Thin-Section X-Ray CT "Dissection" of Front and Back Plates, Fingerboards, and Corpus Volumes of 14 Cremonese Stringed Instruments: Density, Mass Distribution, and "Balanced Chi" Relationships

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Abstract

X-ray computed tomography (CT) was used to measure the densities and masses of the front and back plates, fingerboards, and internal corpus volumes of 14 valuable Cremonese stringed instruments (13 violins and one cello) crafted by the luthiers Nicolo Amati, Antonio Stradivari, Giuseppe Guarneri del Gesù, Pietro Guarneri of Mantua, and Michele Angelo Bergonzi. The average densities of the front and back plates and fingerboards were 0.38 ± 0.03 g/cm³, 0.58 ± 0.05 g/cm³, and 1.25 ± 0.18 g/cm³, respectively. We observed no significant difference among the densities of the front plates, the back plates, or the fingerboards of these luthiers. Thin-section CT technique was used to dissect isolated front and back plates, fingerboards, and internal corpus volumes from which mass distributions were determined. The average values of the mass of violin front and back plates and fingerboards were 58.9 ± 9.8 g and 92.2 ± 13.2 g and 64.3 ± 10.9 g, respectively. The average violin corpus volume was 1,939 ± 102 cm³. Strong correlations were observed for four relationships: 1) between the center of mass (COM) of front plates with the position of the mensur, 2) between the COM of the back plates and the soundpost position, 3) between the COM of the fingerboard and its attachment position at the neck, and 4) between the total corpus volume and the position of the soundpost. These four special relationships indicate the presence of "balanced chi." Such a condition exists when the plate COM matches either the mensur of the front plate, or the center of the soundpost of the back plate, or when the COM of the fingerboard is at the attachment position to the neck, or when the position of the soundpost divides the longitudinal corpus volume into two equal volumes. A number of the old Cremonese instruments were observed to be in a state of balanced chi for one or more of the four relationships.

The purpose of this study was to determine if the positions of essential and normal anatomical structures of bowed stringed instruments (such as the mensur, soundpost, and fingerboard) correspond to the x-ray computed tomography (CT) slice containing the center of mass (COM), or balance points, of the front and back plates and fingerboard. We postulate that the alignment, or balanced chi, of the CT slice containing the COM of the front and back plates and fingerboard with the mensur, soundpost, and fingerboard is an important feature in the basic structure of bowed stringed instruments. Both Hans Weisshaar [1] and Simone Sacconi [2] have referenced balanced alignment, and we believe modern luthiers may benefit by employing this concept.

CT has been shown to be a powerful and safe tool for the noninvasive investigation of stringed instruments of the violin family. Since 1989, we have CT scanned many hundreds of stringed instruments of varying quality. Using modern medical CT scanners, high-quality images of submillimeter thicknesses (0.500 mm and 0.625 mm) provide true isotropic, high-resolution volumes. CT also gives the modern luthier and acoustical scientist a method to characterize normal structures in stringed instruments, such as plate outlines, thicknesses, and graduations. CT also detects defects within the plates, such as cracks and wormholes. Subsequent repair with glue, cleats, and internal wooden patches are also detected [3–6]. Also, from CT scans we were able to determine that master luthiers of the Amati family did not form the shape of their plates by bending them [7].

CT also provides accurate measurements of internal corpus volumes. We have previously shown a unique balance relationship of the corpus volume; the center of the soundpost is positioned so that the corpus volume is divided in two equal volumes [6]. The soundpost-volume ratio (SPVR) is 1.00 when the longitudinal volumes at the center of the soundpost position are equal.

All CT scan images can be thought of as density pictures. CT images consist of many thousands of pixels (picture elements less than 1 mm on a side), each with a unique degree of grayness depending upon the density of the material the x-ray passes through. Materials with low densities, such as air, have an opposite degree of grayness when compared with materials of higher densities, such as bone or ebony. Materials with densities between air and ebony have a degree of grayness in proportion to their densities.

An individual CT image slice is represented by a single 512-kilobyte DICOM (Digital Imaging and Communication in Medicine) file. Typical CT scans generate between 600 and 2,000 individual DICOM files, depending upon the slice thickness. The resulting two-dimensional CT images are comprised of approximately one-quarter million pixels (picture elements), each of which has a specific Hounsfield Unit (HU) number. (Godfrey Hounsfield, an electrical engineer, was awarded a Nobel Prize in 1979 for his role in inventing the CT scanner.)

By convention, the HU attenuation number of air, water, and bone is −1,000, 0, and +1,000, respectively. For objects between the density of air and the density of bone, the correlation between the density and attenuation of x-rays is nonlinear. Typical HU values for maple and spruce are −430 and −630, respectively, a difference of only 200 HU.

Using CT we measured the densities of front and back plates and fingerboards of 14 stringed instruments crafted between 1654 and 1759 in Cremona, Italy (two violins by Nicolo Amati, four by Antonio Stradivari, five by Giuseppe Guarneri *del Gesù,* one by Pietro Guarneri of Mantua, one by Michele Angelo Bergonzi, and one cello crafted by Stradivari). None of the 14 instruments had a patch in their back plate, but all had front-plate patches.

The masses of the front and back plates and fingerboards were determined using the following technique. For every individual [AQ1] axial image of the plate, the internal area was measured. Knowing the fixed CT slice thickness (either 0.5 or 0.625 mm), the volume of each axial slice was calculated. The mass of each CT slice was calculated by multiplying the density by its slice volume.

A mass distribution profile curve was created by plotting individual CT slice mass (y-axis) against CT slice number (x-axis). As shown by elementary calculus, for very thin CT slice thicknesses, the area beneath the mass distribution profile curve approximates the actual or total mass. The accuracy of this total mass determination increases with decreasing CT slice thickness.

The front and back violin plates are each comprised of two components we call the major and minor plates. The major front and back plates are the plates carved by the original maker; each contains the edges plus the portion of the plate exposed only to the internal corpus volume of the instrument. We define the minor plate as the portion of plate exposed only to the internal corpus volume, with the edges and blocks removed. This is illustrated in Fig. 1, which shows CT images of the edge, minor, and major plates of the front of the *Betts* Stradivari violin.

Figure 2 illustrates an example of a single CT transaxial image of the back plate of the *Kreisler* Guarneri *del Gesù* violin through the dorsal pin. The region of interest (ROI; in green) measured areas of the edge and the minor of this individual CT slice. The area of the edge and minor and was 0.45 cm^2 and 3.65 cm^2, respectively, so the total area of this individual CT slice was 4.10 cm^2. The CT slice thickness was 0.05 cm and therefore the volume of this individual CT slice was 0.20 cm^3. The density of the *Kreisler* was 0.57 g/cm^3, and therefore the mass of this individual slice was 0.11 g.

In general, the mass of the entire, or major plate was determined by the following formula, [AQ2]

$$\text{CT mass-entire plate} \cong \sum_{n=1}^{m} (\text{mass slice-individual major plates})_n$$

$$= \sum_{n=1}^{m} (\text{CT mass slice-individual "edges"})_n$$

$$+ \sum_{n=1}^{m} (\text{CT mass slice-individual "minor" plates})_{n'}$$

where n is the individual slice number and m is the number of the final individual CT slice number.

Mass distribution profile curves were constructed for the edges and minor portions of front and back plates and also for the fingerboards for each instrument. The x-axis

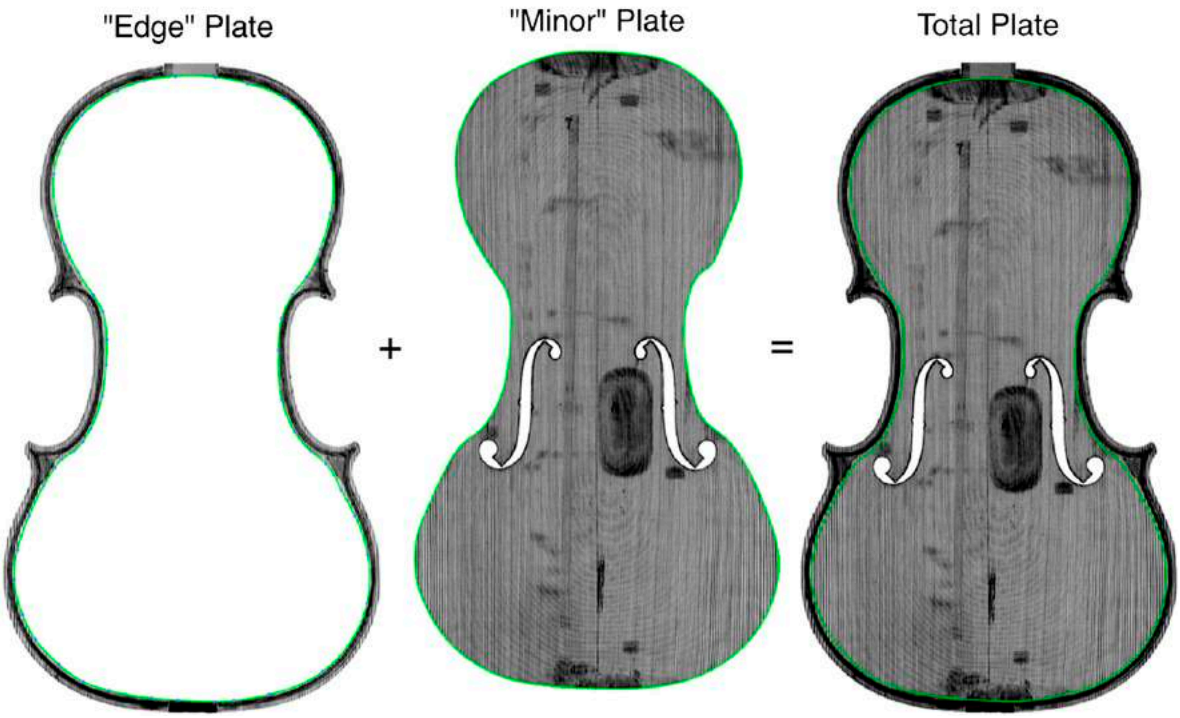

Figure 1. CT images of the edge and minor portions of the top plate of the Betts *Stradivari violin. The edge includes the purfling to the margin of the plate. The minor portion is the plate area excluding the edge. The composite of these two CT images equals the major plate shown on the right.*

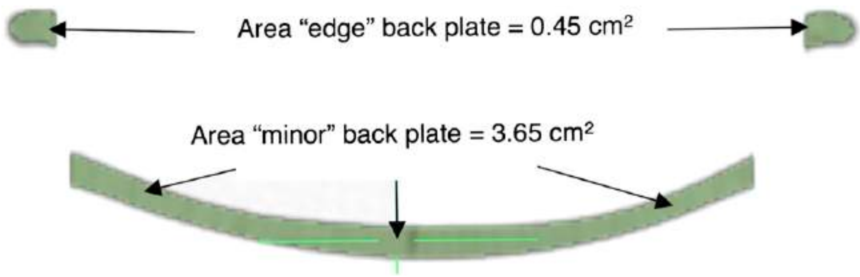

Figure 2. A 0.5 mm CT transaxial section of the back plate of the Kreisler *Guarneri* del Gesù *violin made through the dorsal pin in ROIs (in green): a) the edge area and b) the minor area.*

of these curves is the CT slice number and the *y*-axis is the mass of the individual slice. For all front plates, the CT slice containing the COM and position of the mensur was measured. For all back plates, the center of the mass and the center of the soundpost position were
[AQ3] determined. For all fingerboards, the CT slice(s) containing the COM and the attachment of the fingerboard to the neck were determined.

When a plate's CT slice containing the COM is positioned on a straight edge, the plate will be in equilibrium and find itself in perfect balance. The COM can be moved by removing wood from the inside surface of the plate. Wood removed near the upper and lower block will have a greater effect moving the center of balance than wood removed from the middle bout. The CT slice containing the COM is a thin volume that contains all portions of the part. So if a straight edge (such as a ruler) is positioned 90° from the longitudinal axis and placed on the same CT slice position that contains the COM, the plate should be balanced by gravity. If the ruler is moved to a CT slice not containing the COM, the plate will not balance.

We define balanced chi as a condition where the CT slice containing the COM of a part of the instrument matches the position of normal anatomy (such as the mensur of the front plate, the center of the soundpost position on the back plate, and the point of attachment of the fingerboard to the neck). The threshold limits for balanced chi are 0.5 mm or 0.625 mm, the thickness of the CT slice at the COM.

We found a correlation between the COM of the front plate to the mensur, the COM of the back plate to the center of the soundpost, and the COM of the fingerboard to its attachment on the neck. We believe the correlation of the COM with the mensur of the front plate, the COM of the back plate and center of the soundpost position, and the COM of the fingerboard to the attachment on the neck provides maximum transfer of translational motion and minimal transfer of rotational motion.

Internal corpus volumes were also measured in a manner similar to that previously described [8]. Internal corpus areas were measured for each CT image and corpus volume distribution curves were derived. The area beneath the corpus volume distribution curve represents the total internal corpus volume. The center of the soundpost position was then correlated with the position of one-half of the corpus volume. We find a correlation of the center of the soundpost position with the center of the corpus volume in all instruments.

We call these four conditions of balance [AQ4]
between the mensur, center of the soundpost, and fingerboard balanced chi. (Chi is an important Chinese medical concept and can loosely be translated into the Western ideas of energy flow, air, breath, spirit, and life force.) The chi is balanced when it flows into the CT slice containing the COM of the front or back plate.

METHODS

Many different CT scanners were used to scan the 14 Cremonese instruments during the 24 years of this study, and included the

GE LightSpeed, GE HighSpeed, and Siemens Somatom models. These scanners routinely yield many hundreds or even thousands of CT images of either 1.0 mm or 0.625 mm thickness each with true isotropic, high-resolution volumes. When small anatomical structures such as the three bones of the middle ear are evaluated, the thinnest slice thickness is used. The CT technologist chooses the slice thickness prior to scanning so all the resulting images will have the same thickness.

To obtain the highest quality CT images, it is important to prepare the instrument prior to CT scanning. The most serious degradation of image quality in CT scanning is caused by the presence of metal within the x-ray beam and is called the metallic artifact. The metallic artifact is seen in any CT scan containing even the smallest amount of metal and is created by the inability of CT imaging software to assign correct HU numbers and pixel positions for any volume containing metal. The resulting CT image shows bizarre streaking artifacts causing the complete loss of usable image data. To eliminate metallic artifact we remove all portions of the instrument containing metal, including metal strings, finger tuner, and the tailpiece. We also routinely remove the pegs and bridge. If the bridge cannot be removed, we substitute gut for metal strings.

Prior to CT scanning, careful attention must be directed to proper positioning of the instrument on the CT table; the three axes of the violin must be aligned with the three orthogonal laser lights of the CT scanner (Fig. 3). Incorrect positioning and poor alignment could cause serious postprocessing imaging errors. To avoid these potential problems, the instrument should be positioned on the CT table with the back lifted away from the tabletop, usually by ~10 to 15 cm. Raising the instrument with sponges or other objects can do this, but we have often seen degradation

Figure 3. A violin in position for a CT scan measurement. A red He-Ne laser beam is used as the reference for positioning the axis of the violin with the x, y, *and* z*-axes of the CT scanner. A special holding device attached to the end button elevates the violin above the table, facilitates alignment of the axis, and avoids artifacts from support material such as sponges.*

of the CT images caused by the density of the foam itself and also by dirt and old contrast material spilled within the foam.

For high-quality spatial resolution and accurate measurement of the plate mass, we routinely scan using a high-mA technique with very thin collimation (0.625 mm or 1.0 mm) slice thickness. The resulting DICOM image files were then recorded on a CD-ROM for subsequent analysis. Postprocessing image manipulation was done with a MacBook Pro computer (2.93-GHz Intel Core 2 Duo Processor, 8-Gb, 1067-MHz DDR3 RAM, 6-MV L2 cache with 1.07-GHz bus speed). We used a powerful, open-source CT imaging software program for the MacIntosh computer called "OsiriX" [9]. OsiriX produces high-quality 2-dimensional images in three orthogonal projections and virtual instruments in volume and 3D surfaces reconstruction. OsiriX also provides quantitative measurements such as length, area, volume, and HU, the latter being proportional to density.

For calibration purposes, CT measurements of the density of spruce and maple samples were performed in the usual fashion. Using a GE Somatom CT scanner, each sample was carefully weighed and then immersed in water and the volume of water displaced was measured. A line of identity between CT densities vs. actual densities was obtained. This linear relationship between HU numbers and actual density was used to determine the density of the front and back plates and fingerboards.

We measured the density of original wood of the plates and fingerboards in the following manner: To avoid artificially high HU values near the edges of the plates [8], we carefully sampled HU values from each plate. Multiple ROIs were drawn deep within the interior of each plate, carefully avoiding features such as wormholes, glue lines, cleats, internal patches, and metallic artifacts. A typical ROI was ~4 to 5 cm in length. About 20 to 40 ROIs were obtained from the front and back plates and fingerboard, and the average HU value for each part was then calculated.

Figure 4 shows examples of typical ROI measurements of HU of the *Betts* Stradivari front and back plates. The upper image shows a portion of the front plate with two ROIs (HU values of −599 and −608). These ROIs were drawn to avoid measurement of the soundpost patch or glue lines. To avoid the artifact from edge enhancement, all ROIs were drawn as close to the center of the plate as possible. The lower image shows a portion of the back plate with a ROI HU of −448. For each instrument, 20 to 40 ROIs of the front and back plates were obtained and the average HU for the plate was calculated.

Generation of Mass Distribution Curves

Mass distribution curves for the front and back plates and fingerboards were obtained in the following manner. CT-generated DICOM files of violins were imported into OsiriX and, using digital cutting tools, the plates were segmented into many hundreds of separate axial images. Areas of the minor plate and edges were measured using an image cutting tool, and then a 3D regional graphing tool filled in the internal areas of each slice for the minor and edge plates. The bassbar was not digitally removed from the front plate.

Individual CT slice areas were then imported into Excel™ software, and mass distribution curves were created for the minor plate and edge of the front and back plates and fingerboards of each instrument. Incremental CT slice masses were calculated by the formula:

$$\text{CT slice mass}_n = \text{CT plate density} \times \text{CT slice volume}_n.$$

CT mass distribution curves generated by plotting CT incremental masses (*y*-axis) were then plotted against the individual CT slice number (*x*-axis).

The CT slices containing the COM and position of the mensur, the center of the soundpost, and the position of fingerboard attachment to the neck were then determined. The distances between the CT slice containing the COM and the mensur of the front plate, the CT slice containing the COM of the back plate and the center of the soundpost, and the CT slice containing the COM of the fingerboard and attachment to the neck were measured. These distances were then transformed into the mass of the plate located between the CT slice containing the COM and the mensur of the front plate, the center of the soundpost on the back plate, and attachment of fingerboard to

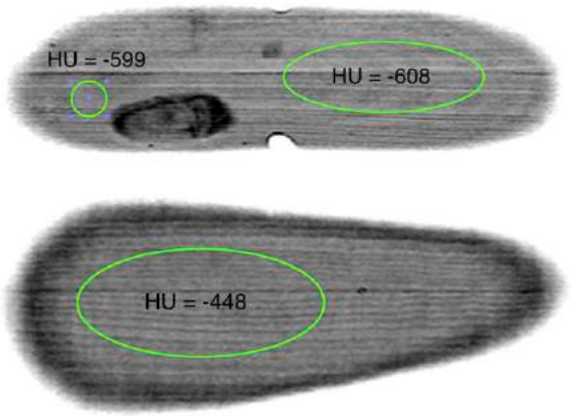

Figure 4. Typical CT measurements of the front and back plates of the Betts *Stradivari violin. The ROI was drawn within the center of the back and front plates to avoid edge enhancement. 20 to 40 ROIs (4–8 cm long × 0.01–0.03 mm wide) were evaluated.*

the neck. The percent of total mass between the mensur and COM for the front plate, the center of the soundpost and COM, and the attachment of the fingerboard and COM were measured.

Internal corpus volumes were also measured for the instruments. Each CT image of the body had its internal area measured and the internal volume calculated. Internal corpus volume curves were generated and volumes determined for each instrument.

A ratio of corpus volume between the center of the soundpost and the upper and lower margins of the corpus volume was calculated. We have previously called this ratio the soundpost-corpus volume ratio (SPCVR) and have shown it to be close to 1.0. Thus, the center of the soundpost position divides longitudinal corpus volume into two equal volumes.

RESULTS

CT measurements of the density ρ and mass of front and back plates and fingerboards of 13 important Cremonese violins and one cello are listed in Table 1. The average densities of the front plates, back plates, and fingerboards were 0.38 ± 0.03 g/cm^3, 0.58 ± 0.05 g/cm^3, and 1.24 ± 0.18 g/cm^3, respectively. Our confidence in the accuracy of these CT measurements was supported by the near-unity correlation coefficient R (= 0.997) obtained from a linear regression analysis of the densities of spruce and maple (7 samples) measured by standard tools and by CT scan values (HU number) as shown in Fig. 5:

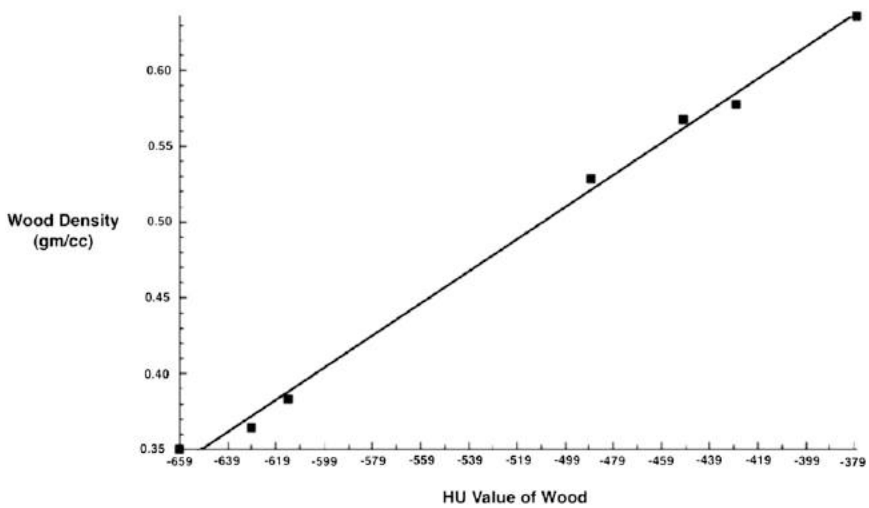

Figure 5. Comparison of the densities of spruce and maple measured by standard tools and by CT scans using the equation ρ(g/cm^3) = 0.001055 • CT density (HU) + 1.038. A near-unity correlation coefficient (R = 0.977) was observed.

Table 1. CT density and mass of front and back plates and fingerboards of 14 Cremonese bowed stringed instruments.

	Density of Top (g/cm^3)	Mass of Top w/Bassbar (gm)	Density of Back (g/cm^3)	Mass of Back (g)	Density of Fingerboard (g/cm^3)	Mass of Fingerboard
Guarneri family (n = 6)						
The *Kreisler* Guarneri *del Gesù*, 1733	0.40	61.5	0.57	90.6	0.92	46.3
Guarneri *del Gesù*, 1735	0.34	49.6	0.53	83.4	1.21	64.7
Guarneri *del Gesù*, 1739	0.37	50.0	0.59	82.2	1.18	67.6
The *Plowden* Guarneri *del Gesù*, 1735	0.35	54.6	0.54	114	1.38	70.8
The *Baron Vitta* Guarneri *del Gesù*, 1730	0.39	65.0	0.56	95.5	1.68	79.7
Pietro Guarneri of Mantua	0.39	46.9	0.63	86.4	no fingerboard	no fingerboard
Antonio Stradivari (n = 5)						
The *Willemotte*, 1734	0.35	66.2	0.56	100.2	1.28	73.2
The *Betts*, 1704	0.42	64.4	0.55	94.3	1.13	51.7
The *Titian*, 1715	0.35	57.5	0.56	98.7	1.26	76.7
The *General Dupont*, 1727	0.37	50.2	0.60	89.5	1.18	54.0
The *Countess Stanlein cello*, 1707	0.39	296.4	0.54	457.5	1.20	363.1
Nicolo Amati (n = 2)						
Violin, 1679	0.39	61.9	0.56	67.0	1.14	61.1
The *Brookings*, 1654	0.47	79.9	0.74	116.5	1.31	61.3

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Table 1. Continued

Michele Angelo Bergonzi (n = 1)						
Violin, 1749	0.37	70.1	0.55	95.3	1.07	52.3
Average CT density (n = 14)	0.38		0.58			
standard deviation			0.05			
Average CT mass of violins (n = 13)		58.9		92.2		
standard deviation		9.8		13.2		
Average CT density of fingerboards (n = 13)					1.25	
standard deviation					0.186	
Average CT mass of violin fingerboards (n = 13)						64.3
standard deviation						10.9

$$\text{Density of wood samples} = (0.001055 \times \text{CT HU}) + 1.038\ (\text{g/cm}^3).$$

Mass Distribution Curves of Front and Back Plates and Fingerboards

The average CT masses of violin front plates (with bassbar), back plates, and fingerboards were 58.9 ± 9.8 g, 92.2 ± 13.2 g, and 64.3 ± 10.9 g, respectively.

The percent fractional mass between the CT slice containing the COM and mensur or center of the soundpost for the front and back plates and fingerboards are shown in Tables 2, 3, and 4, respectively. The average percent fractional mass between the CT slice containing the COM of the front plate and mensur was 1.1 ± 1.1%. The average percent fractional mass between the CT slice containing the COM of the back plate and the center of the soundpost was 1.8 ± 2.7%. The average percent fractional mass between the CT slice containing the COM of the fingerboard and the attachment point on the neck was 0.8 ± 0.8%.

Mass distribution curves for the edge, minor, and total front and back plates of the *Betts* Stradivari violin are shown in Figs. 6 and 7. The mass distribution curves of the edge, minor, and total plates are represented by red, blue, and green curves, respectively. The edge mass distribution curve (red) shows

Table 2. Front plate CT COM and mensur relationships for 13 important Cremonese violins and one cello made prior to 1750.

	Separation between mensur & COM (mm)	Fractional mass between mensur & COM (%)
Guarneri Family (*n* = 6)		
The *Kreisler del Gesù*, 1733	0.0	0.0
Violin, del Gesù, 1735	7.5	1.8
Violin, del Gesù, 1739	7.5	1.7
The *Plowden del Gesù*, 1735	8.0	2.4
The *Baron Vitta del Gesù*, 1730	0.0	0.0
Pietro Guarneri of Mantua	0.0	0.0
Antonio Stradivari (*n* = 5)		
The *Willemotte*, 1734	4.0	1.1
The *Betts*, 1704	2.0	0.8
The *Titian*, 1715	2.0	0.6
The *General Dupont*, 1727	3.1	0.8
The *Countess Stanlein* **cello**, 1707	0.0	0.0
Nicolo Amati (*n* = 2)		
Violin, 1679	9.3	2.5
The *Brookings*, 1654	0.0	0.0
Michele Angelo Bergonzi (*n* = 1)		
Violin, 1749	1.2	0.7

Average distance between mensur and COM = 3.7 ± 4.2 mm
Average % fractional mass between mensur and COM = 1.1 ± 1.1%

Table 3. Back plate CT COM and center-of-soundpost relationships for 12 important Cremonese violins made prior to 1750.

	Separation between mensur & COM (mm)	Fractional mass between mensur & COM (%)
Nicolo Amati (*n* = 2)		
Violin, 1679	9.3	1.7
The *Brookings*, 1654	3.1	1.5
Antonio Stradivari (*n* = 4)		
The *Willemotte*, 1734	0.0	0.0
The *Betts*, 1704	0.0	0.0
The *Titian*, 1715	0.0	0.0
The *General Dupont*, 1727	0.6	0.2
Guarneri Family (*n* = 5)		
The *Kreisler del Gesù*, 1733	0.0	0.0
Violin, del Gesù, 1735	1.2	0.3
Violin, del Gesù, 1739	0.6	0.2
The *Plowden del Gesù*, 1735	0.0	0.0
The *Baron Vitta del Gesù*, 1730	2.5	1.1
Michele Angelo Bergonzi (*n* = 1)		
Violin, 1749	4.4	1.1

Average separation between soundpost & COM = 1.8 ± 2.7 mm
Average % fractional mass between soundpost & COM = 1.8 ± 2.7%

higher masses of the upper and lower corners. The minor mass distribution curve of the front plate (blue) shows two focal regions of decreased mass caused by the upper and lower *f*-hole eyes. Note the CT slice containing the COM is at the position of the mensur, a condition of front plate balanced chi. It is interesting that a large portion of the mass distribution of the front upper bout was fairly uniform. The mass distribution profile of the total front plate (green) shows less mass in the middle bout, especially at the upper eyes of the *f*-holes.

Figure 6 shows the mass distribution profile curves of the edge, minor, and total plates for the *Betts*' back plate. The edge mass distribution curve (red) shows higher masses of the upper and lower corners. Note the CT slice containing the COM is at the position of the center of the soundpost, a condition of back-plate balanced chi. Because of the relatively thick graduations of the middle bout, the minor mass distribution (blue) shows a mass that is nearly as great as the mass of the upper bout. The mass distribution profile of the total back plate (green) was surprisingly uniform except for the masses of the upper and lower corners.

Mass distribution curves for the front and back plates, fingerboard, and corpus volume distribution curve of the *Kreisler* Guarneri *del Gesù* violin are shown in Figs. 8 to 11. Figure 8 shows the *Kreisler* Guarneri *del Gesù* violin front plate (with bassbar) mass distribution. The mass of the front plate is 61.5 g. The position of the mensur is at the CT slice containing the COM, a condition of balanced chi of the front plate. Note the

Table 4. Fingerboard CT COM and neck relationships for 12 important Cremonese violins and one cello made prior to 1750.

	Separation between mensur & COM (mm)	Fractional mass between mensur & COM (%)
Giuseppe Guarneri *del Gesù* (*n* = 5)		
The *Kreisler*, 1733	1.0	0.4
Violin, del Gesù, 1735	5.6	2.2
Violin, del Gesù, 1739	2.5	0.4
The *Plowden del Gesù*, 1735	0.0	0.0
The *Baron Vitta del Gesù*, 1730	5.0	3.3
Antonio Stradivari (*n* = 5)		
The *Willemotte*, 1734	11.0	4.7
The *Betts*, 1704	1.8	0.1
The *Titian*, 1715	3.0	1.2
The *General Dupont*, 1727	3.7	1.9
The *Countess Stanlein* **cello**, 1707	18.5	8.8
Nicolo Amati (*n* = 2)		
Violin, 1679	1.2	0.5
The *Brookings*, 1654	0.0	0.0
Michele Angelo Bergonzi (*n* = 1)		
Violin, 1749 w/beech back	3.1	1.4

Average separation between mensur and COM = 3.1 ± 3.4 mm
Average % fractional mass between mensur and COM = 0.8 ± 0.8%

relative uniformity of mass of the lower and upper bouts and the lower mass of the middle bout. The lowest mass of the front plate was at the eyes of the upper *f*-hole.

Figure 9 shows the mass distribution profile of the back plate of the *Kreisler* Guarneri *del Gesù*, whose total mass is 90.6 g. The position of the center of the soundpost was at the CT slice containing the COM of the back plate, a condition of balanced chi for the back plate. The CT mass of the middle bout is relatively high because of increased thickness of the back plate. Note the increased mass caused by the upper and lower corners.

Figure 10 shows the mass distribution profile of the fingerboard for the *Kreisler* Guarneri *del Gesù* violin. The mass of the fingerboard was 46.3 g. Note the diminished mass of the fingerboard caused by the scoop. The CT slice containing the COM is very close to the point of attachment, a condition of near balanced chi of the fingerboard. Note the slight increase in mass caused by the nut.

Figure 11 shows the internal corpus volume profile for the *Kreisler* Guarneri *del Gesù* violin, whose total volume is 1,855 cm^3. The center of the soundpost of this violin was positioned at the center of corpus volume, satisfying another condition of balanced chi.

Internal Corpus Volume Curves

All the stringed instruments demonstrated balanced chi for the internal corpus volume, a relationship as we previously described [8].

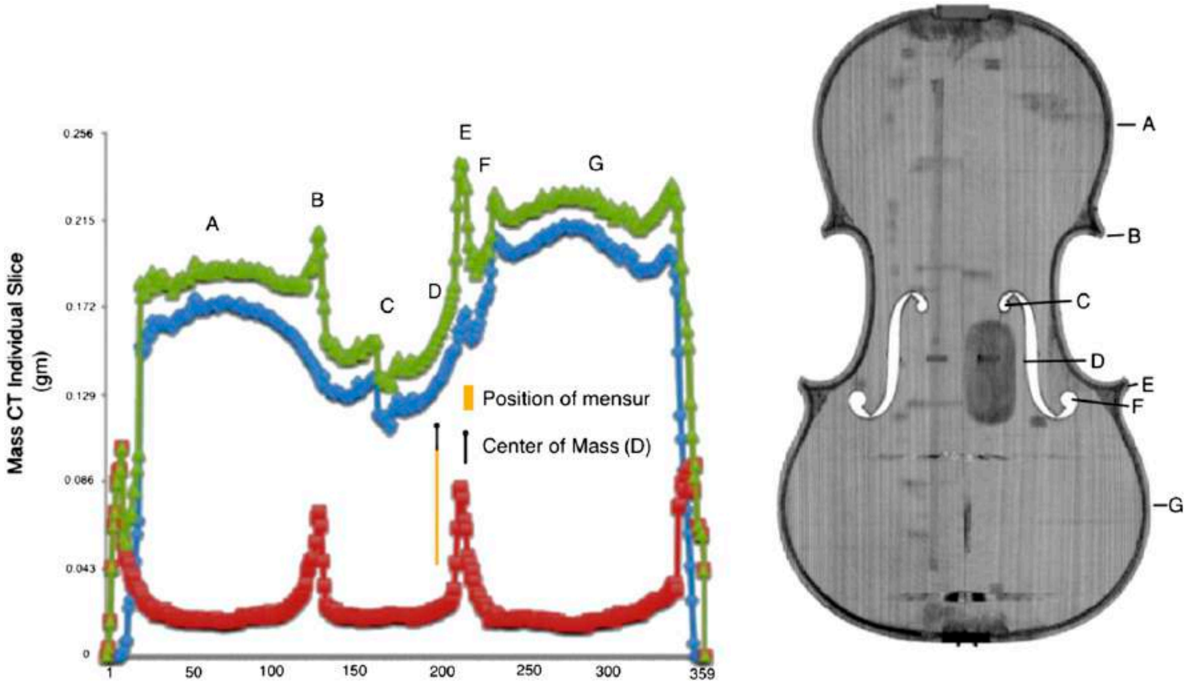

Figure 6. Mass distribution curves of the front plate of the Betts *Stradivari violin. Measured masses for each of 359 CT slices of the edge, minor, and total (61.5 g) plates are represented by the red, blue, and green curves. The lower and upper bouts have relatively uniform mass distributions, as commonly observed.*

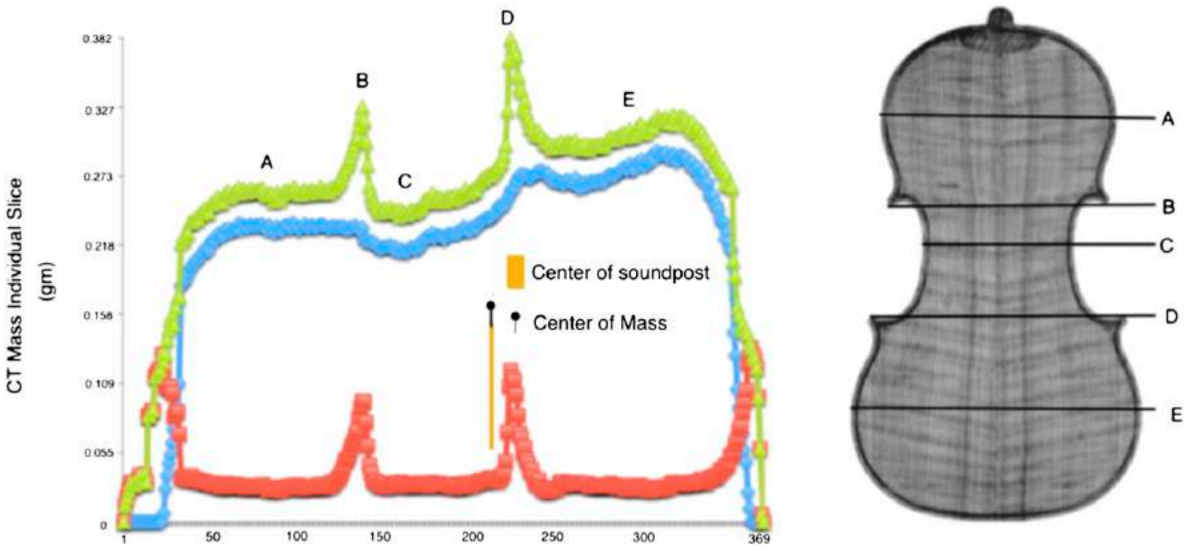

Figure 7. Mass distribution curves of the back plate of the Betts Stradivari violin. Measured masses for each of 369 CT slices of the edge, minor, and total (90.6 g) plates are represented by the red, blue, and green curves. The lower and upper bouts have relatively uniform mass distributions, as commonly observed. The mass of the minor back plate is relatively uniform because of the greater mass of the middle bout compared with the upper and lower bouts.

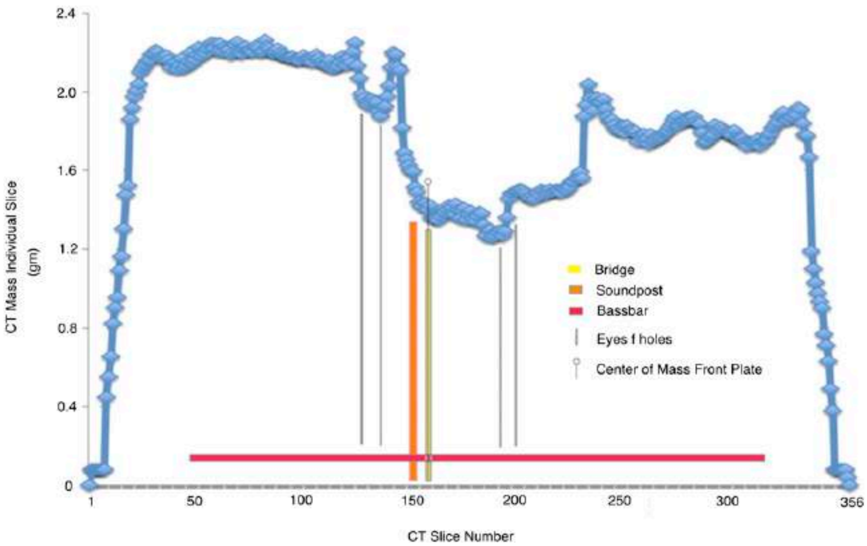

Figure 8. Mass distribution of the top plate (with bassbar) plate of the Kreisler Guarneri del Gesù violin for 356 CT slices (total mass = 61.5 g). The bridge is positioned at the COM, a condition of balanced chi of the top plate. Note the relative uniformity of mass of the lower and upper bouts.

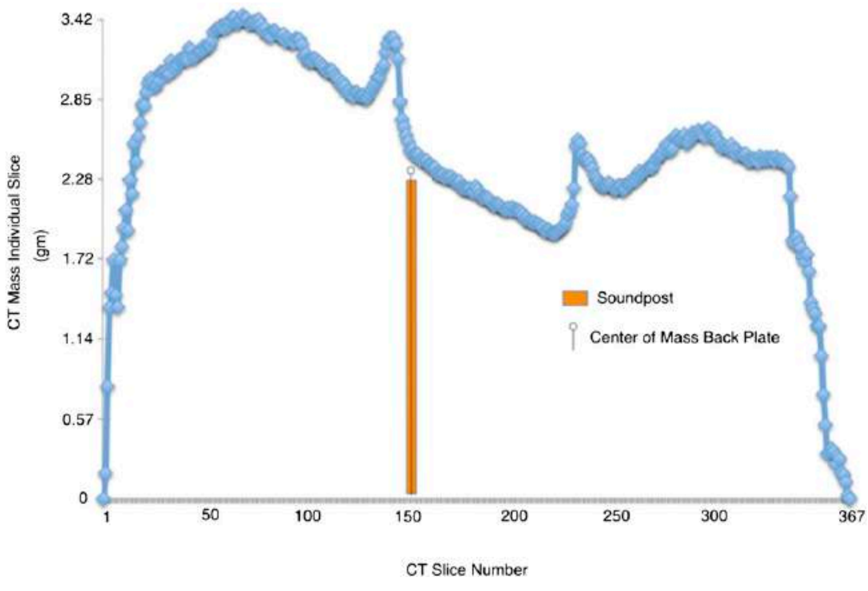

Figure 9. Mass distribution of the back plate of the Kreisler *Guarneri* del Gesù *violin for 367 CT slices (total mass = 90.6 g). The soundpost is positioned at the COM, a condition of balanced chi for the back plate.*

Table 5 shows the corpus volumes and center of soundpost volume ratios for all instruments tested. The average corpus volume of the violins was 1.939 ± 102 cm^3 and the average SPVR was 1.000 ± 0.000.

Instruments with balanced chi of the front plate (Table 6) included the *Kreisler* and *Baron Vitta* Guarneri *del Gesù* violins, the violin by Pietro Guarneri of Mantua, and the *Countess Stanlein* Stradivari cello. Instruments with

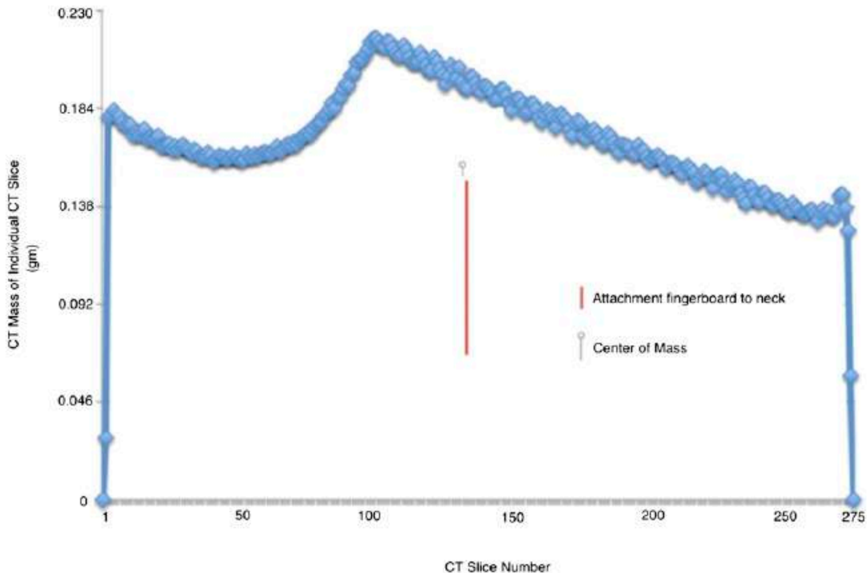

Figure 10. Mass distribution of the fingerboard of the Kreisler *Guarneri* del Gesù *violin for 275 CT slices (total mass = 46.3 g). The diminished mass due to the scoop in the thickness causes the COM to shift toward the button. The COM is very close to the point of attachment, a condition of nearly balanced chi for the fingerboard.*

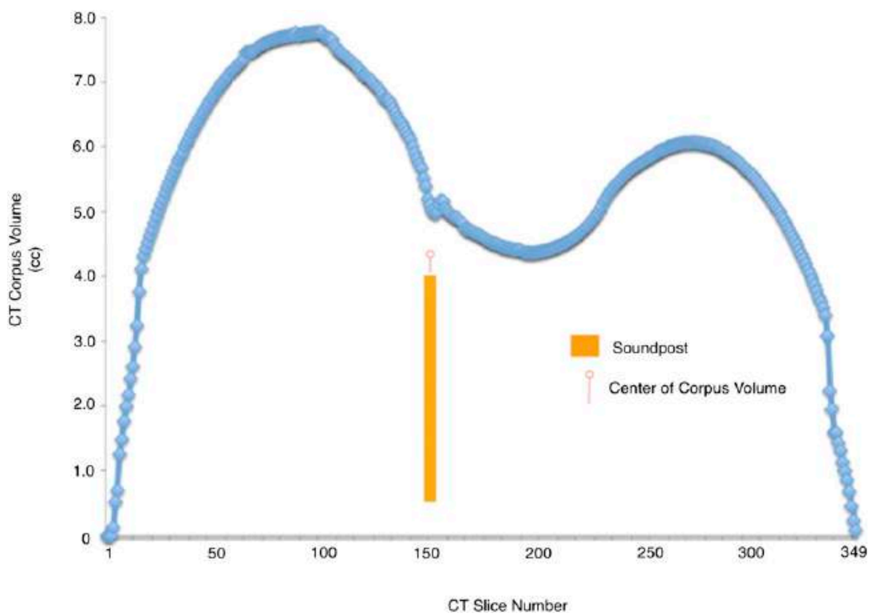

Figure 11. Internal corpus volume profile of the Kreisler *Guarneri* del Gesù *violin for 349 CT slices (total volume = 1,855 cm^3). The soundpost is positioned at the center of corpus volume, a condition satisfying balanced chi.*

Table 5. Corpus volumes and soundpost/corpus volume ratios for 12 important Cremonese violins and one cello made before 1750.

	Corpus volume (cm^3)	Soundpost/corpus volume ratio
Nicolo Amati ($n = 2$)		
Violin, 1679	1,932	0.999
The *Brookings*, 1654	1,841	1.002
Antonio Stradivari ($n = 5$)		
The *Willemotte*, 1734	2,060	0.995
The *Betts*, 1704	1,991	1.018
The *Titian*, 1715	1,891	1.009
The *General Dupont*, 1727	1,990	0.999
The *Countess Stanlein* **cello**, 1707	32,748	0.993
Giuseppe Guarneri *del Gesù* ($n = 5$)		
The *Kreisler*, 1733	1,855	1.006
Violin, 1735	1,743	1.005
Violin, 1739	1,990	1.002
The *Plowden*, 1735	1,831	0.977
The *Baron Vitta*, 1730	1,934	1.007
Michele Angelo Bergonzi ($n = 1$)		
Violin, 1749 w/beech back	2,099	1.035

Average corpus volume, violins = 1,939 ± 102 cm^3
Average soundpost/corpus volume ratio = 1.000 ± 0.000.

Table 6. Important Cremonese violins (and one cello) with the most balanced chi.

Balanced Front Plate	Balanced Back Plate	Balanced Fingerboard
Kreisler Guarneri *del Gesù*	*Kreisler* Guarneri *del Gesù*	*Brookings* N. Amati
Baron Vitta Guarneri *del Gesù*	*Plowden* Guarneri *del Gesù*	
Pietro Guarneri of Mantua, violin	*Willemotte* Stradivari	
Countess Stanlein Stradivari **cello**	*Titian* Stradivari	
	Betts Stradivari	

balanced chi of the back plate included the *Plowden* and *Kreisler* Guarneri *del Gesù* violins and the *Titian, Betts,* and *Willemotte* Stradivari violins. Balanced chi of the fingerboard was found in the *Brookings* N. Amati violin and the *Plowden* Guarneri *del Gesù* violin.

DISCUSSION

In 1991, Lindgren [10] demonstrated that medical CT scanners provide accurate linear correlation of actual density vs. CT density in green and dry wood. Fromm, et al. [11] used a CT scanner to measure CT density distribution of water in newly cut and dried spruce and oak. They found that CT provides images of high spatial resolution and showed CT to be a sensitive indicator of wood density and water distribution in newly cut and dried wood.

Taylor [12] measured the density of *Picea sitchensis* using CT technology and observed that CT can easily distinguish juvenile and adult wood. He also found adult wood comprised of narrow annual rings with little density differential and juvenile wood comprised of wide annual rings with high-density differential.

In studying the *Plowden* Guarneri *del Gesù* and two violins by Antonio Stradivari (the *Titian* and the *Willemotte)*, Zygmuntowicz and Bissinger [13] found CT to be a powerful and practical component when it is integrated with information from modal and spectral analysis.

We are agreement with Bissinger [14] that ". . . *any* quantitative relationship between violin substructures and the assembled structure is
[AQ5] surprising and thus important."

Some may question the accuracy of CT HU measurements and their correlation with actual wood density. Recently, Borman and Stoel [15] published CT density data of spruce and maple plates of two violins by Stradivari and one by Guarneri *del Gesù* that correlate well with our measurements. Figure 12 shows the good correlation between our data (red) and Borman and Stoel's measurements (black).

It is important to understand that our concept of balanced chi is not dependent upon absolute values of density. If an inherent error in measurement of CT HU values is present at the time of scanning, this error will be present in every single CT image of the instrument. A determination of the CT slice containing the center of balance, or balanced chi will not be affected since every HU error will be exactly canceled on both sides of the line of balanced chi.

We have previously shown a balanced chi relationship for internal corpus volume of bowed stringed instruments [8]. We have shown that the position of the center of the soundpost within the longitudinal corpus volume exactly divides the entire longitudinal volume into two equal portions.

Using CT derived densities, detailed mass distribution curves for the edges and minor plates are constructed. Summation of mass elements from the edge curve and the minor curves yields the total mass distribution curve. The CT slice containing the COM, or position of balance upon a straight edge perpendicular to the long axis, is then determined and

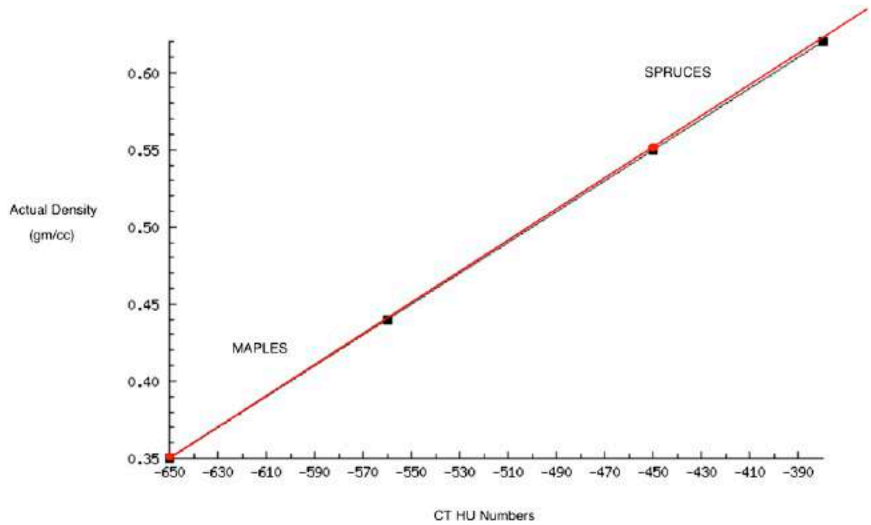

Figure 12. The values of CT density measured by Stoel and Borman (S&B) and Sirr and Waddle (S&W) for the top and back plates of three violins (the Titian *Stradivari, the* Willemotte *Stradivari, and the* Plowden *Guarneri* del Gesù*) were in close agreement.*

compared with the position of the mensur, center of the soundpost, and fingerboard attachment to the neck.

Balanced chi of the front and back plates and fingerboard occurs when the center of balance matches the CT image containing the mensur of the front plate and center of the soundpost on the back plate and the fingerboard attachment to the neck. Balanced chi for the corpus volume occurs at the center of the soundpost position. We found four balanced chi, or nearly balanced chi, positions in many of the instruments we have CT scanned.

The instruments evaluated in this study did not have the chinrest attached. We made this decision because the metal in the chinrest would have caused extensive metallic artifact degradation of the image quality of much of the lower bout.

We postulate that the four balanced chi relationships of the front and back plates, fingerboard, and corpus volume provide conditions such that the mechanical energy of the player's bowing arm will flow into the violin in such a way that it will be transformed into optimal projected sound.

SUMMARY

X-ray CT was used to measure the density and mass of the plates and fingerboards of 14 important instruments (13 violins and one cello) made in Cremona in the 17th and 18th centuries by members of the Amati, Stradivari, and Guarneri families. The average densities of the front and back plates and fingerboards were 0.38 ± 0.03 g/cm^3, 0.58 ± 0.05 g/cm^3, and 1.25 ± 0.18 g/cm^3, respectively. We observed no significant difference of the densities of the front plates, the back plates, or the fingerboards of these luthiers. Thin-section CT technique was used to dissect isolated front and back plates, fingerboards, and internal corpus volumes from which mass distributions were determined. The average values of the mass of the violin front and back plates and fingerboards were 58.9 ± 9.8 g, 92.2 ± 13.2 g, and 64.3 ± 10.9 g, respectively. The average violin corpus volume was 1,939 ± 102 cm^3.

From our CT measurements we observed strong correlations for four relationships: 1) between the COM of front plates with the position of the mensur, 2) between the COM of the back plates and the soundpost position, 3) between the COM of the fingerboard and its attachment position at the neck, and 4) between the total corpus volume and the position of the soundpost.

These four special relationships indicate the presence of balanced chi. Such a condition exists when the plate COM matches either the mensur of the front plate, or the center of the soundpost of the back plate, or when the COM of the fingerboard is at the attachment position to the neck, or when the position of the soundpost divides the longitudinal corpus volume into two equal volumes. A number of the 14 old Cremonese instruments were observed to be in a state of balanced chi for one or more of the four relationships.

POSTSCRIPT

Several weeks prior to mailing this manuscript for consideration of publication, one of the authors (JW) found mention of balanced chi of the front plate by his mentor, Hans Weisshaar [1]:

> During the early development of the violin in Brescia, makers determined the "center" for graduations by balancing the table or back on a straightedge. The notches of the soundholes were placed in line with the balance point of the plate. The thickness of each plate was probably done empirically and no great care or accuracy is apparent. The plates were graduated quite unevenly and rasp marks can be clearly be seen in the few Brescian instruments which are still in their original state.

Further careful review of Simone Sacconi's classic book, *The "Secrets" of Stradivari* [2], revealed another mention of the front plate balance point. When describing the original "G" model, Sacconi states:

> *B [the position of the mensur] represents the acoustic centre of the instrument of*

the centre of gravity which divides the belly into two equal surfaces of equal weight and along which the inside notches of the ff holes and the feet of the bridge are placed; . . .

ACKNOWLEDGMENTS

The authors wish to express our deep gratitude to Mr. Andre Larson for permission to CT scan valuable instruments from the National Museum of Music, and Carleen Hutchins for her encouragement. We also wish to acknowledge Carol Lynn Ward Bamford of the Library of Congress for allowing CT of the *Betts* Stradivari and the *Kreisler* violins. The authors are grateful for the many helpful comments by CT technologists Jeremy Kuznia, Linda Sybrant, and Jacob Hanenburg. We also wish to express our gratitude to the numerous musicians, radiologists, CT technologists, and hospital administrators who generously allowed us use of their medical CT scanners.

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AUTHOR QUERIES
DATE 16/09/2014
JOB NAME VSA
ARTICLE 24209
QUERIES FOR AUTHORS Sirr et al

AQ1) Approve edit for clarity.

AQ2) Please carefully review all instances of formulas and equations to ensure they appear as intended.

AQ3) Is this what you meant, or are you talking about two separate CT slices (in which case, it should be "CT slices" with the plural verb)?

AQ4) Do all four of these conditions need to be met in order for the chi to be balanced? It's not clear from the sentence as written. Perhaps: "When these four conditions of balance affecting the mensur...fingerboard are met, we call the result "balanced chi." ?

AQ5) This has been edited to match the original quotation, please confirm this is OK.