

Review of the Uses of Computed Tomography for Analyzing Instruments of the Violin Family with a Focus on the Future

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Abstract

X-ray computed tomography (CT) has proven to be a valuable tool in studying antique, as well as new, instruments of the violin family. This article reviews the history and workings of CT and then focuses on the future and the relatively new method of quantitative analysis of CT images. Potential new uses of the obtained data are presented.

X-ray computed tomography (CT) has become a valuable tool in the ever-changing toolkit of the modern stringed instrument maker, allowing extensive study of antique instruments with no risk to their delicate surfaces. Until recently, CT images were only used for visual analysis, but with changes in capture methodology over the past 10 years and the possibilities full digitization presents for automated analysis, we are now witnessing the opening of a huge vista of opportunities. In certain circumstances, a limitation of analysis prior to this current era was the unreliability of the “human factor.” As will be evident in this article, although CT currently has relatively low resolution (~0.5 mm), there are distinct advantages to the mechanization of analysis, which helps overcome the variability of user interpretation.

HISTORY OF CT

X-ray imaging is based on the fact that as x-rays pass through an object they lose a certain amount of their energy (attenuation) before arriving at their destination (receptor array). The

remaining energy that arrives therefore constitutes a density map of their travels.

Computed Axial Tomography (CAT), or Computed Tomography (CT), is based on the principles of x-ray imaging with the addition of computer-assisted (computed) dissection of the transmitted rays into distinct “slices” (tomography, from *tomos*, the Greek word for slice), which can then be manipulated into many different views (formats). Figure 1 shows the different slices and the terms typically used. Each slice is made up of voxels (three-dimensional pixels), which effectively record in an xyz format everything scanned, i.e., a recording of every cubic mm (or whatever the maximum resolution of the particular machine) of the scanned object. An immediate advantage of CT is that since everything the x-rays strike is recorded, everything discernible can be seen or studied whether one planned on recording this information or not.¹

Sir Godfrey Newbold Hounsfield [1] played a pivotal role in the development of CT, building on the mathematical foundations established by Allan McLeod Cormack in the late 1950s and

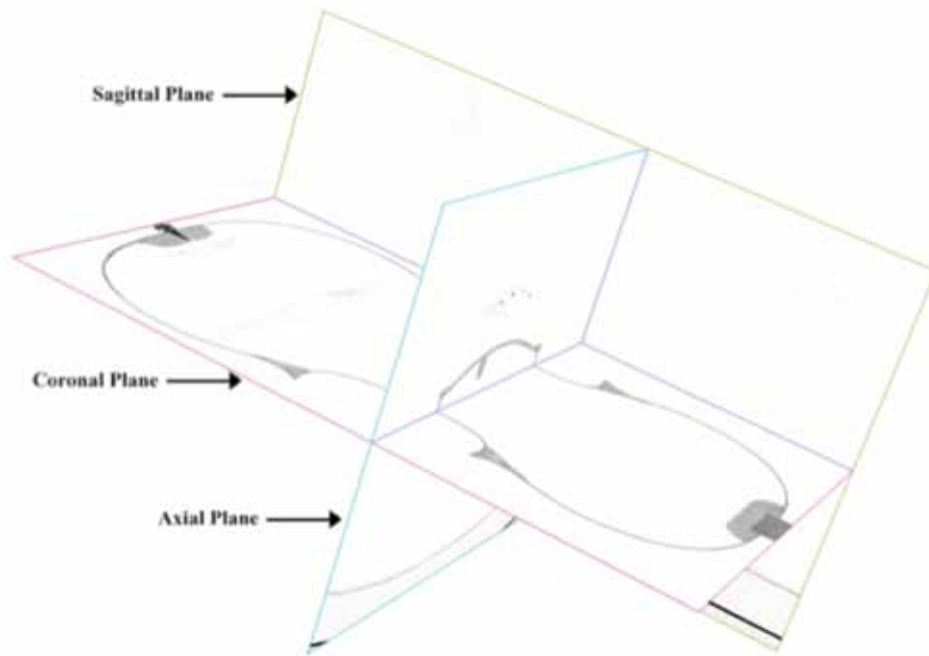


Figure 1. Various slice directions and the terms associated with each.

published in 1963 and 1964 in the *Journal of Applied Physics* [2]. They received a joint Nobel Prize in 1979 for their roles in the development of CT, and Hounsfield's name was given to the measurement units of recorded x-ray attenuation. The Hounsfield unit (HU) is based on the density of air (-1000 HU), water (0 HU), and up to bone (>1000 HU). For the purpose of this article, densities of interest for spruce are within the range of -650/-560 HU (0.35-0.44 g/cm³), maple -450/-380 HU (0.55-0.62 g/cm³), boxwood 70/110 HU (1.07-1.11 g/cm³), and ebony 130/260 HU (1.13-1.26 g/cm³).

In the late 1970s and early 1980s scientists realized that CT could be applied to other than strictly medical uses. An example is Harwood-Nash's CT study of ancient Egyptian mummies [3]. In 1997 Sirr and Waddle [4] reported their studies of CT scans of violins, and several articles by them and others have been published about the use of CT and violins [5, 6, 7]. A list of significant dates and events in the development of CT is presented in Table 1.

CURRENT USES

As stated previously, although there are resolution limitations with the current generation of

scanners (~0.5 mm³ for most hospital scanners), there remains a multitude of uses for CT when studying instruments. The use that people are most accustomed to seeing is that of allowing virtual slicing of an instrument to view the arching and thickness at any location. This is very useful information. Once printed at 1:1 scale, it is very simple to make arching templates for use in the making process as well as seeing the thickness variations of the top and back plates. An example of this is presented in Ref. [8], where images of a 1735 violin by Guarneri *del Gesù* are shown.

Another use is the identification of repairs, restoration work, and natural damage (worms, etc.) [7]. This has been very helpful on numerous occasions when counseling a client on potential acquisitions as well as in insurance claim resolution.² When copying or studying an instrument it also gives important information on bassbar location, size, orientation, etc. (as an example of one of many such uses), which provides a better understanding of how an instrument is currently functioning.³ This may or may not be something that the new maker would choose to replicate, but these kinds of details are helpful in the understanding of sound production.

When comparing archings, etc., of instru-

Table 1. Significant dates and events in the development of CT.

| | |
|---------|---|
| 1929 | Radon; basic mathematical principles |
| 1963-64 | A.M. Cormack: image reconstruction |
| 1971 | G.N. Hounsfield: technological advances |
| 1971 | First scanner for human heads |
| 1974 | First scanner for full human body |
| 1974 | Third-generation scanner |
| 1977 | Fourth-generation scanner |
| 1979 | Nobel prize awarded to A.M. Cormack and G.N. Hounsfield |
| 1980s | Technological refinements |
| 1983 | Dynamic spatial reconstructor |
| 1983 | Electron beam CT scanning |
| 1987 | Scanners with continuously rotating tube |
| 1989 | Spiral CT (helical CT) |
| 1991 | Dual-slice spiral CT |
| 1991 | CT angiography |
| 1995 | Real-time reconstruction |
| 1998 | Multi-slice CT (4 detector rows) |
| 1999 | Multi-slice cardiac imaging |
| 2001-02 | Multi-slice CT (8/16 detector rows) |
| 2004-08 | Multi-slice CT (16/64 detector rows) |
| Current | Cone beam CT (320 detector rows) and advances in micro-CT |

ments, it is easy to overlay CT images one upon the other to see the variations between makers and periods. In Fig. 2A a 1735 Guarneri *del Gesù* violin has been overlaid upon a 1715 Stradivari, aligning the backs first (differences in rib heights make it impossible to align both plates simultaneously), and in Fig. 2B aligning the tops. The ability to view archings in this manner allows a much broader understanding of the particular maker's work compared to another maker's as well as the evolution of a particular maker's opus.

DENSITOMETRIC ANALYSIS

In the 1980s the shift began, as in many other fields, from analog capture to digital, which allowed greater manipulation of obtained information. Since CT is based on density, and the

resultant digital images were a map of density variations, this was a perfect field for exploration into the possibilities of quantitative analysis. This would in effect be taking the information to a more pristine iteration, i.e., to pre-imaging where the individual density values could be worked with directly.

User interpretation of data has been a mainstay of all imaging techniques, and although there are undoubted advantages to this, there are also disadvantages. As in the images of overlaid arches (Fig. 2), it is readily apparent where divergences of shape occur. For most purposes this is adequate for the instrument maker. However, if one were interested in comparing 20 or 30 arches of a specific maker and attempting to find an evolutionary pattern, this would likely not be the technique that would lead to usable answers. Rather, a quantitative review of the data would

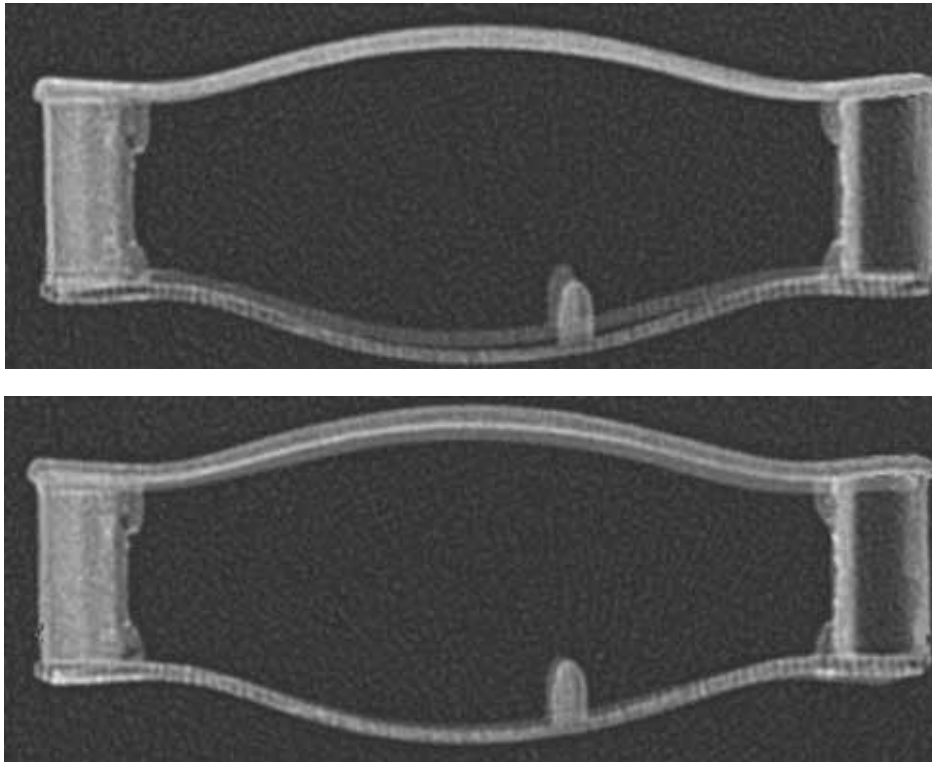


Figure 2. An axial image of a 1735 Guarneri del Gesù violin overlaid upon an axial image of a 1715 Stradivari at the same location, with backs aligned and with tops aligned. Due to differences in rib heights, it was not possible to align both plates simultaneously.

more likely yield a better understanding of these changes over time. An algorithm could be constructed that would take into account arch height, plate width at the region of interest, and the individual Cartesian coordinates at each point, which could then be compared to that particular relative point on all the other instruments. To date this hasn't been done, but it is quite feasible and would provide yet another way to understand the workings of instruments that function well and those that don't.

One of the current authors (BS) [9], building on the quantitative use of CT in lung densitometry, has devised such an algorithm that effectively sends a virtual "spider" to delineate the boundaries of wood and air of an instrument and can therefore define an individual plate. Figure 3 shows the separation of the outside of the plate and air (superior delineation point [SDP]), the inside of the plate and air (inferior delineation point [IDP]), and a third point, which is halfway between the two (medial point [MP]). Using a mixture of each of these, data can be extracted and presented in a way that shows

clearly several important "views" of an instrument. Using just the SDP gives elevation maps; using SDP and IDP gives thickness maps; using MP gives median density, etc. Details of this technique can be found in Ref. [10].

Once the data have been configured in the desired fashion they can then be exported to an imaging format to more readily interpret the results. Some of the ways that quantitative analysis is currently being used in the luthier's field are presented below.

Figure 4 is a density map (generated from the MP) of the top of a violin by Guarneri *del Gesù* dated 1735. The individual grain lines can be seen as well as repairs. Although the repaired areas are most likely of a fairly similar wood density as the original wood, the penetration of hide glue (glue has much higher density than spruce) into the wood causes a localized increase in density visible as a lighter color (extremely low density, the surrounding air is seen as black). The density variations of the purfling material as well as the glue holding it in place are seen. The algorithm has some difficulty delineating

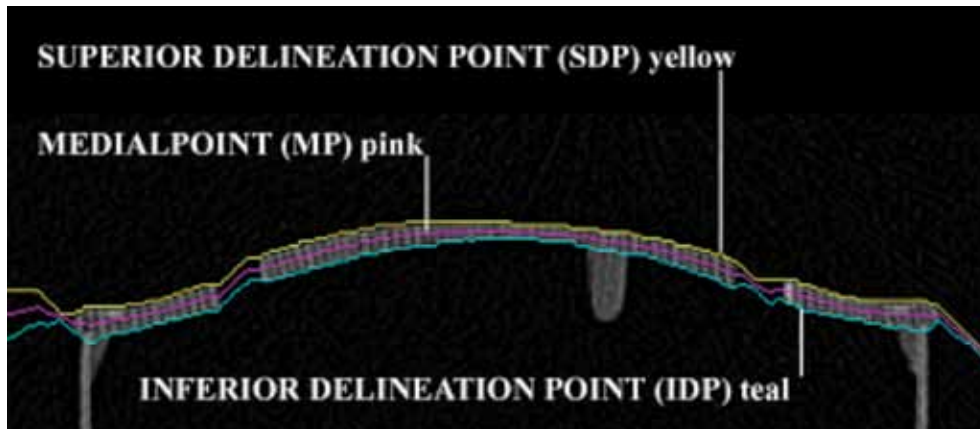


Figure 3. The separation of the outside of the plate and air (superior delineation point SDP), the inside of the plate and air (inferior delineation point IDP), and a third point, which is halfway between the two (medial point MP).



Figure 4. Density maps (generated from the MP) of the top and back of a violin by Guarneri del Gesù dated 1735.

structures of very similar density so the bassbar is somewhat visualized. Varnish and sealer infiltration into the endgrain of the *f*-holes (or possibly dirt accumulation in the endgrain?) is also seen. The extremely high density of the metal associated with the E-tuner, the ball-ends of the strings, and the chinrest hardware causes a localized whiteout effect called “artifact,” in this case metal artifact. Scanning instruments that are not strung up avoids this problem but also removes one of the most attractive features of CT scanning: its complete non-invasiveness. However, most musicians do not object to the removal of the chinrest and the E-tuner, and replacement of the metal E-string with a gut string, which greatly improves the clarity of the data and resulting image.

ELEVATION PROFILES

Figure 5 shows the top and back plates of three violins by Guarneri *del Gesù* and two by Antonio Stradivari (generated from the SDP). Whereas Sacconi [11] and others provided what was

referred to as level contours, which were mostly hypothetical, quantitative analysis can generate “real” topographic maps of instruments, clearly showing arching styles as well as deformations due to age. As one gets more experience viewing these images it becomes easier to identify variations in arching styles and localization of deformation. Metal artifacts are again the cause of blurring at the bottom of the images and the “dot” effect from the string ball-ends.

THICKNESS MAPS

Plate thickness measurements have been considered by many luthiers as important data, and whenever possible makers measured as many different points as they could. However, until the modeling work done by Loen [12], these data were often a jumble of numbers with little cohesiveness. With the advent of the visualization abilities afforded by Loen’s techniques, it became possible to get an understanding of the graduation patterns used by makers.

Figure 6 shows thickness maps generated

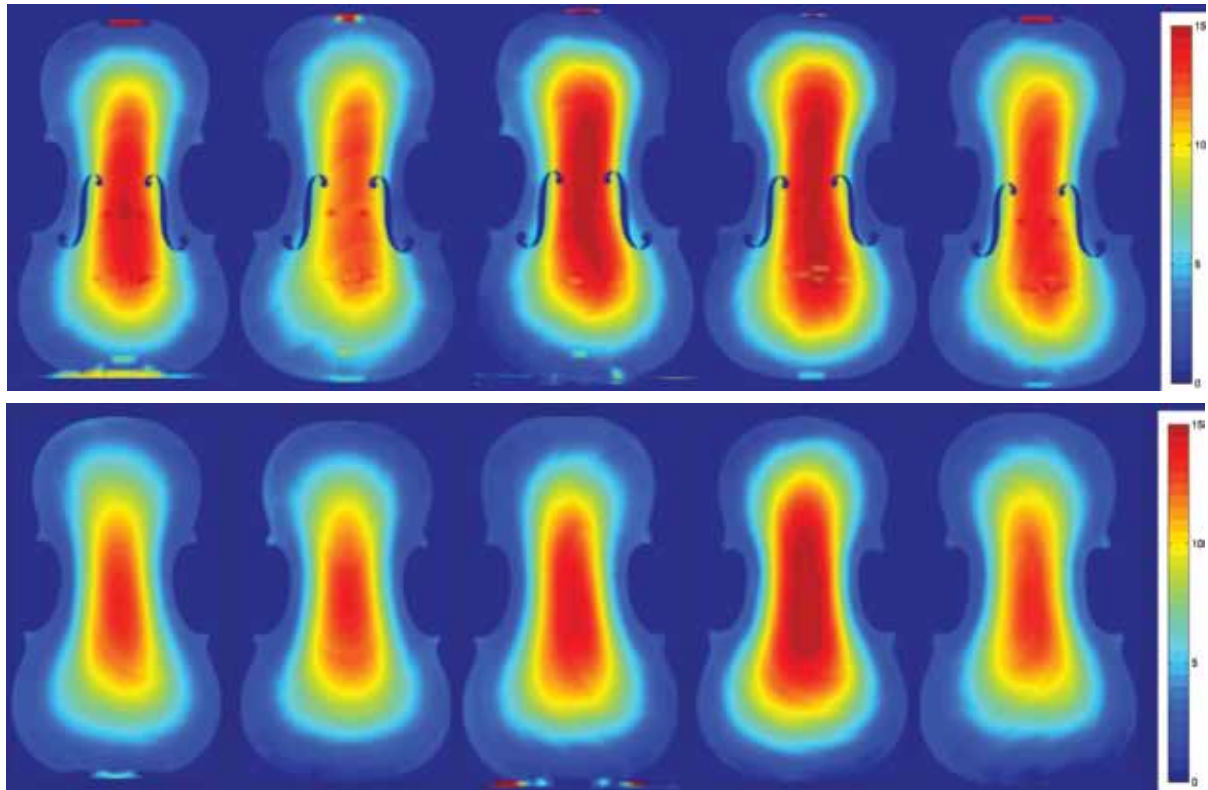


Figure 5. The top and back plates of three violins by Giuseppe Guarneri del Gesù (lft to rt: 1, 2, 3) and two violins by Antonio Stradivari (4, 5) (generated from the SDP) showing the elevation profiles.

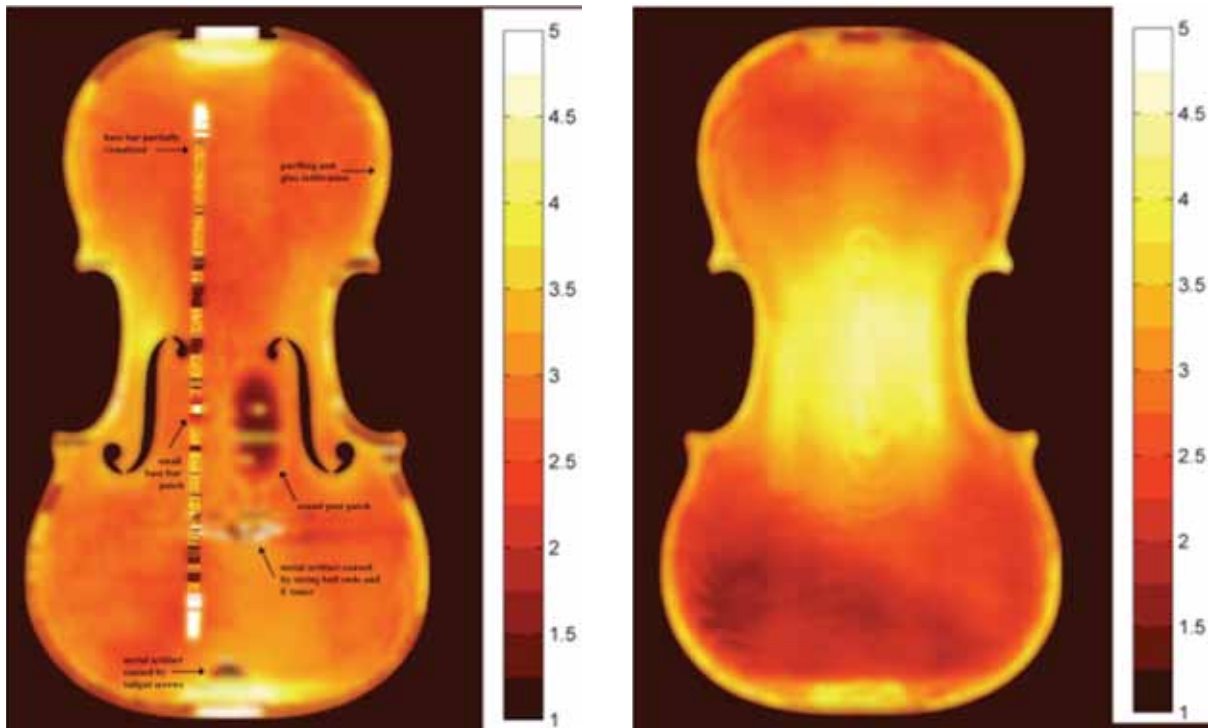


Figure 6. Thickness maps generated from the SDP and IDP of the front and the back of a violin by Antonio Stradivari, 1715, known as the Titian. Scale is in mm. Boundaries are blurred due to the ~0.2-mm resolution.

from the SDP and IDP of the front and back of the *Titian* Stradivari violin of 1715. In this particular instance the virtual spider “found” the separation between the original wood and the soundpost patch wood rather than the inside of the instrument. For this reason the image is based on the thickness of the original remaining wood at this location instead of the total thickness. We have included this image as an interesting anomaly.

Due to metal artifacts, there is a certain amount of distortion of the images shown in Fig. 6. Also, the algorithm had some difficulty in differentiating between very similar density values. For this Stradivari violin, the wood/wood juncture of the bridge to the belly is seen as well as that of the bassbar. The area of the bass bridge foot was problematic due to the patch underneath the bassbar.

The initial impression is that that the two maps shown in Fig. 6 have lower resolution than those created from “standard” measurement and modeling systems. In fact, they *must* be so, since the maximum resolution for this particular raw scan is 0.5 mm³. However, as in many other

aspects of instrument makers’ work, a more thorough review may be warranted. Most makers would agree that the currently accepted highest resolution readings are those obtained from a dial caliper with Hacklinger gauge measurements in second place. Caliper measurements are stated to 0.1 mm precision and are accepted as “real” with no need to explain inherent restrictions to their validity.

The accuracy of the data points used for modeling is a subject that has received little attention, although it may be warranted. The *Il Cannone* Guarneri *del Gesù* violin of 1743 has been measured multiple times, and the differences in the results are striking. Measurements by Candi (1937) and Giordano (1995) (using a dial caliper) and Dilworth and Hargrave [13] and Scrollavezza [14] (most likely using a Hacklinger gauge) differ at times by almost 1 mm in the same general areas. Such an example challenges the accuracy of these measurement systems taken as a whole, i.e., the tool as well as the user.

A dial caliper, calibrated and perfectly perpendicular to the plate in the z-plane, will probably give the most accurate reading, but perfect

alignment is required. When not so, it will always yield higher-than-actual numbers. Careful top plate measurements can be quite accurate when the angle of the caliper relative to the plate is adjusted to find the smallest reading. However, attempting back plate measurements with the rest of the instrument intact is a highly problematic undertaking. Anyone who has attempted to repeat measurements knows that it is quite difficult to find the same spot and correct alignment for each measurement, although rarely does a luthier attempt to repeat measurements. If this were a more common practice we believe that the caliper accuracy paradigm would have been questioned long ago. As stated, caliper measurements, when not perfect, will always give larger-than-actual results. Based on our experience we assign this deviation to be conservatively ~0.2 mm, although it can possibly be quite a bit larger.

Hacklinger measurements would seem to avoid some of the pitfalls of caliper measurements in that z-alignment is somewhat easier to find. The magnetic force will hold the gauge in place at the correct angle (if there are no constraints), but this measurement system has other inherent problems. Even when correctly placed and with care not to move the gauge, multiple measurements will give different results with most makers taking an average of three or four measurements. Assigning a standard deviation is more difficult here as “user interface” has an especially strong impact. Nevertheless, we believe that most people who have used these gauges would agree on 0.3 mm as a conservative figure for accuracy (again, when properly calibrated).

To those questioning these standard deviations we ask that a simple experiment be conducted. Choose an instrument to measure and make your standard measurements with a caliper and also separately with a Hacklinger gauge. Then, without the original data present, re-measure this same instrument several days later using the same techniques. We believe that most people will be quite surprised when comparing their data.

Returning to the CT data, the minimum pixel size is 0.5 mm x 0.5 mm and a measurement is recorded every 0.5 mm, which for a violin top or back plate would approach ~200,000 measurements. For this data volume our results

have shown a standard deviation of the mean of ~0.2 mm per measurement. This, along with the ability to state with absolute certainty the xy placement of each measurement to 0.5 mm, begins to show that the most reliable measurements may be those from CT (see Fig. 7 for more details). Although the images don't look as “perfect” as those done with topographic mapping software, the information contained may be the best attainable.

Two other points worth keeping in mind are: 1) we are dealing with hygroscopic materials so there will be native variations due to temperature and humidity values, and 2) as we understand more of the mechanical workings of the violin it may be more important where thicknesses change than what the actual thickness is at any given point.

In recent years there has been more interest in a material properties view of instrument wood, taking into account not only thickness but density and other visco-elastic properties [15]. CT expands our understanding, as we now can know the density, and even density distributions, of the material as well as the thickness. Prior to the melding of the two, the one without the other had limited meaning.

INTERACTION WITH MODAL ANALYSIS

Since xy-location is accurate with CT thickness measurements, it is possible to analyze the relationship between thicknesses and modes of vibration. As in earlier images, one can easily place one upon the other to see the relationship between thickness variations (or archings) and the different modes and their placements. Figure 8 shows two such examples based on the *Titian* Stradivari violin of 1715. One could also overlay the elevation profiles onto modal analysis results.

VOLUMETRIC USES

With quantitative analysis, volumetric data can also be acquired. The air volume contained within a violin can be easily obtained, which may be useful in studying the various air modes. As in the other automated, user interaction-free, data-extraction processes presented so far, each of the roughly 1000 axial CT slices that make up

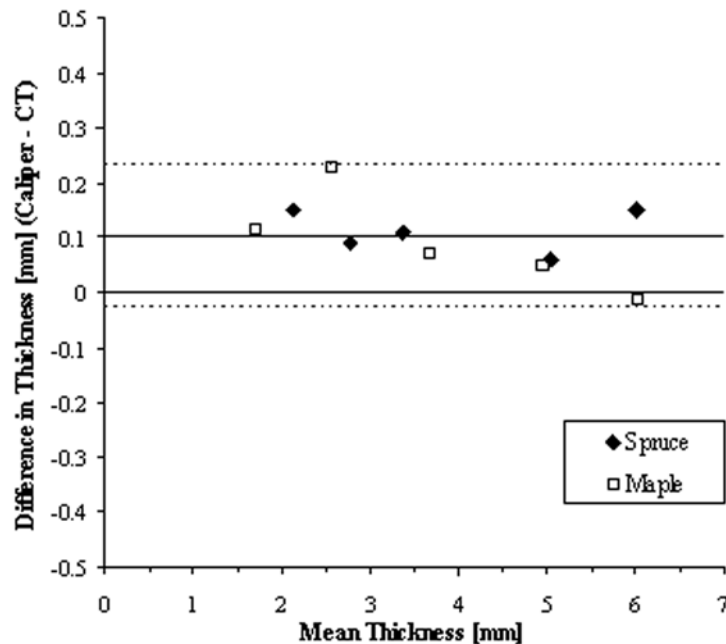


Figure 7. Bland-Altman plot of the thickness measurements; plotting the differences between the CT measurements and caliper measurement against the mean thickness values. Horizontal line: mean difference. Dotted lines: 95% confidence interval of the differences.

a violin body (using overlapping helical slices we obtain one slice every 0.3 mm) is analyzed using the IDP and an amendment application that virtually seals the f -holes. Once this is complete, a “seed” is planted within the interior and allowed to grow until it fills the entire body cavity. This “grown” volume is then measured automatically [10]. This information can be obtained using different techniques (another article in this journal deals with this in more depth).

A further volumetric use of CT (in combination with densitometry) is in the estimation of violin plate weights. Although still in the initial stages of this work with more validation needed, we believe this shows promise. Prior to the development of CT to extract quantitative data, the only way to get plate weights was by use of a scale when the plate was removed from the instrument for repair. Curtin [16] has made such measurements of the weight of the spruce tops of nine Old Italian violins. However, there is very little weight information for back plates since they are rarely removed. With the inherently higher risk of removing the back plate from the rib structure, it is safer to effectuate back repairs by removing the top and working with the ribs in place.

Table 2 contains the averaged density values obtained by CT and this, in conjunction with CT-derived plate volumes (using the SDP and IDP), gives values in Table 3 that are within the expected range considering the predominantly slightly lower densities of antique wood compared to modern wood. These weights do not take into account variations due to humidity and we unfortunately did not acquire this information at the time of scanning. From experience in shop settings, the ambient humidity level can change individual plate weights by several grams, so scale measurements will vary.

OTHER CT FORMATS

Micro-CT has been available for many years and is similar in some ways to medical CT except the machines are much smaller and can therefore only admit objects as wide as 5-10 cm, depending on the machine. This is much too small for full-size violins with lower bout widths greater than 20 cm. However, the voxel dimensions can be as small as 1 μm , which is small enough to study wood detail in depth. Japanese researchers have devised a portable micro-CT that is regularly used in a dendrochronological setting to date ancient temples [17]. Multiple views

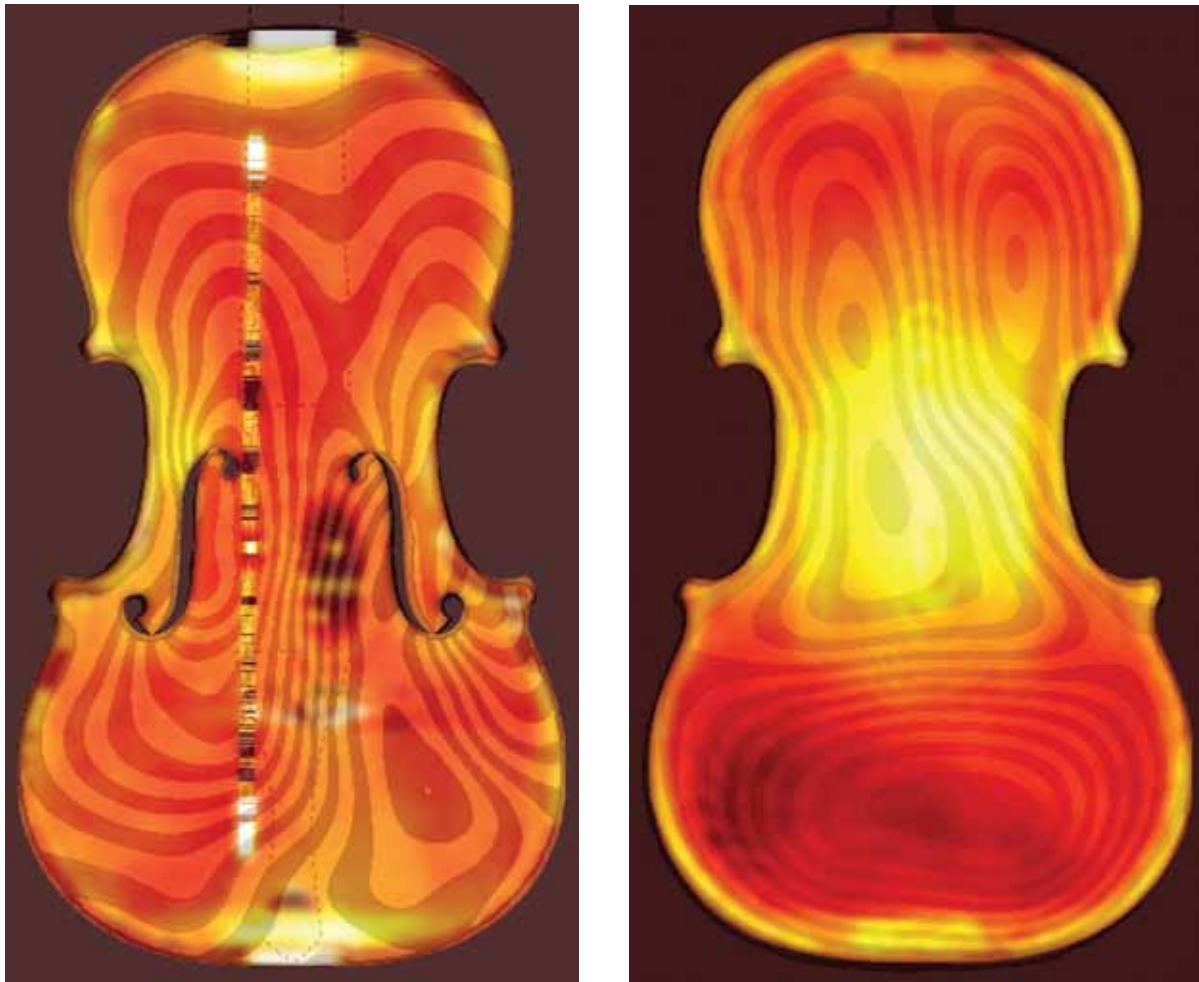


Figure 8. Left: The mode shape associated with the B1+ mode of the Titian Stradivari top overlaid upon the thickness map of the same instrument. By altering opacity it is possible to highlight different features. Right: The same instrument thickness/mode overlay (of the back), but of a mode at 980 Hz. Due to color change from the overlay of one image upon another, when analyzing the relationship thickness/modes, it is best to refer to Fig. 6 for absolute thickness values. Scale is in mm.

Table 2. Density averaged from multiple locations per plate.

| Instrument | Average Density of Back (g/cm ³) | Average Density of Belly (g/cm ³) |
|--|---|--|
| G. Guarneri <i>del Gesù</i> , 1735, <i>Kubelik</i> | 0.560 | 0.342 |
| G. Guarneri <i>del Gesù</i> , 1735, <i>Plowden</i> | 0.533 | 0.340 |
| G. Guarneri <i>del Gesù</i> , 1734, <i>Rode</i> | 0.595 | 0.380 |
| Antonio Stradivari, 1734, <i>Willemotte</i> | 0.574 | 0.379 |
| Antonio Stradivari, 1715, <i>Titian</i> | 0.579 | 0.368 |

Table 3. Plate weights by CT measurement.

| Instrument | Back Plate Weight by CT (g) | Belly Weight* by CT (g) |
|--|--------------------------------|----------------------------|
| G. Guarneri <i>del Gesù</i> , 1735, <i>Kubelik</i> | 89.6 | 59.8 |
| Guarneri <i>del Gesù</i> , 1735, <i>Plowden</i> | 87.9 | 61.3 |
| G. Guarneri <i>del Gesù</i> , 1734, <i>Rode</i> | 88.3 | 67.5 |
| Antonio Stradivari, 1734, <i>Willemotte</i> | 97.8 | 62.3 |
| Antonio Stradivari, 1715, <i>Titian</i> | 93.6 | 61.7 |

*Belly weight measured without the bassbar.

are stitched together to get enough data on tree rings to date the tree's origin. The authors are currently working with researchers in Japan to attempt micro-CT study of violins, but it may be some time before we have publishable data.

The next generation of CT scanners large enough for musical instruments will likely incorporate greater resolution and discernment. Most recent advances of medical CT have been with a goal of faster acquisition speed because movement (as for a live object) results in blurred images. Musical instruments don't present this particular problem, but improved images could be attained by reducing the x-ray scattering, currently the limiting factor for medical CT resolution. This will improve image quality incrementally. A huge leap in resolution will take place when the gantry (where the instrument rests) of micro CT is enlarged enough for the lower bout of a violin (~210 mm) to pass. When this happens, the range of CT uses will increase even further from those offered today.

SUMMARY

CT has proven itself to be an extremely valuable tool in studying musical instruments, with its key importance being that it is done in a completely non-intrusive, non-invasive manner. The subject being studied only needs to be out of its case for a few minutes, placed on soft foam supports, and put back into its case. In this short period of time an incredible amount of information can be acquired. It is no longer necessary to expose these valuable antiques to possible scratches from measurement tools to get a fairly meager amount of information. Data extraction can now be mechanized, which removes the pos-

sibility of human error, and the obtained information can be manipulated in ways never before possible and to much greater effect.

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We would like to express our appreciation to the owners of the antique instruments who were kind enough to lend us their violins for this work. Our special thanks go to George Stoppani for making his modal analysis software available for this work.

NOTES

1. On several occasions this has proven to be very useful as it is often difficult to remember to measure everything that might be of use. Many missing details can be extracted from the recorded data at a later date, if necessary.

2. In 1999 one of the authors (TB) used CT to resolve a dispute between an insurance carrier and a musician regarding a soundpost crack. The evidence provided by the CT images was sufficient to resolve a contentious issue. The owner and the insurance company were pleased with the results, and since that time CT has shown itself to be very useful in these circumstances.

3. Several years ago one of the authors (TB) was commissioned to make a copy of a Guarneri *del Gesù* violin. The owner had been frustrated with previous shop attempts to replace the neck on her violin with a similar feeling neck when her antique neck needed replacement. Measurements with calipers indicated that the dimensions of the original and replacement necks were identical to within 0.1 mm. Only after reviewing CT scans of the original neck did

it become apparent that its shape was slightly asymmetrical, whereas the new neck was perfectly symmetrical. A new neck made with this slight “abnormality” fixed the problem.

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