X-ray CT Measurements of the Internal Corpus Volume and a New Soundpost-Corpus Volume Relationship for Stringed Instruments of the Violin Family

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Abstract
We report a series of computed tomography (CT) scan measurements of the internal corpus volumes of 26 stringed instruments of the violin family, most made prior to 1850. We also introduce a new relationship for the soundpost position relative to the internal corpus volume, which we term the soundpost-corpus volume ratio (SPCVR). It is notable that the average value of the SPCVR for the 24 unmodified instruments was 0.994 ±0.043, indicating that volumes above and below the soundpost are essentially identical. Although this unique anatomic relationship is not yet clearly understood, we believe that the SPCVR may provide an important clue for understanding the functionality of these instruments. Our opinion is that x-ray CT has become the new “gold standard” for internal corpus volume measurements of stringed instruments.

Several unique applications of medical x-ray computed tomography (CT) have been reported since the introduction of CT in the early 1970s. These include CT evaluation of Egyptian mummies and cats, antique sword hilts, old wooden African masks, ancient wooden statues, pre-Columbian vases, statues of Buddha, and the “Iceman” discovered in 1991 in the Alps on the border of Austria and Italy [1-4].

In 1989 we began the first attempt to seriously investigate the role of CT in the evaluation of stringed instruments of the violin family [5]. During 20 years of study we have had the good fortune to perform and evaluate CT scans of the instruments used in this study and many more (see Table 1). We have previously shown that CT provides the modern luthier with a unique tool for noninvasive evaluation of normal structures and their variations, internal damage not seen on the surface, such as cracks and wormholes, and the subsequent repair of damage [6-8]. Loen, Borman, and King [9] also have illustrated the potential usefulness of CT scanning stringed instruments.

Modern CT scanners can provide internal images with exquisite detail. It is not uncommon for a single CT study to consist of hundreds or even thousands of thin images often less than 1.0 mm in width. These images are routinely viewed on a computer monitor as contiguous slices. The data are also routinely reconfigured into three orthogonal planes (axial, coronal, and sagittal) and then reconstructed into three-dimensional...
surface and three-dimensional volume Quick-TimeTM movies.

Scientific investigators have traditionally measured volumes by filling the object with a removable, inert substance, such as rice. The rice is simply poured and shaken into the object to be measured until the object is perceived to be full, and then the rice is poured out into a measuring device, such as a graduated cylinder. CT scans of a violin corpus “filled” with rice in this manner have shown significant air pockets between the underside of the top plate and the top of the rice, thereby causing significant errors in the measurement of true corpus volume.

We present a noninvasive method for the measurement of internal corpus volume using medical CT imaging. Data files from the CT scanner (called DICOM, Digital Imaging & Communications in Medicine) are imported into a Macintosh computer and each two-dimensional image has the internal corpus area measured. Knowing the width of the CT image and internal area of the corpus, we create a plot of the individual corpus area (y-axis) vs. the corresponding CT slice number (x-axis). The resulting curves we call the internal volume profile curves. The area beneath the curve approximates the true internal corpus volume, and as CT slice thickness becomes smaller, the area beneath the curve more closely approximates the actual corpus volume.

The internal corpus volume curve contains a small volume defect, which represents the volume taken by the soundpost. We have measured corpus volume above and below the position of the soundpost and calculated a ratio of these two volumes known as the “soundpost-corpus volume ratio” (SPCVR). From our CT corpus volume measurements of the 25 fine historic instruments, we found the average value of SPCVR to be very close to 1.000, i.e., the volume above the soundpost was nearly equal to the volume of the corpus below the soundpost.

METHOD
We have used many different CT scanners to scan instruments during the 20 years of our investigations. In the early 1990s we used first-generation General Electric CT scanners (GE 8800 and GE 9800). As computer technology improved, CT scan quality also greatly improved and provided beautiful images with much higher spatial and density resolutions. We currently use the newest generation of CT scanners (GE, Toshiba, Phillips, and Siemens) that routinely yield many hundreds or even thousands of CT images of slices of less than 1-mm thickness. These CT scanners provide high-quality images of sub-millimeter thickness and with true isotropic, high-resolution volumes.

CT scanners are required by the U.S. Federal Drug Agency to provide accurate and reproducible measurements. Health physicists using standard plastic phantoms embedded with various objects of known sizes, shapes, and densities routinely monitor scanners for accurate measurement of volumes. If a CT scanner fails quality assurance testing, it cannot be used until the problem has been fixed and subsequent quality assurance tests are passed.

Typically, when the owner of an interesting stringed instrument agrees to a CT evaluation, we arrange scanning time in a local hospital where one of the authors (S.S.) is a radiologist. Because we routinely CT scan instruments during nighttime hours, hospital administrators and CT technologists are usually obliging. As a result, during 20 years of CT scanning of stringed instruments, the cost of both the CT scan and the interpretation of the resulting images has never been passed on to the owner of the instrument.

To obtain the highest-quality CT scan data for subsequent image production and measurement, it is important to prepare the instrument beforehand. The most serious degradation of image quality is caused by the presence of metal within the x-ray CT beam, called “metallic artifact.” Metallic artifact is seen in any CT scan containing even the smallest amount of metal. It is created by the inability of CT imaging software to assign correct attenuation numbers and pixel positions for the volumes in and near the metal. The resulting CT image shows bizarre streaking artifacts. To eliminate metallic artifacts, we strongly recommend removing all portions of the instrument containing metal, such as metal strings, fine tuners, and the tailpiece. We also routinely remove the pegs and bridge since they are not needed for our purposes.

X-ray CT acquisition should be performed using high mA and kVp technique with
a small body parts algorithm such as used for facial bones or the temporal/inner ear. This technique captures high-quality spatial images and is used by radiologists for evaluating small structures, such as the bones of the ear. For violins we routinely CT scan with slice thicknesses of 0.625 mm or less, which results in sets of data that often contain 500 or even thousands of individual image files.

When a CT scan is completed, all of the image files are placed on a CD-ROM and imported into an application for the Macintosh computer called OsiriX [10]. OsiriX is a powerful, open-source CT imaging software program that produces high-quality, two-dimensional images in three orthogonal projections and also “virtual” instruments in volume and 3D surface reconstruction. With OsiriX many different quantitative measurements—such as lineal, area, volume, and HU (Hounsfield units) measurements—are easily obtained for any part of the instrument.

Precise positioning of the string instrument upon the CT scanner table is necessary to obtain high-quality images for quantitative analysis. Instruments positioned at an angle to the three orthogonal planes of the CT scanner result in images that are angulated and difficult to interpret. Accurate measurements made upon angled images are often cumbersome and difficult to interpret.

We have developed a unique, minimally invasive holding device that securely lifts the instrument ~15 cm from the surface of the table. The instrument is positioned on the CT table such that the scroll is directed into the CT gantry. The xyz coordinates of the instrument are precisely aligned using the CT gantry positioning laser lights. The long axis of the instrument is positioned exactly parallel to the long axis of the CT table. The edges of the front plate are positioned precisely parallel to the laser lights, both on the bassbar and soundpost sides. Photographs of our instrument holder and alignment scheme are shown in Figs. 1-3.

For this study, we have used CT scans from 26 stringed instruments (16 violins, four violas, four tenor violas, and two cellos). All but a few were crafted in northern Italy from 1560 to 1801.

Originally we measured the corpus volume of a violin with sushi rice, but we were not certain if the rice filled the entire violin. We demonstrated this by placing sushi rice grains into the f-hole holes of a violin and gently shaking to evenly disperse the rice within the corpus until no more rice would go in. Indeed, a CT scan of the rice-filled violin revealed that the rice did not fill the entire instrument. Therefore, any measurement

Figure 1. The instrument-holding device provides quick and easy alignment of the instrument with the CT scanner’s three orthogonal (transaxial, coronal, and sagittal) spatial positioning lasers. Precise alignment is necessary for accurate computer image processing.
Figure 2. Violin positioned on the CT table. The CT-positioning lasers were oriented precisely along the three orthogonal axes of the violin.

Figure 3. Side view of violin and holder device.
based upon rice volume underestimates the true internal corpus volume.

CT measurements of the internal corpus volume of the set of musical instruments were performed in the following manner: Each instrument was carefully positioned upon the CT table and a CT scan with high spatial resolution was performed. The resulting DICOM image files were copied onto a CD and imported into OsiriX, where each image had its internal corpus area measured. Internal corpus area was measured by tracing the inner margin of the front plate (excluding the bassbar), inner margin of the ribs, and the inner margin of the back plate. The soundpost volume was excluded from the measurement of internal areas.

We sometimes receive CT files of stringed instruments which are degraded by the presence of metallic artifacts. In those cases where the metallic artifacts destroy the margins of the plate, we hand-draw the plate’s surface.

The internal corpus volume profile curve is created by plotting every CT slice number (x-axis) with the corresponding internal corpus area (y-axis). Because each instrument has a unique shape and arching, the corresponding details of the internal corpus volume profile curve are unique for that instrument.

CT measurement of internal corpus volume is determined by a mathematical method similar to that used in basic calculus to determine the area under a curve. Once the internal volume profile curve is obtained, the internal corpus volume is calculated by multiplying the internal corpus area for each CT slice by the slice thickness. The slice thickness is determined prior to the scan and does not change during scanning. Individual slice corpus volumes are then summed to produce the total volume, and when the slice thickness is very small, this closely approximates the true internal corpus volume.

We have also discovered a new internal volume relationship that we call the soundpost-corpus volume ratio (SPCVR). The SPCVR is obtained by dividing the internal corpus volume into two separate volumes determined by the position of the soundpost. One internal volume is defined by the soundpost position and contains the volume of the upper bout and much of the middle bout. The second internal volume, also defined by the soundpost position, contains the volume of the lower bout and a small portion of the middle bout. The SPCVR is the ratio of these two adjacent subvolumes. It follows that the SPCVR decreases when the soundpost is moved toward the scroll and, conversely, increases when the soundpost is moved toward the button. When the volumes of the upper and lower chambers are equal, the SPCVR is exactly 1.0.

RESULTS

CT images of a violin filled with sushi rice are shown in Fig. 4. Note the large air pockets persisting beneath the front plate. These could not be eliminated after five to 10 minutes of careful shaking and refilling the corpus with additional rice. A follow-up CT scan demonstrates persistent air pockets within the corpus, which cause underestimation of the true corpus volume.

Examples of typical CT images used to measure corpus volumes are shown in Figs. 5 and 6. Figure 5 is an example of a tracing outlining the corpus area. The tracing is done by hand and requires patience and skill with the computer mouse. Figure 6 is a composite three-dimensional volume image made of thousands of pixels from sequential two-dimensional area internal outlines of a Guarneri tenor viola. Each red pixel in this three-dimensional image represents a point on the inner surface of the corpus. Note the internal volume voids caused by the soundpost, bassbar, corners, and upper and lower blocks. The voids of the f-hole holes can also be clearly seen.

The CT-determined corpus volumes and the corresponding values of the SPCVR of 26 stringed instruments are listed in Table 1. For 24 of these instruments the mean value of the SPCVR is 0.994 ±0.043, a value very close to unity. The King cello and tenor viola by Andrea Amati were not included in calculating this mean value because they had at some point in their history been reduced along their midlines [11]. The SPCVR for these instruments is 0.818 and 0.899, respectively, more than two standard deviations below normal values.

Examples of corpus volume curves are shown in Figs. 7 to 10. The volume defect caused by the soundpost is readily apparent. The values of the SPCVR for the Montagnana cello, Guarneri tenor viola, J. Stainer violin (1668), and an
Figure 4. Examples of axial two-dimensional CT scans of a rice-filled violin corpus at (a) the soundpost, (b) the bridge, and (c) the lower bout. The small, high-density, oval structures within the violin are individual grains of sushi rice. Substantial air gaps beneath the front plate are readily visible and cause underestimation of the true internal corpus volume.
Figure 5. Example of an individual, 0.12-mm thick, 2D axial CT slice through the middle bout of a cello made by Domenico Montagnana (Venice, 1730). The green line outline of the internal corpus margin was formed by the connection of 65 individual blue pixels. Each pixel was hand-drawn with the click of a mouse. The bassbar is not included in the calculation of the interior volume of the corpus.

Figure 6. A single 3D QuickTime™ image is comprised of thousands of pixels outlining the internal margins of the corpus of a tenor viola. Each bright pixel represents a hand-drawn click of a mouse upon the internal margin of the corpus. Natural internal voids in the volume are caused by the soundpost, bassbar, corners, upper block, and lower block. The voids of the f-hole holes can also be clearly seen.
Table 1. Internal corpus volumes and soundpost-corpus volume ratios of 26 violin family instruments scanned with x-ray CT.

<table>
<thead>
<tr>
<th>Scanned Instrument</th>
<th>Internal Corpus Volume (cm³)</th>
<th>SPCVR(^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Violins</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A. Amati, 1560</td>
<td>1,864</td>
<td>0.986</td>
</tr>
<tr>
<td>A. Amati, 1574</td>
<td>1,673</td>
<td>1.011</td>
</tr>
<tr>
<td>G. Amati, 1609</td>
<td>1,586</td>
<td>1.031</td>
</tr>
<tr>
<td>N. Amati, 1628</td>
<td>1,948</td>
<td>0.994</td>
</tr>
<tr>
<td>A. Stradivari, 1693, the <em>Harrison</em></td>
<td>1,922</td>
<td>0.964</td>
</tr>
<tr>
<td>A. Stradivari, 1704, the <em>Betts</em></td>
<td>1,991</td>
<td>1.018</td>
</tr>
<tr>
<td>A. Stradivari, 1715, the <em>Titian</em></td>
<td>1,891</td>
<td>1.009</td>
</tr>
<tr>
<td>A. Stradivari, 1732, the <em>Hammig</em></td>
<td>1,896</td>
<td>0.951</td>
</tr>
<tr>
<td>A. Stradivari, 1734, the <em>Willemotte</em></td>
<td>2,060</td>
<td>0.995</td>
</tr>
<tr>
<td>G. Guarneri del Gesù, 1735, the <em>Plowden</em></td>
<td>1,831</td>
<td>0.977</td>
</tr>
<tr>
<td>A. Guadagnini, 1759</td>
<td>1,948</td>
<td>0.952</td>
</tr>
<tr>
<td>J. Stainer, 1668</td>
<td>2,025</td>
<td>1.044</td>
</tr>
<tr>
<td>M. Goffriller, 1727</td>
<td>1,884</td>
<td>0.964</td>
</tr>
<tr>
<td>G.B. Ceruti, 1801</td>
<td>1,851</td>
<td>1.031</td>
</tr>
<tr>
<td>N. Vuillaume, ca. 1850</td>
<td>1,998</td>
<td>0.964</td>
</tr>
<tr>
<td>G. Rabut, 1989 (New York)</td>
<td>1,902</td>
<td>1.008</td>
</tr>
<tr>
<td><strong>Violas</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A. Amati, 1560</td>
<td>3,164</td>
<td>0.899(^*)</td>
</tr>
<tr>
<td>G.P. Maggini, before 1632</td>
<td>3,401</td>
<td>0.907(^**)</td>
</tr>
<tr>
<td>C. Bergonzi, ca. 1730-1750</td>
<td>2,936</td>
<td>1.05</td>
</tr>
<tr>
<td>N. Bergonzi, 1781</td>
<td>3,111</td>
<td>1.044</td>
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<tr>
<td><strong>Tenor Violas</strong></td>
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<td></td>
</tr>
<tr>
<td>G. Bertolotti da Salò, before 1609</td>
<td>6,421</td>
<td>0.920(^**)</td>
</tr>
<tr>
<td>A. Guarneri, 1664</td>
<td>5,185</td>
<td>1.046</td>
</tr>
<tr>
<td>Mantegazza, 1793</td>
<td>5,650</td>
<td>0.979</td>
</tr>
<tr>
<td>J. Stainer, 1650</td>
<td>8,394</td>
<td>1.080</td>
</tr>
<tr>
<td><strong>Cello</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A. Amati, ca. 1560, the <em>King</em></td>
<td>31,625</td>
<td>0.818(^*)</td>
</tr>
<tr>
<td>D. Montagnana, 1730</td>
<td>32,844</td>
<td>1.008</td>
</tr>
</tbody>
</table>

\(^a\) The average SPCVR (excluding the two reduced instruments\(^*\)) = 0.994 ±0.043.

* The viola and cello created by Andrea Amati were later reduced along their midlines [11]. As a result, the SPCVR of these two instruments is between 2 to 3 standard deviations below the mean value for the unmodified instruments.

** These two instruments were made in Brescia. All the other instruments were made by luthiers who were influenced by the violinmakers of the Amati family in Cremona.
Figure 7. Internal volume profile curve for a cello made by Domenico Montagnana (Venice, 1730). The internal corpus volume is 32,844 cm$^3$, and the SPCVR = 1.008. The arrow points to the diminished volume due to the soundpost.

Figure 8. Internal volume profile curve for the tenor viola by Andrea Guarneri (Cremona, 1664). The area under this curve represents a volume of 5185 cm$^3$, and the SPCVR = 1.046. The arrow points to the diminished volume due to the soundpost.
Andrea Amati violin (ca. 1560) are 1.008, 1.046, 1.044, and 0.986, respectively.

DISCUSSION

CT scanning provides two-dimensional density images of remarkable clarity and accuracy. Using OsiriX, we have taken the original CT DICOM image files and produced three-dimensional images and volume measurements. Unique volume profile curves can be generated for every instrument. The area under these curves, multiplied by the slice thickness of the individual CT image, approximates the internal corpus volume of the scanned instrument.

We show excellent agreement with Stoel and Borman [12], who have recently published internal corpus volumes of three of these violins: the Plowden Guarneri del Gesù, the Titian Stradivari, and the Willemotte Stradivari (regression coefficient, $r = 0.997$). We have also discovered a relationship between the soundpost position with respect to the total internal corpus volume.

This research was directed primarily at determining only one facet of violin “anatomy”: the measurement of internal corpus volumes. The observation of an apparent relationship between the soundpost position with respect to the total internal corpus volume (SPCVR ~1.0 for 24 of the instruments) is unexpected and intriguing. It is also interesting that the SPCVR of the two Andrea Amati instruments is less than 1.00 (0.859 averaged), a result consistent with their having been reduced along their midlines, i.e., their upper chamber volumes are significantly smaller than their lower chamber volumes.

Acoustically, we are unclear why the soundpost position divides the total internal corpus volume in two equal volumes, or if this finding is significant. However, in the history of medicine and discoveries in radiology, it is not uncommon for an anatomic relationship to be well defined before complete understanding of its functionality is known. This remains an interesting topic for future research. Much has been written about the A0 mode of stringed instruments, and its significance in the outcome of the sound. The A0 mode is primarily an air volume mode.

SUMMARY

Medical CT scanning of stringed instruments is safe and noninvasive and should be considered the new “gold standard” for measuring internal corpus volume. We have used x-ray CT to

Figure 9. Internal profile volume curve for a violin made by Jacob Stainer (Absam, 1668). The area under this curve represents a volume of 2,025 cm$^3$, and the SPCVR = 1.044. The arrow points to the diminished volume due to the soundpost.
measure the internal corpus volumes of 25 old and valuable stringed instruments, crafted between 1560 and 1850, plus one 20th-century violin. The internal volumes of three of these violins have also been measured by Stoel and Borman [12] using CT, and our results are in excellent agreement with theirs.

We have also observed an apparent relationship between the soundpost position with respect to the total internal corpus volume. From CT scans of 24 of the instruments, we found the average value of the soundpost-volume ratio to be 0.994 ±0.043, a value very close to unity. This indicates that the internal corpus volume bounded by the soundpost and the lower bout and a portion of the middle bout is nearly equal to the volume bounded by the soundpost and a portion of the middle bout and upper bout. We believe this internal corpus volume relationship may play an important role in the functionality of instruments of the violin family.

As Guy Rabut [13] said in a recent article, “There has always been some mystery about what happens when a violinmaker takes a soundpost setter and begins to move a soundpost. In Romantic languages, the name for the soundpost is also the word for ‘soul’ (anima in Italian, âme in French, alma in Spanish) . . . one that is more appropriate to the role it plays.”

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