivarius violin at the level of the corner blocks. The front plate is anterior (arrow), and the back plate is posterior (arrowhead).

nana in 1730 was successfully copied in 1990. An English cello, circa 1800, was copied in 1995 on the basis of CT details. In 1996, a viola was created on the basis of CT scans of Stradivarius and Amati instruments. This viola was awarded a Gold Medal for craftsmanship and tonal quality at the 12th International Competition for Violins, Violas and Cellos of the Violin Society of America.

It is well known that when an experienced luthier repairs a damaged instrument, the repair is often very difficult to visualize (14). In 11 of 14 stringed instruments greater than 100 years old, we discovered defects and repair work that appeared minor with surface inspection, yet involved a large volume of the instrument's internal structure. Repair work is readily detected with CT since glue, made from converted collagen, and filler material have an attenuation much greater than the attenuation of wood. Determination of the original glue used for construction from glue used for repair can usually be distinguished from distribution of the glue. Glue lines associated with the original construction of the instrument are symmetric, involving the ribs, blocks, and center joint of the plate. Glue lines associated with repair to cracks or wormholes are usually asymmetric.

These abnormal conditions and repair may adversely affect the performance and the value of the instrument. CT examination was used to help determine factually the valuation of several stringed instruments. Our results from CT scanning played an important role in the transaction of several expensive violins and, in two cases, extensive internal damage discovered with CT ultimately led to cancellation of the purchase.

CT of the scroll and front and back plates provides a unique image of the internal grain line structure. This "fingerprint" cannot be altered by paint or varnish and provides each instrument with a unique identifier. This feature could provide a valuable clue when attempting to identify lost or stolen stringed instruments.

In conclusion, we find CT provides the modern luthier and acoustic scientist with a unique, noninvasive tool that yields important qualitative and quantitative information. CT produces high-resolution images of normal instrument structure, such as the elegant curves of the outlines and archings. Many abnormal conditions commonly affecting old masterpieces, such as wormholes and cracks, can be easily detected and assessed. For any portion of the instrument, CT provides accurate measurements of both wood thickness and density. Collimator thickness has no effect on CT attenuation measurements of wood.

CT also provides the modern luthier and acoustic scientist with a measuring tool that assists in the accurate reproduction of instruments. We believe that CT examination should also play an important role in the valuation, insurance, and identification of rare and expensive bowed stringed instruments. ■

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