Use of CT in Detection of Internal Damage and Repair and Determination of Authenticity in High-Quality Bowed Stringed Instruments[1]

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Computed tomography (CT) was used to evaluate 17 high-quality violins and cellos crafted between 1633 and 1872 by master craftsmen such as Guarneri, Amati, and Stradivari. Multiple high-resolution CT scans were obtained in each instrument, and additional scans were obtained when defects or repair was detected. Varying degrees of internal damage (eg, wormholes, air gaps, plastic deformities of wood) or repair (eg, glue lines, filler material, wooden cleats and patches) not seen at visual inspection were detected in all 17 instruments. In addition, CT allowed noninvasive identification of the internal wood grain pattern unique to each instrument, thereby facilitating verification of authenticity to help protect against loss, theft, or forgery. The information provided by CT analysis of valuable bowed stringed instruments may prove useful to prospective buyers or to insurance companies that specialize in insuring such instruments against accidental loss or damage.

Index terms: Computed tomography (CT), high-resolution • Computed tomography (CT), utilization • Musical instruments

RadioGraphics 1999; 19:639–646

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■ INTRODUCTION

Ever since Antonio Stradivari crafted bowed stringed instruments in Cremona, Italy in the late seventeenth and early eighteenth centuries, there has been intense speculation concerning the "secret" of the spectacular sound produced by these instruments (1,2). In his extensive study of stringed instruments, Sacconi (1, p 104) characterized the sound produced by Stradivarius violins as unique in terms of promptness of response, tone color palette, purity of tone, and power of penetration. The superiority of these instruments derives from a thorough understanding and masterful application of pertinent principles of acoustic physics and chemistry involving the quality and cut of the wood; the shape, curvature, thickness, and tapering of the spruce front and maple back plates; the inclination and spacing of the *f*-holes; and the position of the spruce bass bar (1, p 5).

Working in collaboration, a radiologist (S.A.S.) and a luthier, or maker of stringed musical instruments (J.R.W.), previously demonstrated that computed tomographic (CT) evaluation of bowed stringed instruments provides valuable information for the luthier who wishes to study and construct a replica of a masterpiece (3). Radiographic analysis of extremely valuable bowed stringed instruments, including the 1715 "Cremonese" Stradivarius violin, has previously been performed (4). However, unlike radiographic evaluation with its intrinsic limitations, CT analysis furnishes both qualitative and quantitative information that is unique to the interior structure of each instrument. High-resolution, thinly collimated CT scans reveal the elegant curves (archings) and changing thicknesses (graduations) of the front and back plates and the gently curving outlines of the instrument (3). In an earlier study, we demonstrated that CT measurements of front and back plate thickness and attenuation correlate well with actual wood thickness and wood density measurements ($P < .001$) (3).

Because of the age of these instruments, which often exceeds 200 years, damage and subsequent repair is inevitable. Damage to bowed stringed instruments has multiple causes including trauma, worm infestation, rapid changes in temperature and humidity, and plastic deformity of the wood.

Accidents are the most common cause of damage to stringed instruments. Traumatic damage varies from catastrophic (ie, resulting in complete destruction of the instrument) to relatively minor. When repairing a damaged instrument, the luthier is equipped with various binding materials such as animal glue and a putty-like filler material. In addition, a variety of very thin wooden binding devices known as cleats and patches may be positioned for additional support (5). Cleats, which are simply thin pieces of wood, are glued to the inner surface of the plate across a crack. Cleats are often found grouped together along the longitudinal length of the front or back plate in the direction of a glued crack. Internal patches are thin wooden structures that are embedded within the original wood (5).

CT may help detect wormholes caused by larvae from the beetle *Anobium domesticum* (3). The female lays her eggs on the surface of the wood. Immediately after hatching, the larvae burrow into the interior wood, creating a network of wormholes. At the surface, the diameter of the wormhole is usually only a fraction of a millimeter. As the worm develops into adulthood, however, the diameter of the wormhole may grow to several millimeters (6). If the wormholes involve a large portion of the wood interior of a vital component of the instrument, the involved wood may weaken and fracture (5, p 93).

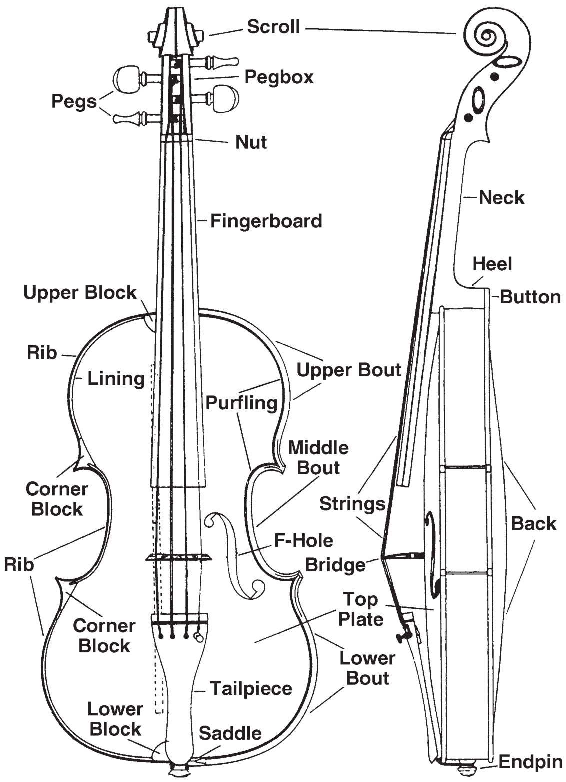
Another common cause of damage is rapid changes in temperature or relative humidity (7, p 80). Such damage is becoming more common with increasing use of air transportation for instruments. Internal stresses caused by differential expansion forces directed parallel and perpendicular to the wood grain are proportional to the equilibrium moisture content and the coefficient of thermal linear expansion of the wood (7, pp 80, 138).

Plastic deformity of wood over a long period of time is caused by unrelenting string pressure that is transmitted to the front plate by the bridge and a tight sound post. Plastic deformity is frequently observed in the middle portion of the front and back plates of old instruments and often manifests as sunken and bulging arches (5, p 24).

We have previously shown that animal glue and filler material used to repair stringed instruments have high attenuation and are easily seen at CT (3). Wooden cleats and various internal wooden patches (eg, chest patches, sound post patches) are also easily detected because the orientation and spacing of the grain lines of the wooden patches differ from the original internal grain pattern. CT is also effective in determining the size and depth of internal patches relative to the thickness of the original wooden plate.

Accurate determination of an instrument's authenticity is of great importance to a modern luthier. High-quality bowed stringed instruments are almost always accompanied by papers of authenticity. Depiction of internal structures

Figures 1, 2. **(1)** Schematic shows front and side views of a typical violin. The spruce front plate on the bass side of the instrument has been removed, exposing the blocks, the linings, and the maple ribs. The spruce sound post would be carefully positioned between the front and back plates, 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. **(2)** Schematic demonstrates a transaxial view of a violin through the middle bout at the level of the bridge. Note the *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. (Figs 1 and 2 reprinted, with permission, from reference 3.)



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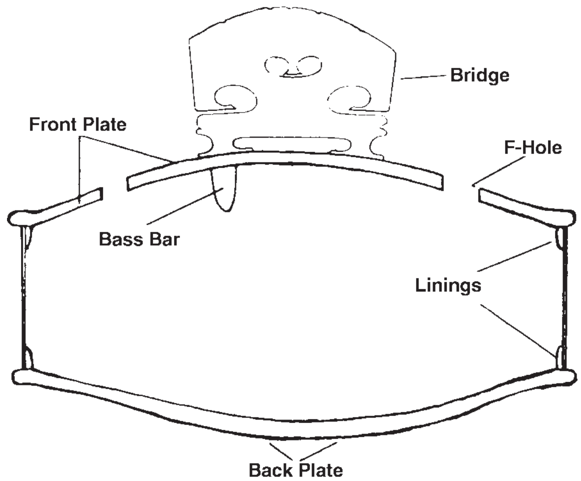


2.

such as wood grain lines, wormholes, and wooden patches and cleats with CT may help identify a valuable instrument to protect against loss, theft, or forgery.

A schematic of a typical stringed instrument, which normally consists of over 80 individual wooden parts, is shown in Figure 1. The body consists of a spruce front plate, a maple back plate, and maple sides (ribs). Figure 2 illustrates a typical cross-sectional view through the maple bridge. A spruce sound post is carefully wedged between the front and back plates of the body. The spruce bass bar, which lies parallel to the long axis of the body, is attached to the inner surface of the front plate on the side opposite the sound post.

In this article, we describe and illustrate the use of CT in high-quality bowed stringed instruments for detection of internal damage (eg, wormholes, air gaps, plastic deformities) and repair (eg, glue lines, filler material, wooden cleats and patches) and for verification of authenticity.

■ MATERIALS AND METHODS

Since 1988, we have used CT to evaluate 17 high-quality bowed stringed instruments built between 1633 and 1872 (mean year of construction, 1724) (Table). Some of these instruments were crafted by such famous luthiers as Andrea Guarneri, Nicolo Amati, and Antonio Stradivari from the Cremona school of violin making and are valued at over $1 million.

Several different CT scanners were used, including the following models: DR, RD, and Somatom Plus 4 (Siemens, Iselin, NJ); HiSpeed Advantage 8800 and 9800 (GE Medical Systems, Milwaukee, Wis); and PQ 5000 (Phillips, Lincolnshire, Ill).

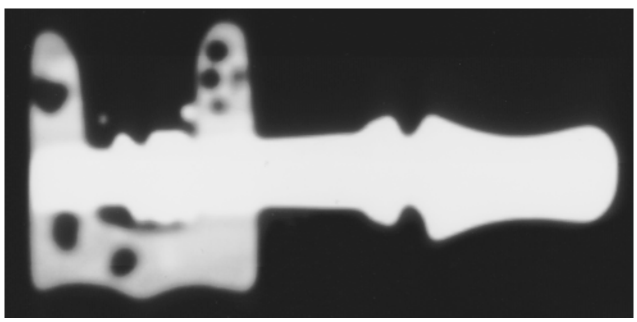
Before a violin was examined with CT, the chin rest and G string were removed to minimize metallic artifact. For transaxial imaging, the instrument was placed on its back in the center of the scanning table with the scroll pointing toward the gantry. For coronal imaging, the instrument was carefully supported within the gantry. We obtained multiple high-resolution CT scans (1-mm collimation) of various parts of the violin, including the scroll, the peg box, the front and back plates, the ribs, and the region of the bridge and sound post.

Multiple high-resolution CT scans with 10-mm collimation were obtained of the corresponding parts of the cellos, which were positioned on the scanning table in a similar fashion as the violins.

Maker and Place and Year of Construction of High-Quality Bowed Stringed Instruments Scanned with High-Resolution CT

	Maker	Place of Construction	Year of Construction
Violins	Nicolo Amati	Cremona, Italy	1654
	Jacob Stainer*	Absam, Germany	1659
	Andrea Guarneri	Cremona, Italy	1633
	Antonio Stradivari†	Cremona, Italy	1698
	Antonio Stradivari	Cremona, Italy	1672
	Antonio Stradivari‡	Cremona, Italy	1702
	Antonio Stradivari	Cremona, Italy	1720–1725
	Giuseppe Grancino	Milan, Italy	1708
	Guidantus*	Bologna, Italy	1720
	Carol Antonio Testore	Milan, Italy	1721
	Giuseppe Guarneri*	Cremona, Italy	1734
	Pietro Antonio Dalla Costa	Treviso, Italy	1752
	Giovanni Guadagnini	Parma, Italy	1759
	Jean Baptist Vuillaume	Paris, France	1872
Cellos	Domenico Montagnana	Venice, Italy	1730
	Anselmo Bellosio§	Venice, Italy	1750
	Thomas Dodd*	London, England	1800

*Instrument attributed to maker.
†"The Lark" violin.
‡"Lord Borwick" violin.
§Front plate only.



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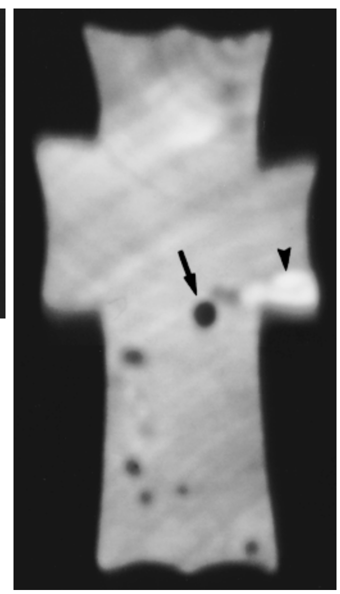

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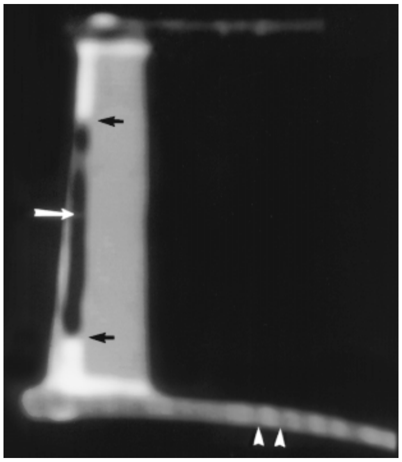
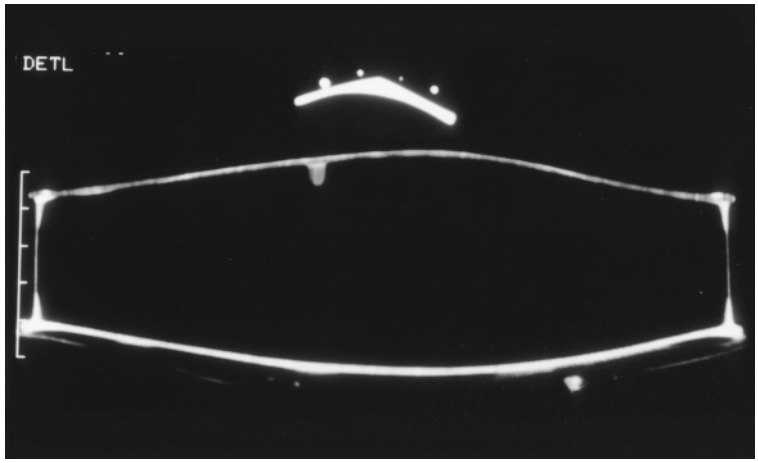
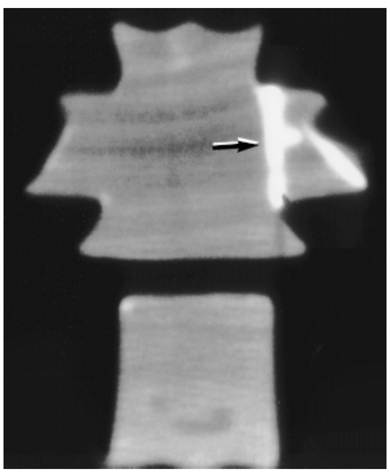
Figures 3, 4. **(3)** High-resolution transaxial CT scan of a valuable violin reveals a network of wormholes in the peg box. The high-attenuation structure is an ebony peg. **(4)** High-resolution transaxial CT scan of a Venetian cello demonstrates a network of wormholes (arrow) in the scroll. A small amount of glue is seen at the edge of the scroll (arrowhead).

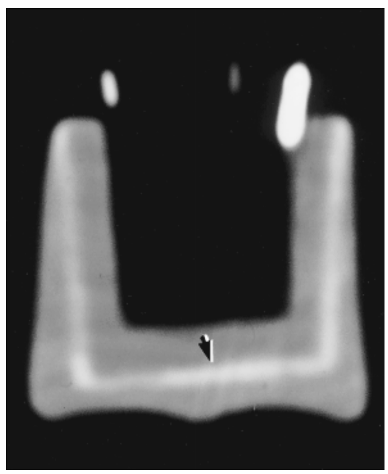


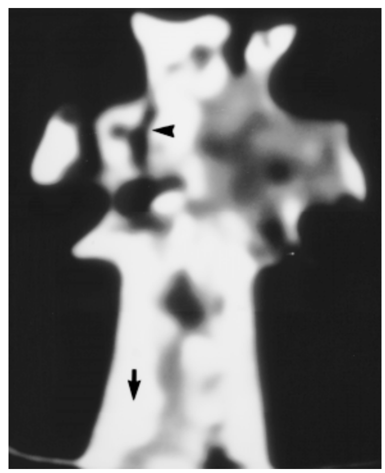


5. 6.

Figures 5, 6. **(5)** High-resolution transaxial CT scan of a Stradivarius violin shows an air gap (white arrow) between the rib and an internal corner block. Note the two air-glue interfaces between the inner surface of the rib and the inner corner block (black arrows). Arrowheads indicate the back plate. **(6)** High-resolution transaxial CT scan of the front plate of a very old and valuable Stradivarius violin shows mild, asymmetric plastic deformity of the front plate and tilting deformity of the ebony fingerboard.







7. 8. 9.

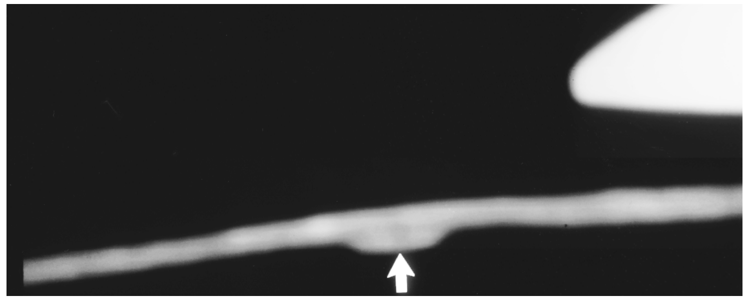
Figures 7–9. **(7)** High-resolution transaxial CT scan of the scroll of an old and valuable Italian violin shows a linear region of high attenuation (arrow), consistent with glue repair. **(8)** High-resolution transaxial CT scan of the peg box of a valuable violin shows a linear area of high attenuation that represents glue repair (arrow). **(9)** High-resolution transaxial CT scan of the scroll of an old Italian violin demonstrates wormholes (arrowhead) and high-attenuation filler material (arrow) occupying a large volume of the scroll. Multiple wormholes several millimeters in diameter were visible on the surface of the scroll. An expert luthier had painted a wood grain pattern on the surface to conceal the filler material.

For all instruments, additional scans were obtained when defects or repair was detected.

■ RESULTS

Varying degrees of damage or repair were detected in all 17 instruments. CT demonstrated damage from worm infestation in two violins and one cello (Figs 3, 4). An air gap between the rib and an internal corner block was detected in a Stradivarius violin (Fig 5). Plastic deformity of wood was detected in five instruments. Figure 6 illustrates deformity of the spruce front plate and ebony fingerboard of a Stradivarius violin.

Cracks repaired with animal glue were detected in all instruments (Figs 7, 8). High-attenuation filler material nearly completely replaced the scroll in one Italian violin (Fig 9).



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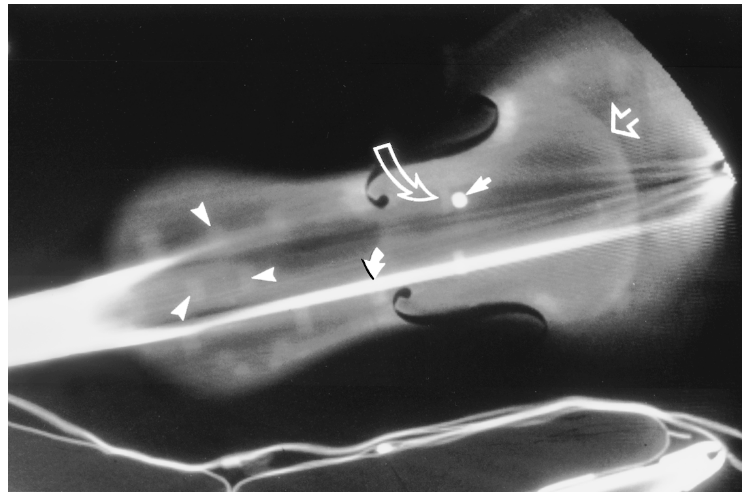

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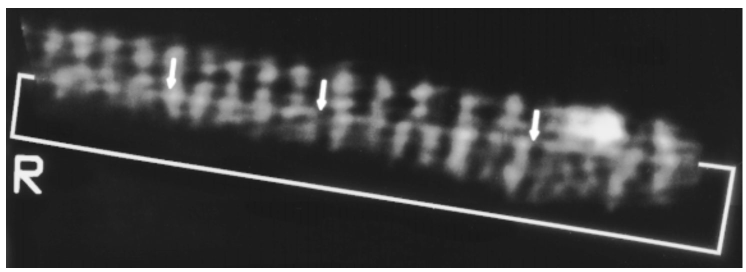


11.

Figures 10, 11. **(10a)** High-resolution transaxial CT scan of a Stradivarius violin shows a wooden cleat (arrow) glued to the inside surface of the front plate. **(10b)** High-resolution coronal CT scan of the front plate shows multiple wooden cleats (arrowheads) and the large, round wooden patch (open straight arrow), which involves almost the entire middle bout of the violin. Note the relationship between the *f*-holes, the bass bar (solid curved arrow), the sound post (solid straight arrow), and the foot of the bridge distal to the sound post (open curved arrow). **(11)** High-resolution transaxial CT scan of the front plate of a high-quality Venetian cello shows the typical appearance of an internal wooden patch (bracket) and its interface with the original front plate (arrows). Note the discontinuity between the grain pattern of the original front plate and that of the embedded wooden patch. This patch occupied nearly 50% of the thickness of the original front plate.

In addition, wooden patches or cleats were detected in all instruments. Figure 10 shows the transaxial and coronal CT appearance of cleats in a Stradivarius violin. The characteristic CT appearance of discontinuity between the grain lines of the original wood and those of an internal wooden patch embedded in the front plate of a Venetian cello is shown in Figure 11. Figure 12 demonstrates an internal wooden patch embedded in the front plate of a violin. The internal wood grain patterns in the scrolls of a Stradivarius violin and a Venetian cello are shown in Figure 13.

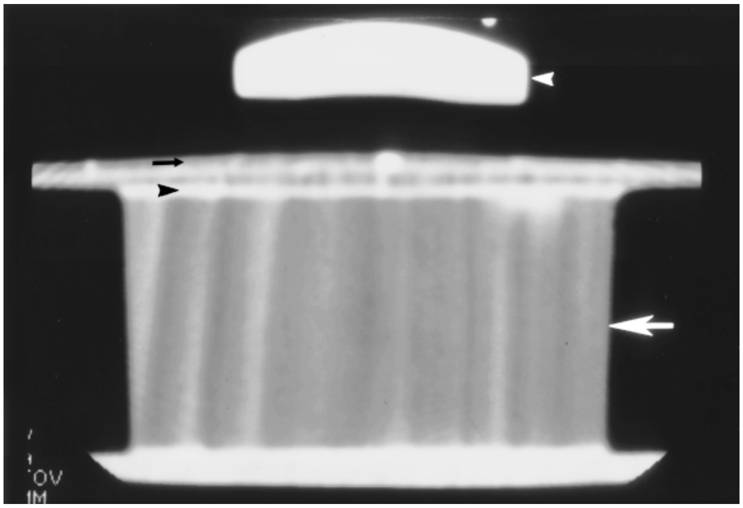
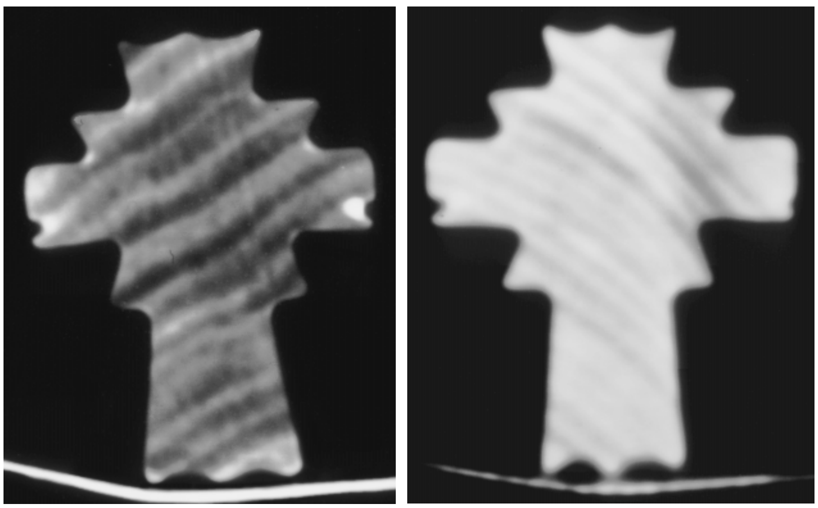


Figure 12. High-resolution transaxial CT scan of a violin demonstrates an internal wooden patch (black arrowhead) positioned between an internal block (white arrow) and the front plate (black arrow). Note the discontinuity between the grain pattern of the newer wooden patch and that of the original front plate. The ebony fingerboard (white arrowhead) has high attenuation.



a. **b.**

Figure 13. High-resolution transaxial CT scans of the scrolls of a valuable Stradivarius violin **(a)** and Venetian cello **(b)** demonstrate internal wood grain patterns unique to these instruments. Such a pattern serves as a “fingerprint” that cannot be altered and enables an instrument to be identified with absolute certainty.

■ DISCUSSION

Damage and repair are often visible on the surfaces of high-quality bowed stringed instruments. By carefully positioning specially designed mirrors inserted into the body of the instrument through the *f*-holes of the front plate, a luthier may visualize repair to the inner surfaces of the front and back plates and the ribs. However, CT is unique in that it allows accurate, noninvasive determination of the nature and extent of internal wood damage and repair.

Because of their great value, high-quality bowed stringed instruments have become targets for theft and forgery, making accurate determination of the origin of these instruments extremely important (8, pp 54–74, 103–119).

According to Huber (9), "If a buyer guesses wrong about both an instrument's condition and its identity, substantial financial loss is an impending possibility." We believe that CT can play a major role in both the accurate determination of the internal condition and the accurate identification of an instrument. We have shown that CT helps identify the "fingerprint" created by the unique internal wood grain patterns of each instrument. CT scans of the internal wood grain patterns of an accurately attributed instrument may be used to identify the instrument in case of loss, theft, or forgery.

High-quality bowed stringed instruments are highly prized, not only for their beautiful transparent golden varnish and graceful craftsmanship, but also for their rich, robust tone. According to Sacconi (1, p 106), "All this is derived not from presumed secrets, but from the systematic concurrence of every structural element, translated into a calculated harmony of relationship." As demand has increased and supply has diminished, the price of these high-quality instruments has risen dramatically (5 [foreword by L Kievman]). Many soloists, chamber musicians, concertmasters, and collectors strive to acquire these rare and expensive masterpieces.

■ CONCLUSIONS

CT of high-quality bowed stringed instruments frequently depicts internal wood damage and repair that is underestimated at visual inspection. CT helps identify the presence and extent of internal wormholes, deformities, air gaps, glue lines, filler material, and embedded wooden patches and cleats. We believe that CT analysis helps accurately determine the nature and extent of internal wood damage and repair and may provide important information to prospective buyers. CT may also help determine the authenticity of an instrument. Insurance companies that specialize in insuring bowed stringed instruments against accidental loss or damage may consider requesting CT analysis before issuing a policy.

Acknowledgments: We thank Ryan Hennen, ARRT, and numerous other technologists who provided generous technical assistance; the radiologists of Rush Presbyterian Hospital, Chicago, Ill, and many other radiologists who kindly provided CT scanners; and Michael Becker Fine Violins (Park Ridge, Ill) and the many luthiers who kindly allowed us generous access to precious bowed stringed instruments.

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