The Secrets of The Stradivari String Instruments. A Non-Destructive Study of Music Instruments from The Smithsonian Institution, The Library of Congress, and Private Collections. A Pilot Study of Seven Violins made by Antonio Stradivari in Cremona, Italy, Between 1677 and 1709.

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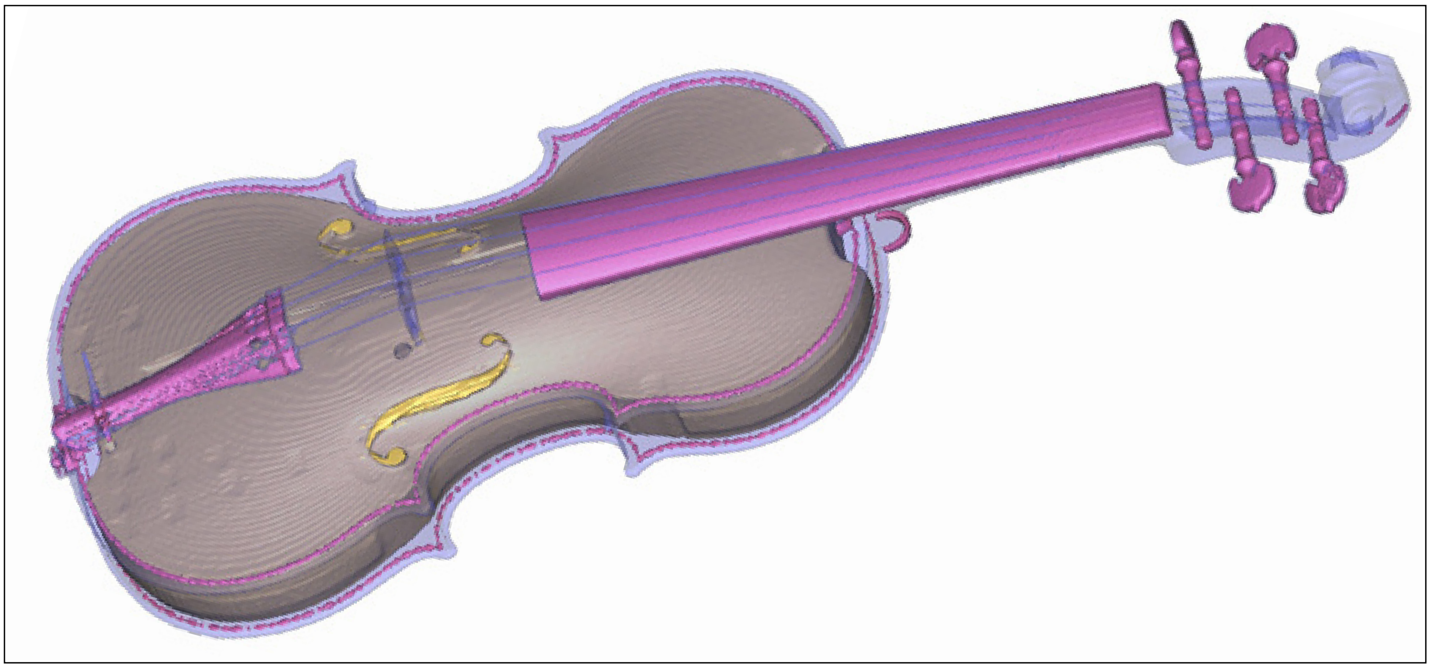


Introduction:

In the world of music instrument making, the name ‘Stradivari’ is universally associated with the world’s most famous and greatest violinmakers. Antonio Stradivari marketed his instruments under the label of ‘Antonius Stradivarius, Cremona’ and belonged to a group of contemporary instrument makers or luthiers, acknowledged as the ‘Cremona school’ and their products as the ‘Cremona instruments’. The best known include Antonio Stradivari (1644–1737), Nicolo Amati (1596–1684), and Joseph Guarneri (1683–1745). The Stradivari workmanship and the qualities of tone associated with his instruments are superb and are generally thought to be unsurpassed by both earlier or later instrument makers (Figure 1) (Beare 1980; Hart 1885; Hill 1984; Leipp 1969; Sacconi 1979).

Antonio Stradivari was born in the northern Italian town of Cremona around 1644. He died at an age of 92 in 1737. During his more than 70 years as an instrument maker of violins, violas, cellos and other plucked and bowed stringed instruments he may have produced more than a thousand. Around 650 instruments have survived and some are still being played and treasured by collectors and musicians alike including some of the world’s leading string players (Doring 1945; Hart 1885; Henry et al. 1902).

From the time of Stradivari and up to modern time, all violin instrument makers have copied the Stradivari design in the belief that no one would be talented enough to improve on the tone quality (Faber 2004). This contemplation, although mostly wrong was particularly emphasized in the mid 19th century when French violinmaker, Jean Baptiste Vuillaume (1798–1875), developed a marketing technique, which centered on the Stradivari design being the best possible, and sold his instrument as exact copies (Millant 1972). Imitations of the Stradivari instruments were manufactured by excellent instrument makers but also mass-produced in factories and sold to the general public (Table 1). Copies of these counterfeit violins are now being found all over the world. Even today some of the world’s best luthiers will tell us that they can sell more instruments if they are marketed as true Stradivari copies and less if marketed based on their own individual design and creation.

Figure 1: Violin, the Greffuhle made by luthier Antonio Stradivari in Cremona, Italy, 1709. It is one of Stradivari's few remaining decorated violins. It is possible that the instrument was build by Stradivari between 1679 and 1687, and repaired by Stradivari in 1709 at which time it got a new label.

LAST NAME	FIRST NAME	TYPE OF INSTRUMENT	YEAR	COUNTRY	NAME	OWNER***
Amati	Nicolo	violin	1650	Italy	Pennink	NMAH
Amati	Nicolo	violin	1654	Italy	Brookings	LOC
Amati	Nicolo	violin	1656	Italy	Louis XIV	NMAH
Amati	Nicolo	viola	1663	Italy	Wirth	NMAH
Amati	Nicolo	violin	1672	Italy	Florian Zajik	NMAH
Amati	Nicolo	violin	1675	Italy		NMAH
Bellini	Luiz	violin	1967	U.S.A.		NMAH
Burgess	David	violin	1984	U.S.A.		NMAH
Bauer*	Chas.*	violin	1910*	U.S.A.*		B. Coon
Gagliano	Gennaro	viola	1762	Italy		NMAH
Gragnanni	Antonio	violin	1783	Italy		NMAH
Grancino	Giovanni	violin	1727	Italy		NMAH
Guadagnini	Johannes	violin	1752	Italy		NMAH
Guarneri	Joseph	violin	1730	Italy	Baron Vitta	LOC
Guarneri	Joseph	violin	1732	Italy	Kriesler	LOC
Juzek	John	viola	n/d	Czechoslovakia		J. Cummings
Klotz	Joseph	viola	1780	Germany		NMAH
Marshall	John	violin	1759	England		NMAH
Meinel	August	violin	1856	Germany		J. Cummings
Moenning	William	violin	1943	U.S.A.		NMAH
Moglie	Albert	violin	1923	U.S.A.		NMAH
Norman	Barak	viola da gamba	1718	England		NMAH
Peresson	Sergio	violin	1980	U.S.A.		NMAH
Peresson	Sergio	viola	1986	U.S.A.		NMAH
Peresson	Sergio	violin	1990	U.S.A.		NMAH
Podesva	Jan	violin	1879	Czechoslovakia		Dietrich
Stainer	Jacob	violin	1645	Austria		KHM
Stainer	Jacob	violin	1650	Austria		NMAH
Stainer	Jacob	violin	1661	Austria		NMAH
Stainer	Jacob	viola	1678	Austria		KHM
Stradivari	Antonio	violin	1677	Italy	Sunrise	H. Axelrod
Stradivari	Antonio	violin	1679	Italy	Hellier	H. Axelrod
Stradivari	Antonio	violin	1687	Italy	Ole Bull	NMAH
Stradivari	Antonio	viola	1690	Italy	Tuscan	LOC
Stradivari	Antonio	viola	1695	Italy	Axelrod	NMAH
Stradivari	Antonio	violin	1699	Italy	Castelbarco	LOC
Stradivari	Antonio	violin	1700	Italy	Ward	LOC
Stradivari	Antonio	cello	1701	Italy	Servais	NMAH
Stradivari	Antonio	violin	1704	Italy	Betts	LOC
Stradivari	Antonio	violin	1709	Italy	Greffuhle	NMAH
Stradivari	Antonio	viola	1727	Italy	Cassavetti	LOC
Unknown		violin	1995	Romania		NMNH
Vuillaume	Claude-F	violin	1735	France		NMAH
Vuillaume	Jean	violin	1859	France		NMAH
Vuillaume	Jean-B	viola	1870	France		NMAH
Vuillaume	Jean-B	violin	1871	France		NMAH
Vuillaume**	Jean-B	violin	1847	France		L. Burgess

Table 1: The collection comes from the National Museum of American History, the Library of Congress, and from private collectors. Notes: (*) Repaired by Charles Bauer in 1910. Instrument maker: unknown. Possibly from Germany. (**) Instrument labeled as made by Jean Baptiste Vuillaume, Paris in 1847. Evaluated to be a copy, possibly from Germany. Instrument maker: unknown. (***) NMAH: National Museum of American History, Smithsonian Institution. NMNH: National Museum of Natural History, Smithsonian Institution. KHM: Kunsthistorisches Museum, Vienna. LOC: Library of Congress, Washington, DC.

What makes the Stradivari instrument so unique? Primarily, this sentiment is founded on the reality that the instruments produced by Stradivari embody some of the best design, the most magnificent art and an exceptional tone quality (Figure 1) (Goodkind 1972; Yokoyama 1986a, 1986b & 2002). However, it is also believed that the marketing scheme based on the Stradivari instruments played a major role in determining its larger influence. This may have resulted in a very conservative approach toward changes and improvements, and as a result we notice little design and quality differences between the Cremona instruments and instruments made today.

Stradivari instruments are deemed to constitute a better playing quality and a better tone than almost any other and similar instrument – why is this? Did he apply some secret features, material and/or chemical treatments to his instrument, which later instrument makers failed to recognize? Did he use special treated wood, special varnish, and did he select wood with very specific density to enhance both the looks and the tone qualities? Or, is it all a product of manipulative marketing in order to sell more instruments? We still do not know for sure, but it is most likely a result of many factors, some known to us, and others still a secret (Michelman 1946; Heron-Allen 1885; Shigo and Roy 1983).

Current Research at the Smithsonian Institution:

In 2000, the National Museum of American History, Smithsonian Institution, asked that the Computed Tomography Laboratory at the National Museum of Natural History to initiate a study of stringed instruments using non-destructive and non-invasive methods knowing we had this technical capability with our Siemens Somatom CT Scanner. The request was to study as many instruments as possible presently located at the National Museum of American History's: Division of Music, Sports and Entertainment. This division includes one of the best and most comprehensive collections of music instruments in the world, of which a large number are still used in monthly performances (Table 1).

The Siemens Somatom CT scanner became a very important tool for scanning this large collection. Within a few years we added instruments from the Library of Congress and from private collections thus significantly increasing our sample size (Table 1). We realized from the beginning that we would learn only a little about construction features if we studied instruments only made by Stradivari. To learn more, we had to include a variety of instruments produced over a time span ranging from before, during, and after Stradivari produced his instruments. Having access to the Smithsonian collection and also to some of the instruments presently at the Library of Congress, we created a list representing a majority of the best and most recognizable luthiers from 1640 to modern time (Table 1). To put all this into the context of general violin production and to add more comparative data, we scanned a series of typical factory mass-produced imitations mostly from between 1850 to the early 20th century, owned by families in northern New England and passed on between generations, most likely brought to the USA by immigrants during the 19th century (Table 1).

Project Definition:

Before starting our data collection it was important for us to develop a clear hypothesis. Therefore, we then followed the principles of creating a scientific hypothesis, testing the development of a research design, a pilot study, data collection, data analysis, results, and finally the acceptance or rejection of our stated hypothesis.

Hypothesis: The majority of high quality and well-made instruments can produce a high tone quality. However, an excellent musician who is playing with their highest passion for the music and the instrument will most likely produce a high tone quality as well. If true, then the instrument maker would have a certain criteria, which would need to be satisfied. This includes: (1) the instrument has to be capable of producing a superior sound, and (2) the instrument would have to please the musician. We believe that all well-constructed instruments can produce a good tone quality, however, there are tone differences between instruments and between musicians playing the same instrument. Thus two instruments would not sound the same, and two musicians would not produce the same tone, although any one of these combinations could easily be reckoned as producing a very high tone quality. That in itself makes it very difficult to

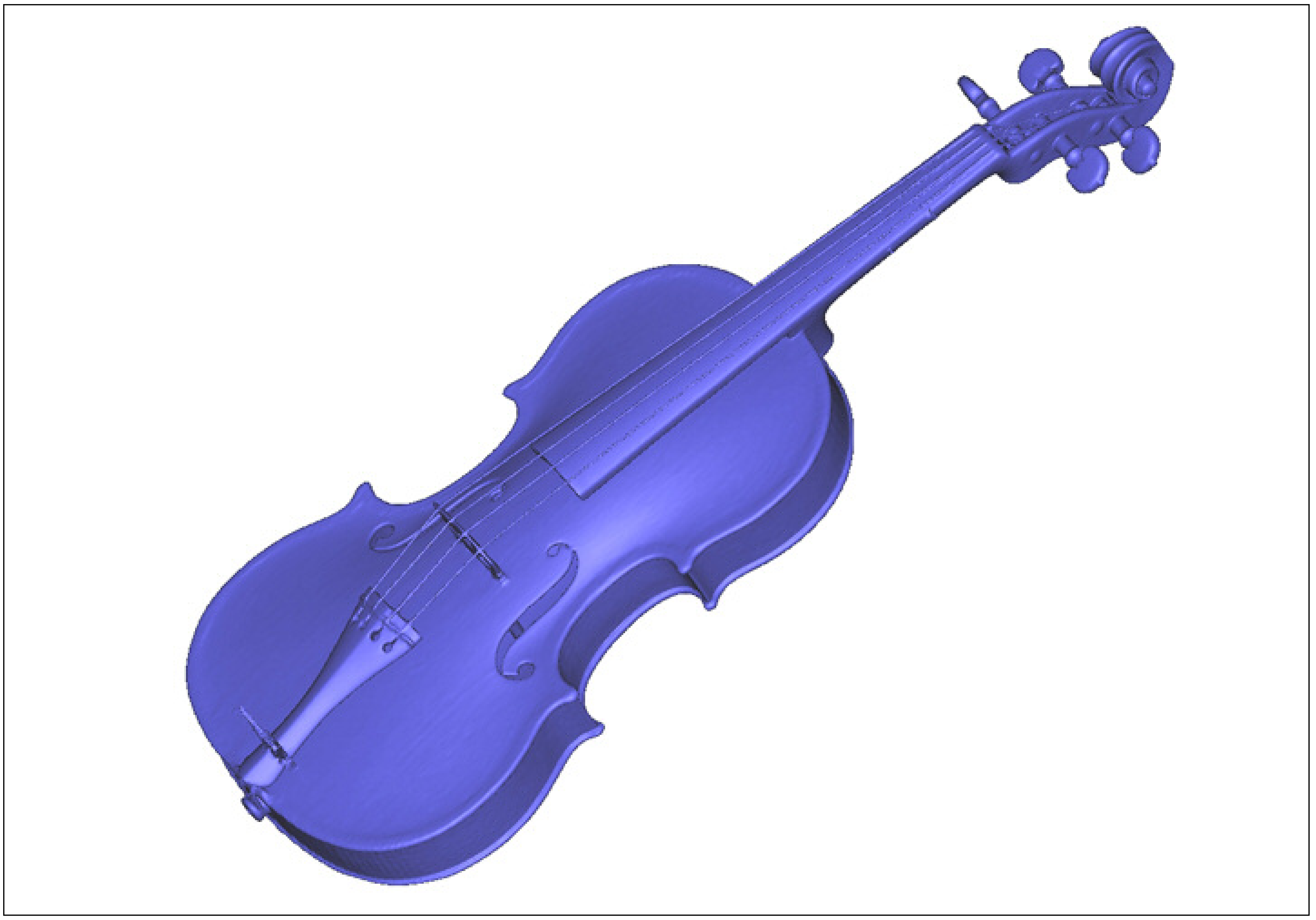


Figure 2. Three dimensional model (3D) violin made by Antonio Stradivari possibly between 1679 and 1687, but labeled as made in 1709. Violin also known as the Greffuhle appears to have been repaired by Stradivari in 1709.

define a research design based on the study of tone quality alone. Accordingly, our research design is focused on engineering features, which the instrument maker can apply to make a good sounding instrument, a pleasing experiment for the musician to play. The instrument maker can accomplish this without jeopardizing the sound quality and the required physical strength of the instrument.

Research design: In designing our research we had to abide by criteria which were non negotiable. First, the research could not in any way alter the instruments, by being destructive or invasive. Secondly, we could not use any kind of equipment, which would harm the instruments or change their configurations. This requires a method of data requisition, which would fulfill the requirements and methods of data processing, allowing us to study and evaluate information from the digital model and would be a true reflection of the original instrument. Our basic research design includes: recording variation within and between time periods; recording and understanding engineering principles; defining construction criteria for what makes a 'superior' instrument; identifying trends in manufacturing principles within and between instrument makers; identifying and studying changes in material characteristics over time; and identifying and evaluating needs for repairs and preservation. In understanding these processes we hope to find trends and features, which will allow us to either accept or reject our stated hypothesis.

To accomplish this we need to create digital models, which are factual representative of the original objects and which allows us to study how the instruments' general architecture and other features change over time and space (Figure 2). High resolution CT scanning was selected to accomplish this goal (Figure 3).

Data Collection: The data collection is divided into two phases: (1) CT scanning of original objects creating a comprehensive body of digital data which is representative of the original objects, and (2) converting and processing the CT data allowing analytical and statistically procedures to be applied.

CT Scanning: Since 2000, we have CT scanned 47 string instruments including violins (n=35), violas (n=10), cellos (n=1) and viola de gamba (n=1) (Table 1). The collection includes multiple instruments manufactured by Nicolo Amati (1596-1684) (n=6), Joseph Guarneri (1683-1745) (n=2), Sergio Peresson (1913-1991) (n=3), Jacob Stainer (1617-1683) (n=4), Antonio Stradivari (1644-1737) (n=11), and Jean Baptiste Vuillaume (1798-1875) (n=3). Collection also includes a single instrument from the following instrument makers: Barak Norman (1688-1740), Luiz Bellini (1935-), David Burgess (1953-), Gennaro Gagliano (1720-1750?), Antonio Gragnani (1780?), Giovanni Grancino (1694-1720?), Johannes Guadagnini (1711-1786), John Juzek (1910?), Jospeh Klotz (Kloz? (Hart 1885)) (1743-1819), John Marshall (1750-1760?), August Meinel (1810?), William Moenning (1883-1962), Albert Moglie (1891-1988), Jan Podesva (1888-1997?), and Claude Vuillaume (1715-1785) (Table 1). Two instruments are of unknown origin, including one repaired by Charles Bauer in 1910 (Table 1). In terms of provenance, four instruments have been manufactured in Austria, two in Czechoslovakia, two in England, five in France, two in Germany, twenty-three in Italy, one in Romania, and eight in the U.S.A. Sixteen instruments have been manufactured between 1645 and 1699, fifteen between 1700 and 1799, seven between 1800 and 1899, and nine between 1900 and 1999 (Table 1). Finally, our research collection comes from the National Museum of American History (Smithsonian Institution) (n=29), Library of Congress (n=8), private collections (n=7), Kunsthistorisches Museum Vienna (n=2), and National Museum of Natural History (Smithsonian Institution) (n=1) (Table 1). It is our hope to increase the sample sizes covering the last two centuries to match the samples we have from between 1645 and 1799. Our data includes complete high resolution CT scanning of all the listed instruments using a series of Siemens Somatom CT scanners located in the Department of Anthropology, National Museum of Natural History, Smithsonian Institution and at the Siemens Medical Solution, Training and Research Center in Cary, North Carolina.

Converting and processing of CT data: The CT scanning was initiated in 2000. Since that time we have scanned instruments using different Siemens Somatom scanners producing different formats of output data (Figure 3). Converting older data to the latest format, in this case Dicom as defined by NEMA (National Electrical Manufacturers Association), has been a relatively easy task and all data has now been processed to agree with to the latest Dicom standards specified by NEMA.

Some of the instruments, which were scanned on one of our first scanners (a Somatom AR.SP scanner), have been re-scanned with our newest Somatom Emotion scanner and with a higher resolution. Studies designed to compare data processing using older data versus newer data have shown that either one can be used with little or no difference between them.

Pilot Study:

Because we are using digital replicas of the original objects we must ensure that the results we are obtaining, using any specific software package, will produce data, which are compatible with the results we would have obtained if we had studied the original objects.

In this report we are reporting our evaluation and results of using two software packages from the Materialise Group in Belgium: Mimics and 3-matic. Evaluating biomedical software is not an easy task. Everything changes so fast that before we will be mastering a specific version, a newer and more advanced version will be released. The selection of software was based on several criteria. This includes: features which will allow us to accomplish our goals, a superior support system, a reliable interface which will allow imports and exports of required formats, and most importantly, an expansion philosophy which will support new development of a software version and will not make our data, results, and future research insolvent.

We have selected seven violins produced by Antonio Stradivari between 1677 and 1709 to be part of our pilot study. In the text and tables we have identified the seven instruments with a ‘S’ followed by the published year of manufacturing. In the case of nicknames given to the instruments we have added these when possible. The results of this pilot study will determine

Figure 3: Siemens Somatom Emotion CT scanner from Siemens Medical Solutions. Scanner is located at the department of Anthropology, National Museum of Natural History, Smithsonian Institution, Washington DC.

Instrument ID:	Stradivari 1700 (Ward)			Stradivari 1687 (Ole Bull)				Stradivari 1709 (Greffuhle)		
Recorded by:	Berglund	Mimics slice	3-matic 3D	Berglund	BF & JH	Mimics slice	3-matic 3D	BF & JH	Mimics slice	3-matic 3D
MAXIMUM LENGTH (mm)		581	581		586	583		587	584	
UPPER BOARD (mm)										
max. length	354	349	348	352	349	350	351	351	351	
top/max. width	165	166	165	167	168	170	170	166	166	
mid/min. width	107	105	104	109	109	110	110	108	108	
lower.max width	204	207	205	207	208	208	209	204	205	
above corner/min. width	148	148	149	150		152	151		149	
below corner/min. width	175	175	174	176		178	178		176	
f-hole/max. length/base	76	76	76	76		76	74		75	75
f-hole/max. length/treble	65	75	75	75		75	76		74	74
BACK BOARD (mm)										
max. length	356	349	348	355		351	350		351	
top/max. width	167	168	169	169	170	172	171	169	169	
mid/min. width	108	108	109	109	110	110	110	109	110	
lower.max width	208	207	206	209	209	211	212	208	209	
MID RIB (mm)										
top/max. width		163			165	166		164	164	
mid/min. width		103			106	106		107	106	
lower.max width		204			204	205		203	204	
HEIGHTS (mm)										
rib, top/max w, base		29			29	29		30	30	
rib, top/max w, treble		29			30	29		30	30	
rib, mid/min w, base		30			29	29		30	30	
rib, mid/min w, treble		30			30	29		31	31	
rib, lower/max w, base		30			30	30		31	31	
rib, lower/max w, treble		31			30	30		30	30	

Table 2. Three violins made by Antonio Stradivari and used for comparisons of metric distances derived from different observers and using different measuring techniques (recordings from the original instruments and recordings from digital models using Mimics and 3-matic software).

how we develop a comprehensive research design for the complete study of all our 47 scanned instruments.

For the pilot study we have selected five areas of interest: (1) Recording of metric data (linear distances) from external and internal surfaces based on the digital models; (2) Comparing the external digital measurements with already published data and our own measurements obtained from the original instruments; (3) Calculating volumes of material used in the entire instrument, the body of the violin, and of the air mass to be found within the body of the violin; (4) Comparing wood thickness recorded from both the upper board and the lower board and display thickness variation in a graphic format; and (5) evaluate our results of the pilot study and how we plan to proceed with the data collection and analytical phases of all 47 instruments.

Metric Measurements: A total of 17 measurements (linear distances) were recorded from the external surfaces of two violins (S-1687 (Ole Bull), and S-1709 (Greffuhle)) (Table 2). A third instrument (S-1700 (Ward)) was used for comparisons between measurements taken by another researcher and results from our digital copy (Berglund 1995a & 1995b). Measurements include the total instrument length, four measurements on the upper board, three on the back

Metrics and Volumes (See Text)	**Strad-1677** *Sunrise*	**Strad-1679** *Hellier*	**Strad-1687** *Ole Bull*	**Strad-1699** *Catelbarco*	**Strad-1700** *Ward*	**Strad-1704** *Betts*	**Strad-1709** *Greffuhle*
MAXIMUM LENGTH (mm)	580	583	583	n/d	581	582	584
UPPER BOARD (mm)							
max. length	346	353	350	351	349	348	351
top/max. width	164	170	170	162	166	168	166
mid/min. width	104	111	110	106	105	109	108
lower.max width	203	210	208	201	207	208	205
above corner/min. width	147	151	152	149	148	151	149
below corner/min. width	173	178	178	176	175	178	176
f-hole/max. length/base	74	75	74	75	76	75	75
f-hole/max. length/treble	76	75	76	76	75	74	74
BACK BOARD (mm)							
max. length	348	352	351	351	349	347	351
top/max. width	165	171	172	161	168	169	169
mid/min. width	107	113	110	100	108	109	110
lower.max width	205	211	211	200	207	209	209
MID RIB (mm)							
top/max. width	160	166	166	157	163	164	164
mid/min. width	101	107	106	105	103	104	106
lower.max width	200	206	205	196	204	204	204
HEIGHTS (mm)							
rib, top/max w, base	30	31	29	30	29	31	30
rib, top/max w, treble	30	31	29	29	29	31	30
rib, mid/min w, base	30	31	29	30	30	31	30
rib, mid/min w, treble	30	31	29	30	30	31	31
rib, lower/max w, base	31	32	30	31	30	31	31
rib, lower/max w, treble	31	32	30	31	31	31	30
at centerline, top/max	57	54	54	55	51	54	56
at centerline, mid/min	68	66	65	65	61	65	66
at centerline, lower/max	59	57	57	56	51	57	58
WOOD THICK. UPPER (mm)							
top/centerline	3.3	3.4	3.5	2.9	2.5	3.4	3.6
mid/centerline	3.2	3.5	3.5	2.9	3.0	2.4	3.1
lower/centerline	2.7	3.4	3.7	3.2	2.5	3.4	3.1
WOOD THICK., LOWER (mm)							
top/centerline	3.7	3.8	3.8	3.2	3.0	3.4	3.6
mid/centerline	4.6	6.4	4.8	4.6	3.9	4.8	5.1
lower/centerline	3.7	3.9	3.4	3.3	3.4	2.9	3.1
VOLUMES (cm^3)							
Volume, complete, all material	732.3	817.8	740.0	n/d	661.8	719.7	749.6
Volume, body, all material	448.7	623.3	546.2	436.7	418.0	455.0	528.7
Volume, body, interior air mass	2061.9	2072.8	2039.5	1938.7	1907.9	2021.3	2068.8

Table 3. Linear metric measurements recorded from seven violins build by Antonio Stradivari between 1677 and 1709. Metric distances are measured in millimeters (mm), and volumes in cubic centimeters (cm^3)

Stradivari, Metric Variation	n	Mean	Range	Range-%
MAXIMUM LENGTH (mm)	6	582.2	4	0.7
UPPER BOARD (mm)				
max. length	7	349.7	7	2.0
top/max. width	7	166.6	8	4.8
mid/min. width	7	107.6	7	6.5
lower.max width	7	206.0	9	4.4
above corner/min. width	7	149.6	5	3.3
below corner/min. width	7	176.3	5	2.8
f-hole/max. length/base	7	74.9	2	2.7
f-hole/max. length/treble	7	75.1	2	2.7
BACK BOARD (mm)				
max. length	7	349.9	5	1.4
top/max. width	7	167.9	9	6.6
mid/min. width	7	108.3	13	12.0
lower.max width	7	207.4	11	5.3
MID RIB (mm)				
top/max. width	7	462.9	9	5.5
mid/min. width	7	104.6	6	5.7
lower.max width	7	202.7	10	4.9
HEIGHTS (mm)				
rib, top/max w, base	7	30.0	2	6.7
rib, top/max w, treble	7	29.9	2	6.7
rib, mid/min w, base	7	30.1	2	6.6
rib, mid/min w, treble	7	30.3	2	6.6
rib, lower/max w, base	7	30.9	2	6.5
rib, lower/max w, treble	7	30.9	2	6.5
at centerline, top/max	7	54.4	6	11.0
at centerline, mid/min	7	65.1	7	10.8
at centerline, lower/max	7	56.4	8	14.2
BOARD THICKNESS, UP (mm)				
top/centerline	7	3.2	1.1	34.4
mid/centerline	7	3.1	1.1	35.5
lower/centerline	7	3.1	1.0	32.3
BOARD THICKNESS, LOW (mm)				
top/centerline	7	3.5	0.8	22.9
mid/centerline	7	4.9	2.5	51.0
lower/centerline	7	3.4	1.4	41.2
VOLUMES (mm^3)				
Volume, complete, all material	6.0	736.9	156.0	21.2
Volume, body, all material	7.0	493.8	205.0	41.6
Volume, body, interior air mass	7.0	2016.0	165.0	8.2

Table 4: Variation in linear distances and volumes between seven violins build by Antonio Stradivari between 1677 and 1709.

board, three from rib-to-rib midway between upper and lower boards and six height measurements, all including the ribs (Table 2). A total of thirty-one measurements (linear distances) and three volume estimates were obtained from digital images using Mimics and 3-matic software (Table 3). Of the thirty-one measurements, twenty-three are compatible with external measurements, two cannot be taken on the original instrument because of attached features such as fingerboards, and tail pieces, and six measurements, all wood thickness, are defined as internal measurements. Finally, three calculated volume estimates have been recorded: (1) volume of all material used to construct the instrument, (2) volume of material used to construct the body of the violin (including sound post and base bar), and (3) volume of the air mass found within the body of the violin (Table 3). All metric measurements (linear distances) are recorded in millimeters (mm), and all volumes are recorded in cubic centimeters (cm^3) (Table 3). We have not recorded non-linear distances as could be measured over a curved surface.

Comparative Studies: The measurements we have recorded from the original instruments compare well with measurements recorded from the digital models (Table 2). When comparing our measurements to similar records by other researchers we find a higher degree of differences. For example, differences found between our records, both original data and digital data, and Berglund's data (Berglund 1995a, 1995b) are caused by poor definitions of landmarks

Figure Digital model of the violin body with external attachments removed. This includes: fingerboard, pegbox, scroll, strings, bridge and tailpiece. Removal is accomplished by using various segmentation procedures in the Mimics software.

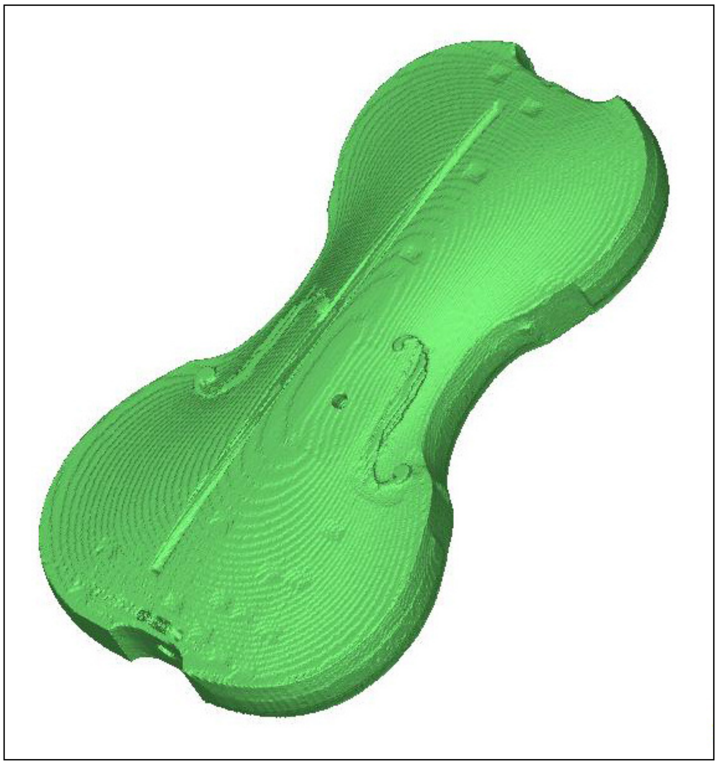


Figure 5: Three dimensional (3D) model of air mass located within the violin body.

(Table 2). Some measurements could not be repeated accurately using our own or other researchers' definitions. For example, we record the top maximum width on both the upper board and the lower board finding the CT slice with the maximum distance between the two ribs. Then, we record the mid-vertical distance between the upper and lower boards using the same slice or location. This is very difficult to repeat because the location where the maximum distance between ribs is taken can fluctuate up to several millimeters without changing the recorded value. However, the vertical distances taken from any of those locations vary significantly when moving the location of the maximum width a few millimeters. We have not compensated for this, yet, but plan to use a top to bottom measurement to identify our landmarks accurately so that we, and others can repeat measurements. Our measurements based on the original instruments compare well with our digital based measurements (Table 2). We conclude that measurements obtained from the digital models using Mimics and 3-matic are true representatives of similar measurements taken on the original objects.

The basic architecture of the violin has changed very little during the last almost 400 years. The complete study of variation over time will be presented when all of our 47 scanned instruments have been studied. The variation based on the thirty-one linear measurements and three volume calculations are seen in Table 4. The sample size is low, thus no specific statistical procedure has been applied. Part of the scroll on the fingerboard is missing in the scan data of S-1699 (Catelbarco), thus the maximum length (complete) and the total volume of material have not been included for S-1699 (Tables 3 & 4). The descriptive data includes the sample size, the mean, the range, and the range calculated as a percentage of the mean (Table 4). The smallest range is found in the maximum length of the complete instrument (0.7%) followed by the upper and lower lengths of the violin body (2.0% and 1.4%). The small variation found in the maximum length is a surprise because the fingerboard may have been replaced during a later time. The small variation in the lengths of the violin body is expected and this should have been followed by a similar small variation in the heights of the ribs. The latter is not the case (Table 4) because of our inability to record the rib heights accurately, caused by small distances and that

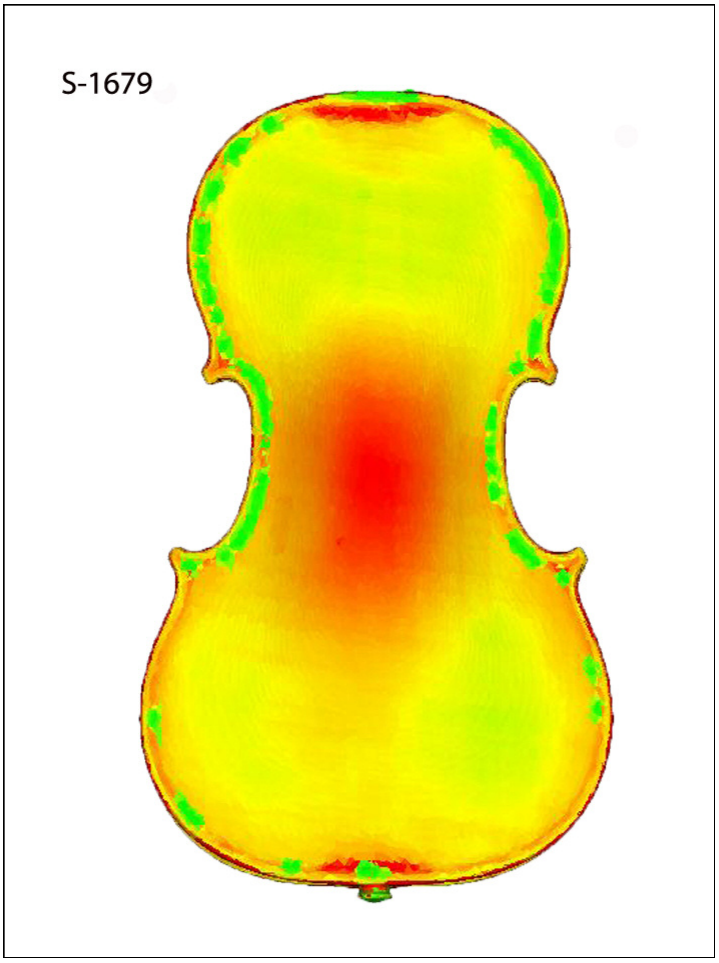


Figure 6: Display of wood thickness of lower board. Red colors indicate thickness at 7 mm or higher. Green colors indicate thickness of 1 mm or less. Center area is generally thicker (more red) than the surrounding areas.

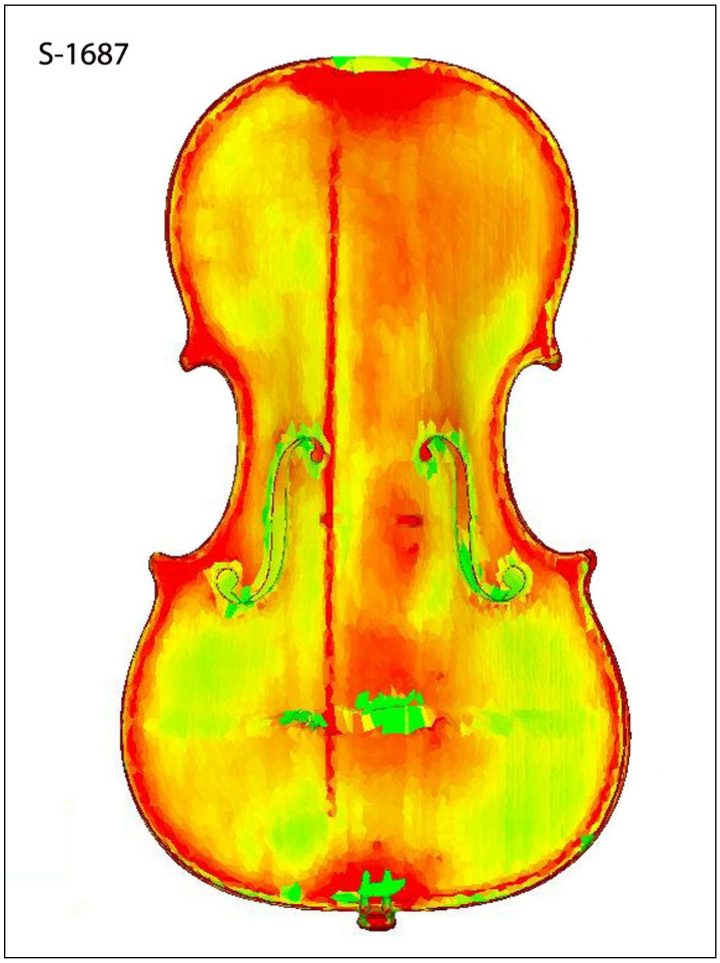


Figure 7: Display of wood thickness of upper board. Red colors indicate thickness at 4 mm higher. Green colors indicate thickness of 2 mm or less. Red line is part of the bass bar located on the inside surface of the upper board.

some of the landmarks may have been covered by glue and varnish. The rib heights, however are remarkably consistent with a range between one mm and two mm (all rounded up to two mm in Table 4).

Large variations of between 11.0% and 14.2% are found in the heights of the violin body as measured at the centerline (Table 4). The much higher height measured between the f-holes when compared to the heights toward the top and the bottom, respectively, suggest a much more pronounced curved architecture at the center of the instrument when compared to the top and bottom parts of the violin body. Stradivari most likely used the same mold for many years as reflected in the little variation in the heights of the ribs, and the maximum lengths of the violin body. The higher variations found in the width measurements of the upper and lower boards are caused by using landmarks on the peripheral part of the boards and not on the ribs. However, the width measurements using landmarks on the center of the ribs also show some variability, which we have explained by ribs being slightly compressed over time and thus deviating from the original positions.

By using the same mold or similar molds to position the ribs in a uniform manner, Stradivari ensured that major parts of the body were kept homogeneous. Thus any variation in size and shape of the body would be caused by changing the upper and lower boards by altering the wood thickness and/or the degree of curvatures of the boards. Apparently, there seems to be a trend of going from curved boards to less curved bodies over time. Stradivari managed this while keeping his basic size and shape of the body consistent and also, as we will see later, keeping the air volume within the body almost constant.

Volumes: Volumes have been recorded in two ways. A mask of the scanned material, with defined upper and lower HU values (Hounsfield Units) is used to calculate the volume of the used material. Volume is also calculated by creating a 3D model (three dimensional model) based on similar mask values, and calculating the mass constituting the 3D model. In six of the seven instruments the difference between the two methods is between 0.5% and 2.0%. Only in one case (S-1704) do we find a difference of 11%. We have not yet identified the problem with the volume calculations of S-1704. But we believe that the error is in the defined mask and not in the 3D model. Tables 3 & 4 show volumes calculated from the 3D models, only.

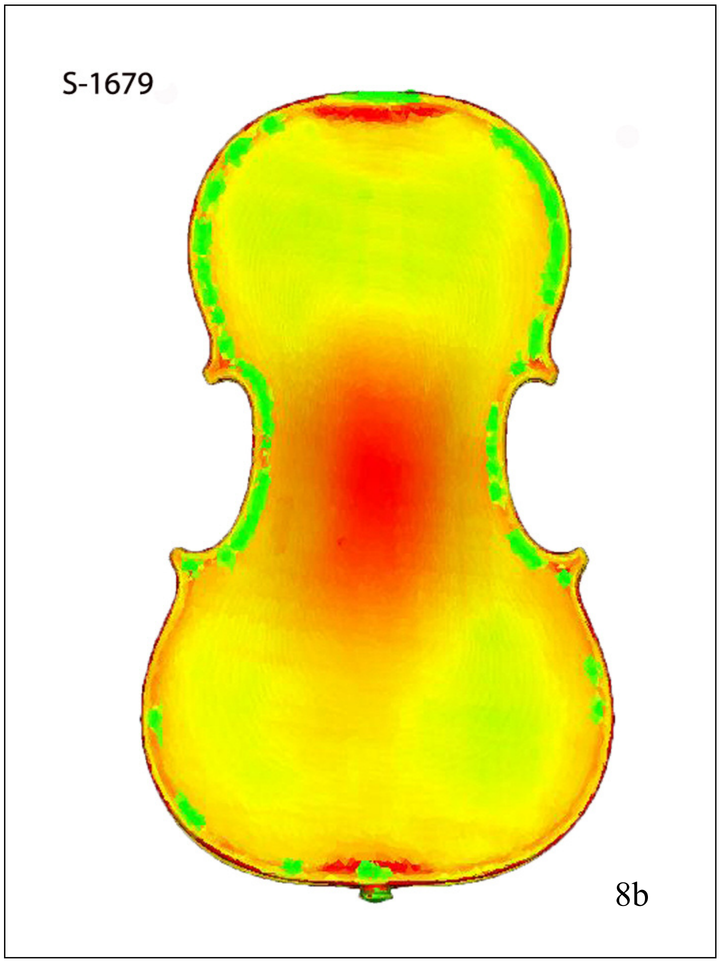
Calculating the volume of the air present within the violin body was accomplished by using the 'region growing' method defining the upper and lower HU values to respectively –900 and –1024 (the HU value of air is -1024 and the lowest recorded HU value of any material in the violin is higher than -900 HU). Then, two methods could be applied: calculating the volume based on the mask data or creating a 3D model of the air based on the same mask values (Figures 4 & 5). Although, we obtain accurate volume estimates based on testing on known objects, such as, bottles and cigar boxes made from wood, the volume data presented in this report should be used for comparative purposes within our seven samples, only, and not as exact and correct values.

The variations found in the volume values reflect little variation in the air volume in the violin body (8.2%) but a large variation in the volume of the wood used in the construction of the violin body (41.6%), (Table 4). Thus Stradivari tried to keep the air volume as constant as possible, even as the trend in construction over time moved in the direction of a thinner wood board. This thinning of the wood could have been an attempt to lower the weight of the instrument making it easier and more comfortable for the musician to play. The instrument with the lowest volume values in all three categories is the S-1700 and the largest is the S-1679. S-1677 has a relatively small body material volume and a larger than average air volume, which is explained by the notation that it may have been 'thinned' at a later time. The large volume found in the S-1709 is explained by the belief that the S-1709 an earlier construction but repaired by Stradivari in 1709 and at which time he most likely replaced his own old label with a new one. Comparing our calculated wood volumes with linear measurements strongly suggest significant correlations between volume calculations and metric dimensions, however, exact values still have to be calculated.

Wood Thickness: Wood thickness is very important. Because the used wood can be very thin it may be difficult to obtain an accurate value using the digital data. The limited resolution of between 0.5 and 1.0 mm of our CT scanners is the main reason for this. We still need to complete a comprehensive pilot study so that we can establish an accurate procedure on how to include pixels with different densities and also which parts of the pixels should be included in the measurements. In the pilot study we have recorded wood thickness using similar criteria and settings. For that reason the numbers can be used as a comparative tool between the seven instruments, only. The decision by the luthier on what wood thickness to use is of high importance in producing a strong and reliable instrument, and at the same time keeping the weight to a minimum. We recorded the wood thickness in six areas based on the digital model: three points on each of the upper and lower boards. All points are positioned in the mid plane as defined by a line between the center of the top block (where the fingerboard is attached to the violin body), and the center of the bottom block (where the tailpiece and end-button are attached to the body).

The thickness of wood used in the construction effects on the weight of the instrument, the strength, and possibly the tone quality. We have not yet established a procedure where we can read the exact wood thickness from the digital data. We have, however used a very powerful tool supplied with the 3-matic program allowing the creation of a 3D model where the surfaces are colored with different colors reflecting the underlying thickness of the wood (Figures 6 & 7). Within a stated range, defined by the operator the technique becomes a very powerful tool in evaluating thickness variation of the upper and the lower boards. Board colors then become a function of board thickness with the lowest thickness being displayed as green and the highest thickness as red (Figures 6 & 7). Thickness between the upper and lower values will be displayed as mixtures of green and yellow, and yellow and red with the yellow color representing

8a



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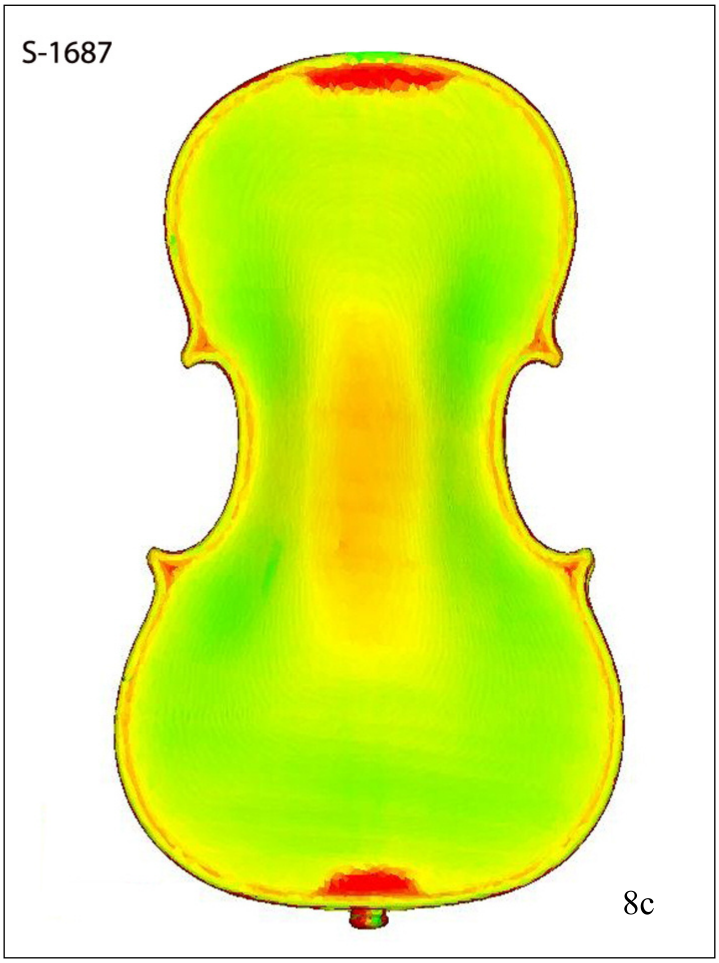

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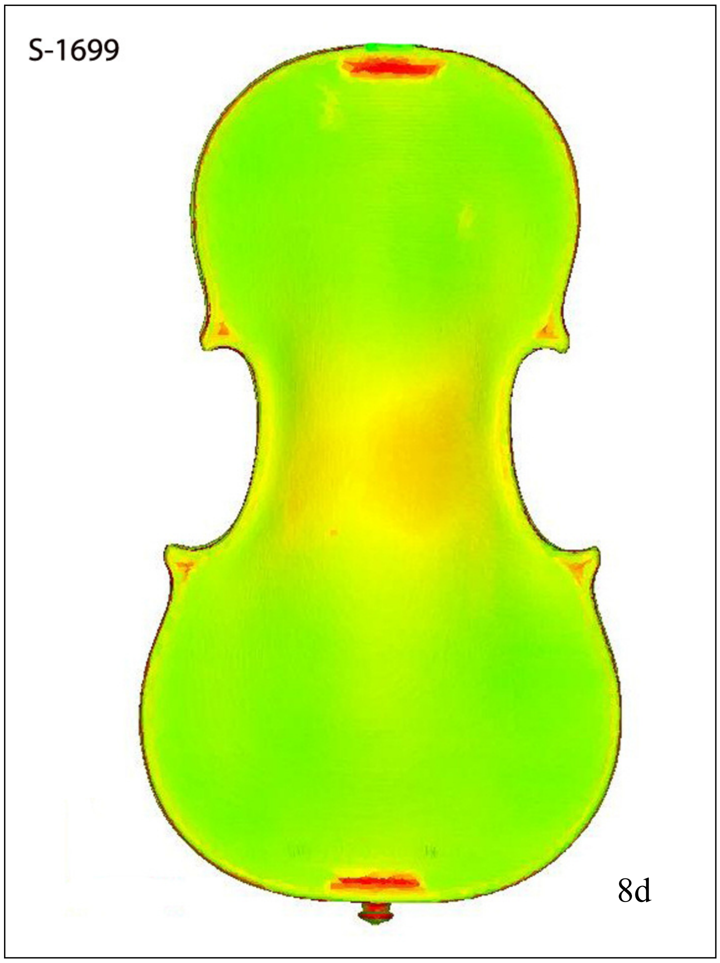

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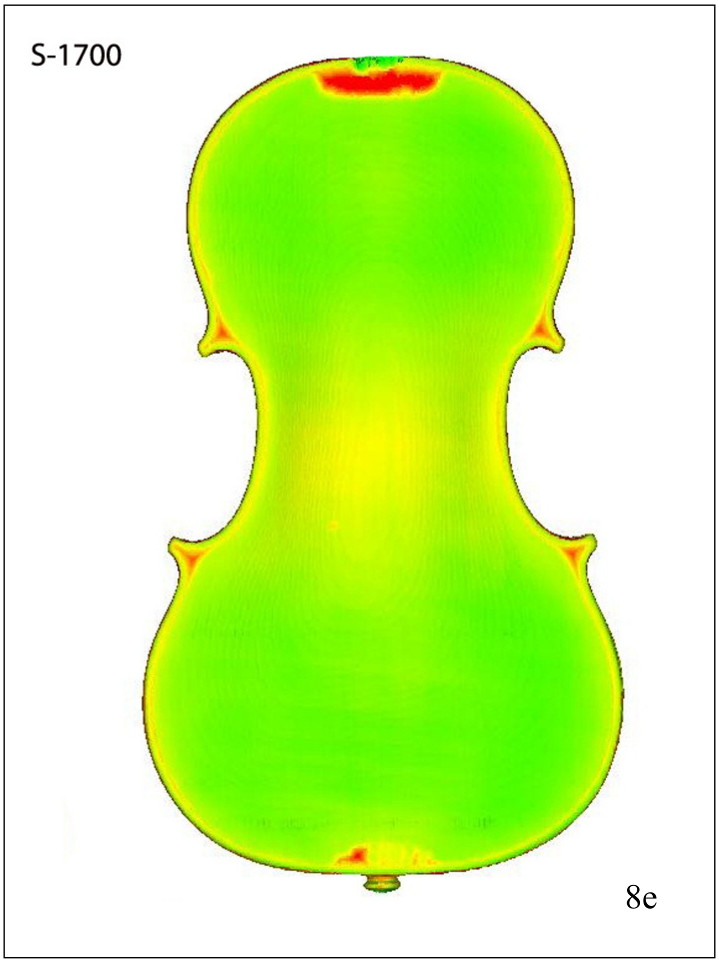
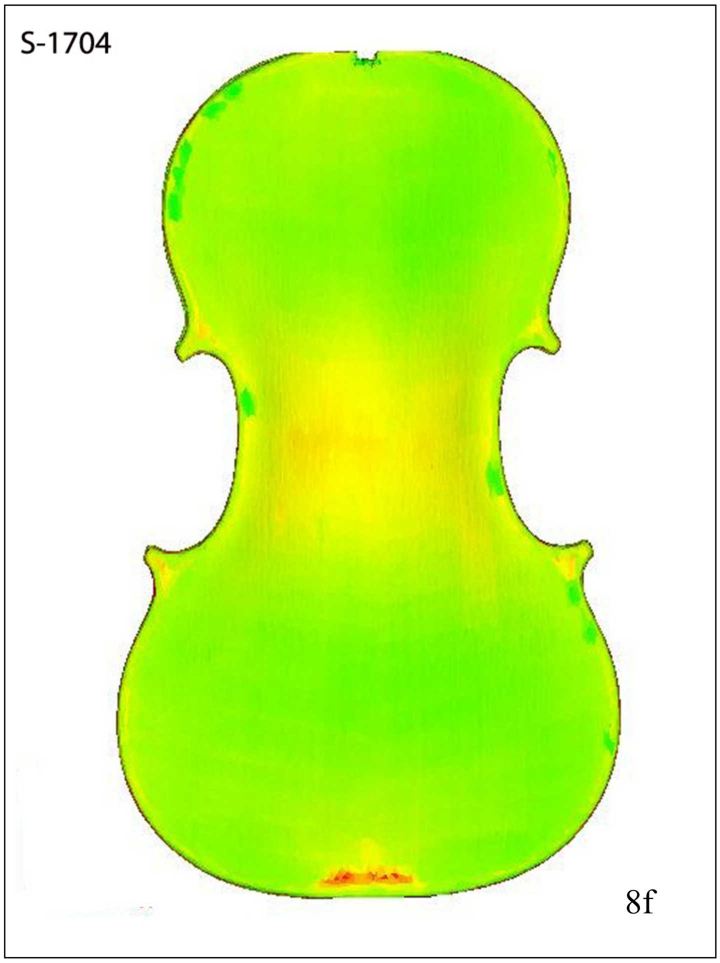
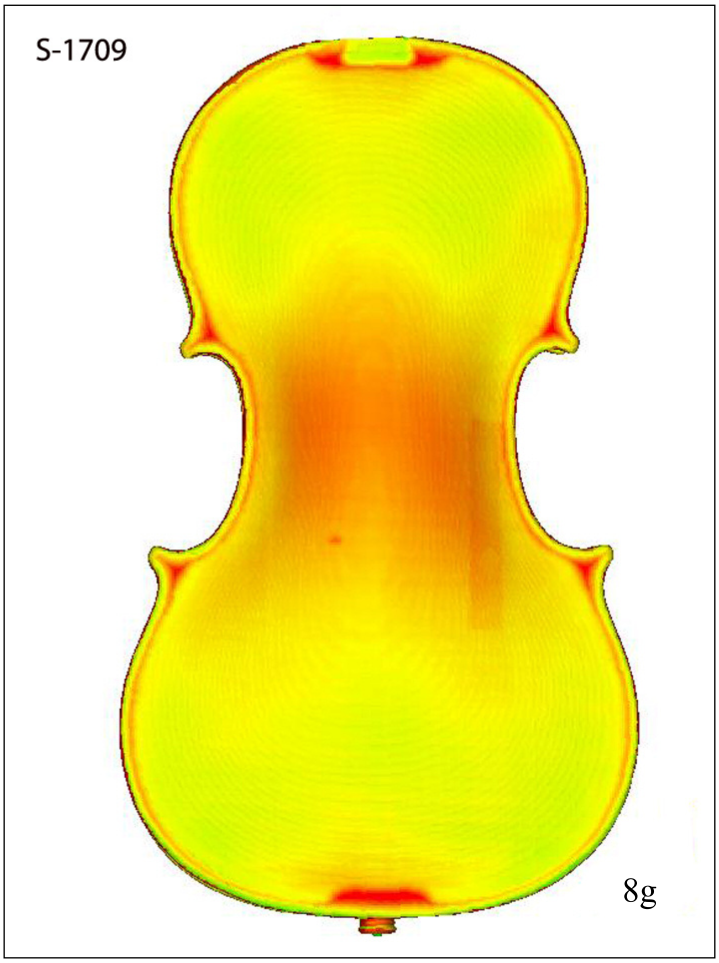
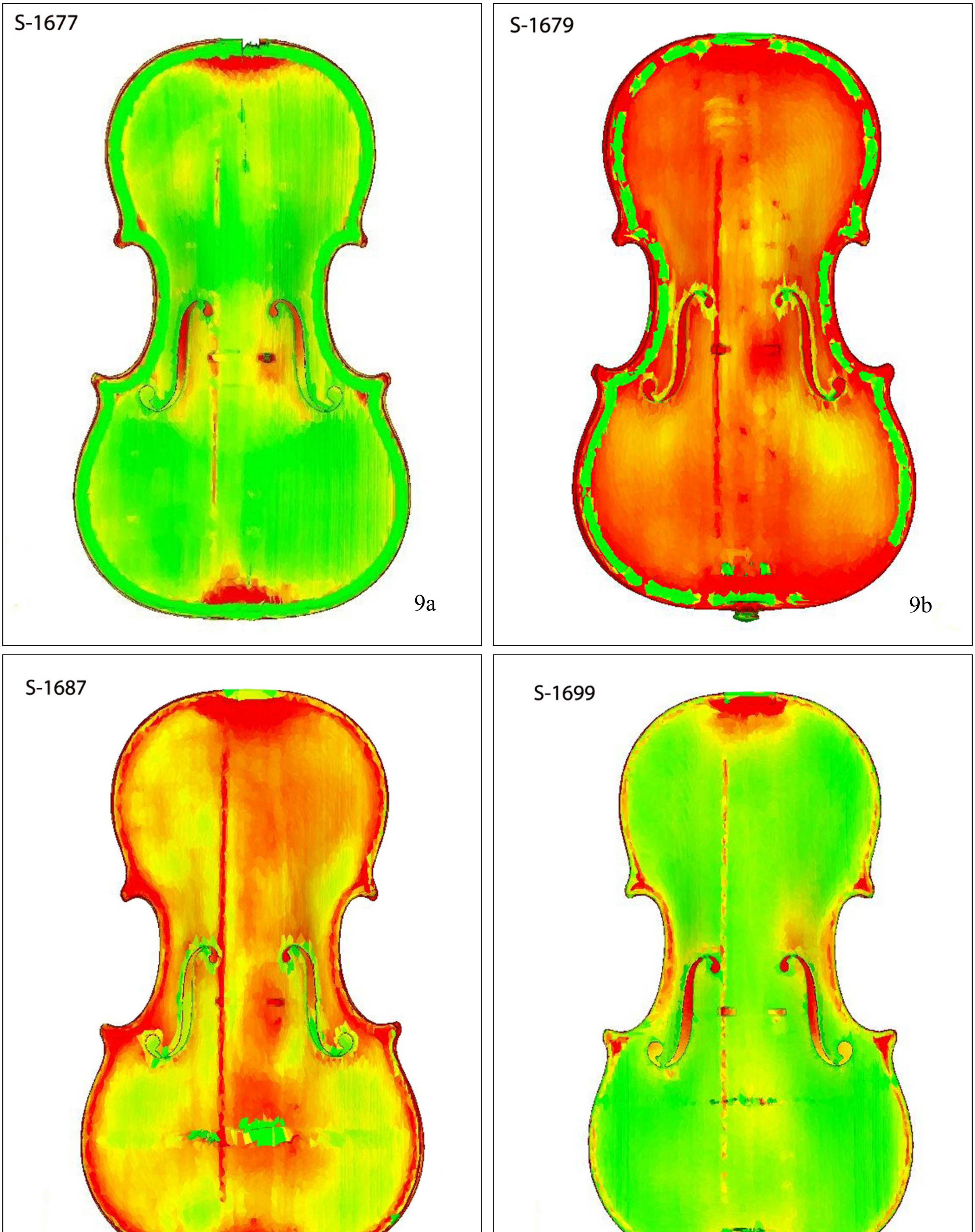
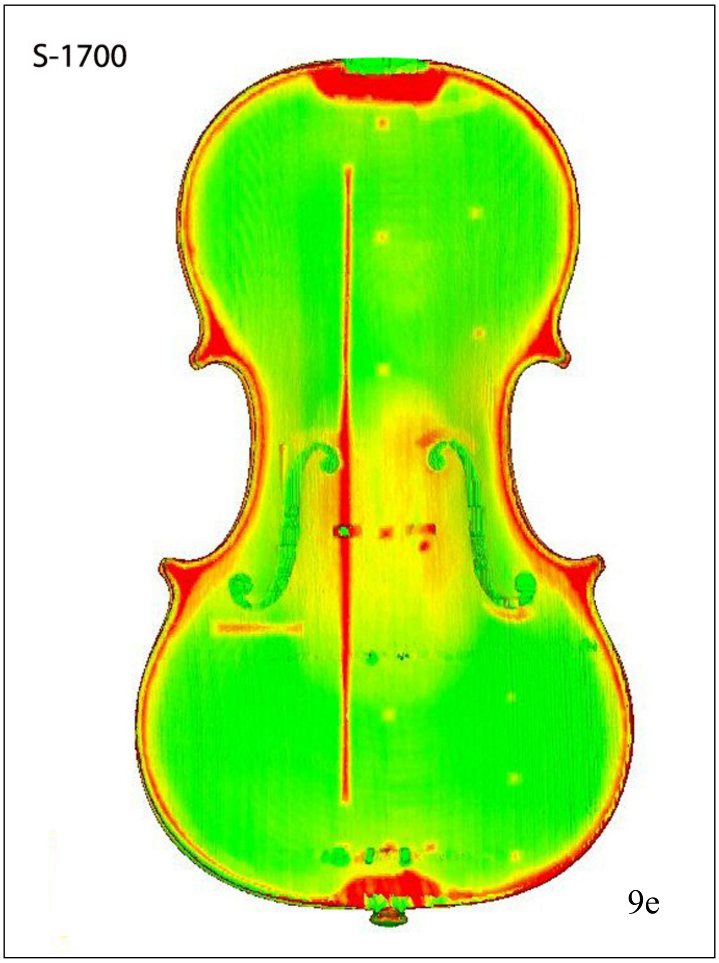


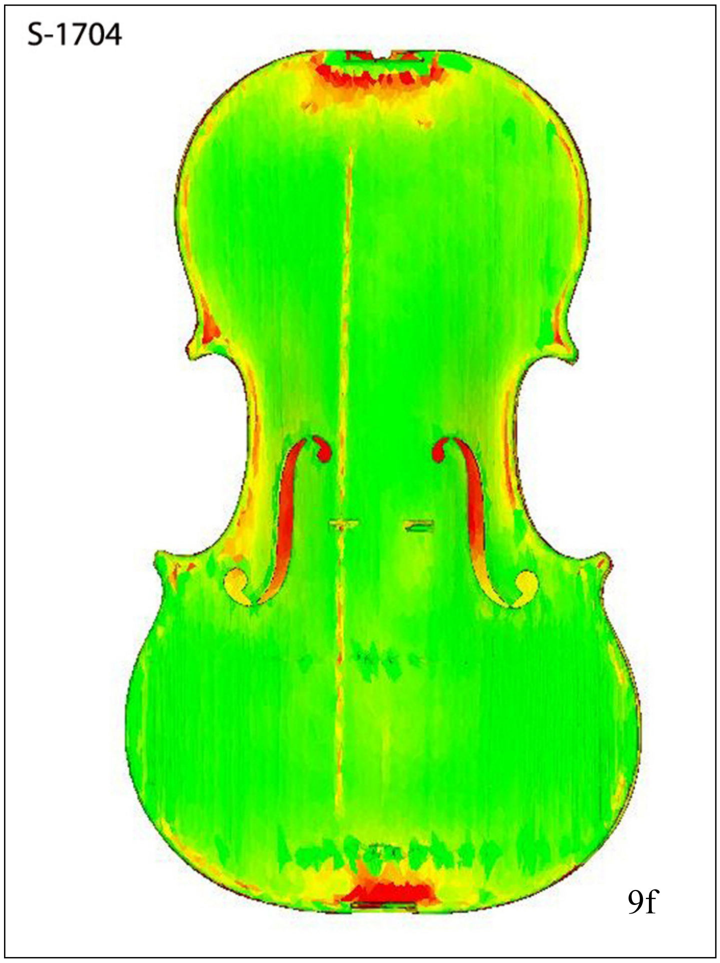


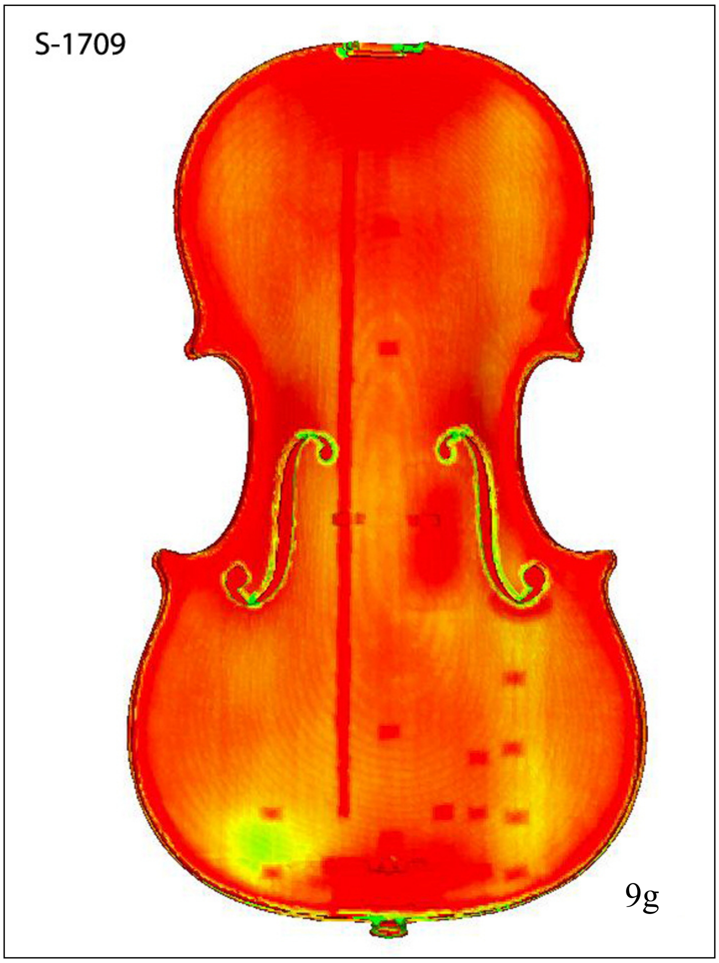


Figures 8a to 8g: Thickness variation of lower boards of Stradivari instruments from 1677 to 1709. Range of color (thickness) is 1 mm to 7 mm, with color being thin and red color being thick. S-1709 (8g) is believed to be an earlier instrument repaired by Stradivari in 1709, perhaps from between 1679 and 1687 based on color variation. S-1677(8a) has most likely been repaired and thinned at a later but unknown time.


S-1677
9a
S-1679
9b
S-1687
9c
S-1699
9d







Figures 9a to 9g: Thickness variation of upper boards of Stradivari instruments from 1677 to 1709. Range of color (thickness) is 2 mm to 4 mm, green color being thin and red color being thick. S-1709 (9g) is believed to be an earlier instrument repaired by Stradivari in 1709, but possibly from between 1679 and 1687 based on color variation. An attempt to thin the upper board may have been initiated at the lower left area (green), but partly failed and never completed. Area was secured with two repair patches (9g). S-1677 (9a) has most likely been repaired and thinned at a later but unknown time. Note repair patches in S-1679 (9b), S-1700 (9e), and S-1709 (9g) suggesting contemporary or later repairs.

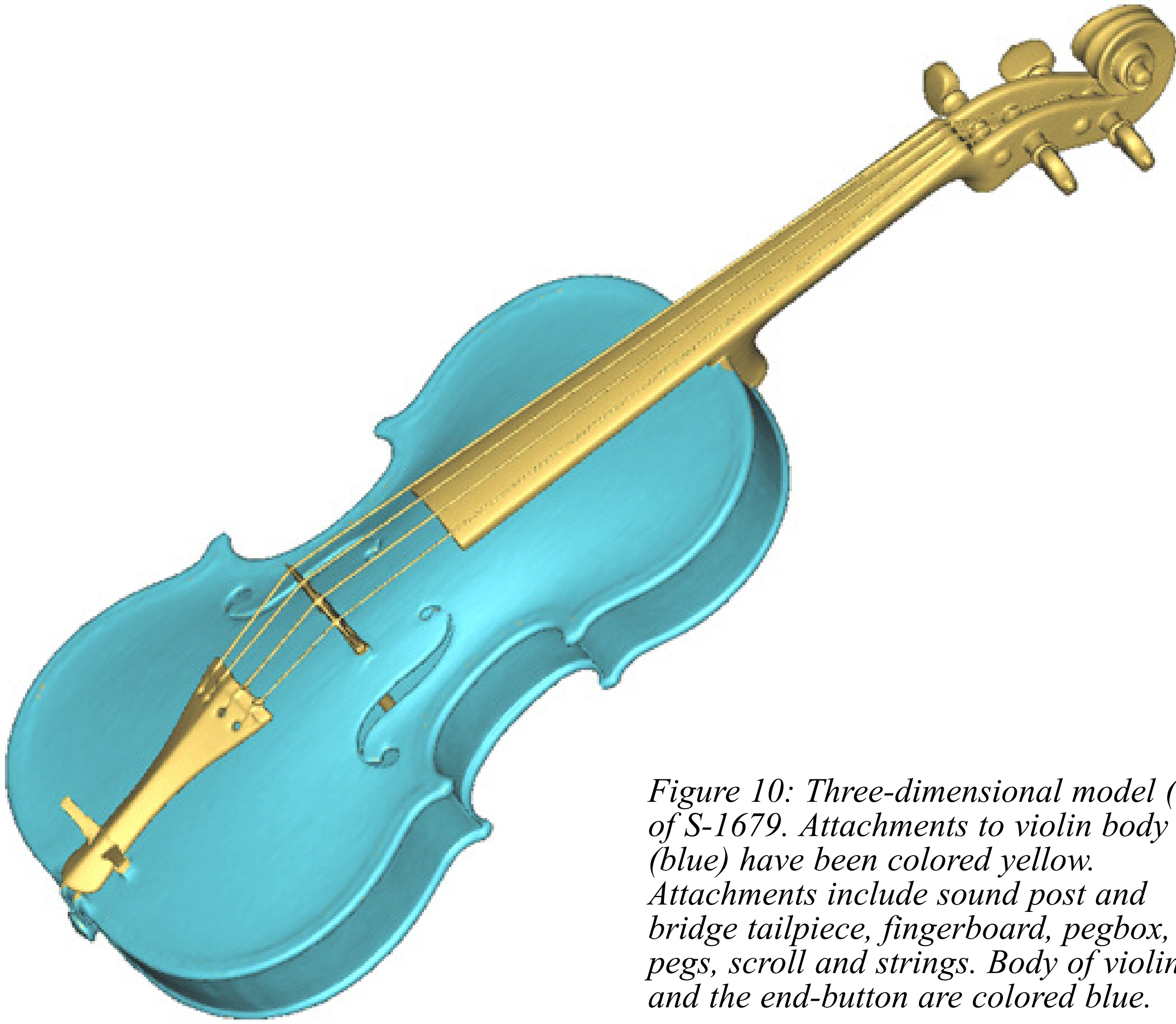


Figure 10: Three-dimensional model (3D) of S-1679. Attachments to violin body (blue) have been colored yellow. Attachments include sound post and bridge tailpiece, fingerboard, pegbox, pegs, scroll and strings. Body of violin and the end-button are colored blue.

the approximate mean value of the range. For the lower board we selected a range from one mm to seven mm and in the upper board a range from two mm to four mm. Thus in the lower board a thickness of one millimeter will be colored green and a thickness of seven millimeters will be colored red. Anything in between will be displayed as colors ranging from green to red with yellow as an approximate mid point. For the upper board a two mm thickness will be green and a four mm thickness will be red. Because the upper and lower boards include different ranges, similar colors in the two boards do not represent similar thickness. However, since we keep the same range for all of the upper boards and all of the lower boards, respectively, we can compare thickness variations between instruments as long as the upper boards are compared separately from the lower boards (Figures 6, 7, 8a to 8g, & 9a to 9g).

Violins manufactured by Nicolo Amati and Jacob Stainer (Table 1), both practicing the trade before Stradivari tend to make instruments with thicker boards. This is especially true in the center part of the lower board between the inner rib curves (Figures 6 & 8a to 8g). In some cases the thickness of the maple wood can reach eight to nine mm. Later instruments tend to be significantly thinner in this area and just slightly thicker than the top and bottom parts of the lower board. Thus there is a time related transition from thicker toward lower, thus lowering the weight of the instrument over time. Figures 8a to 8g show the graphic display of the thickness variation found in the lower board sorted by time of manufacturing. S-1677 (oldest) and S-1709 do not follow this trend. However the instruments from S-1679 to S-1704 show gradient changes from a more yellow/red color to a more yellow/green color, showing that the general thickness of the lower board is becoming thinner, but that the center part is still thicker than the rest of the board within the same instrument (Figures 8a to 8g). One reason for keeping some added thickness in the center area is most likely related to the need of ensuring strength and sta-

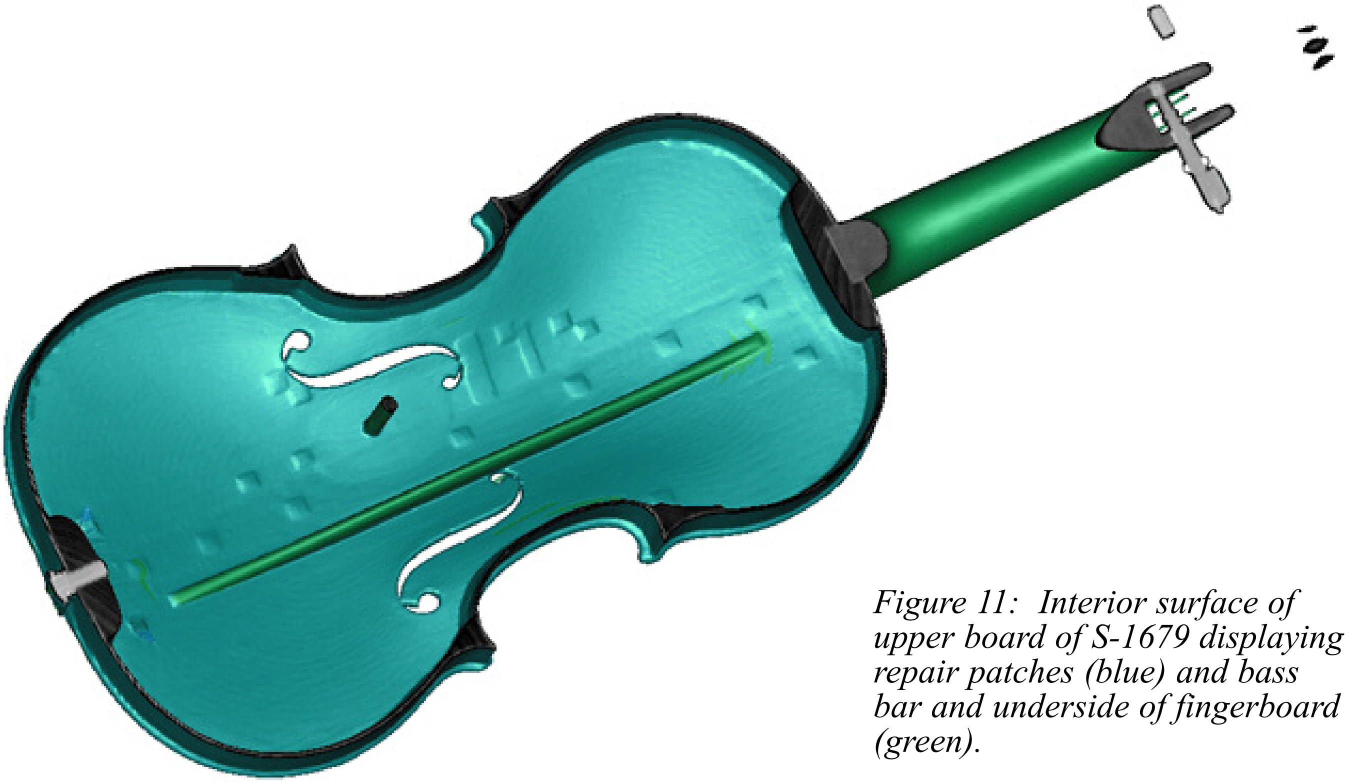


Figure 11: Interior surface of upper board of S-1679 displaying repair patches (blue) and bass bar and underside of fingerboard (green).

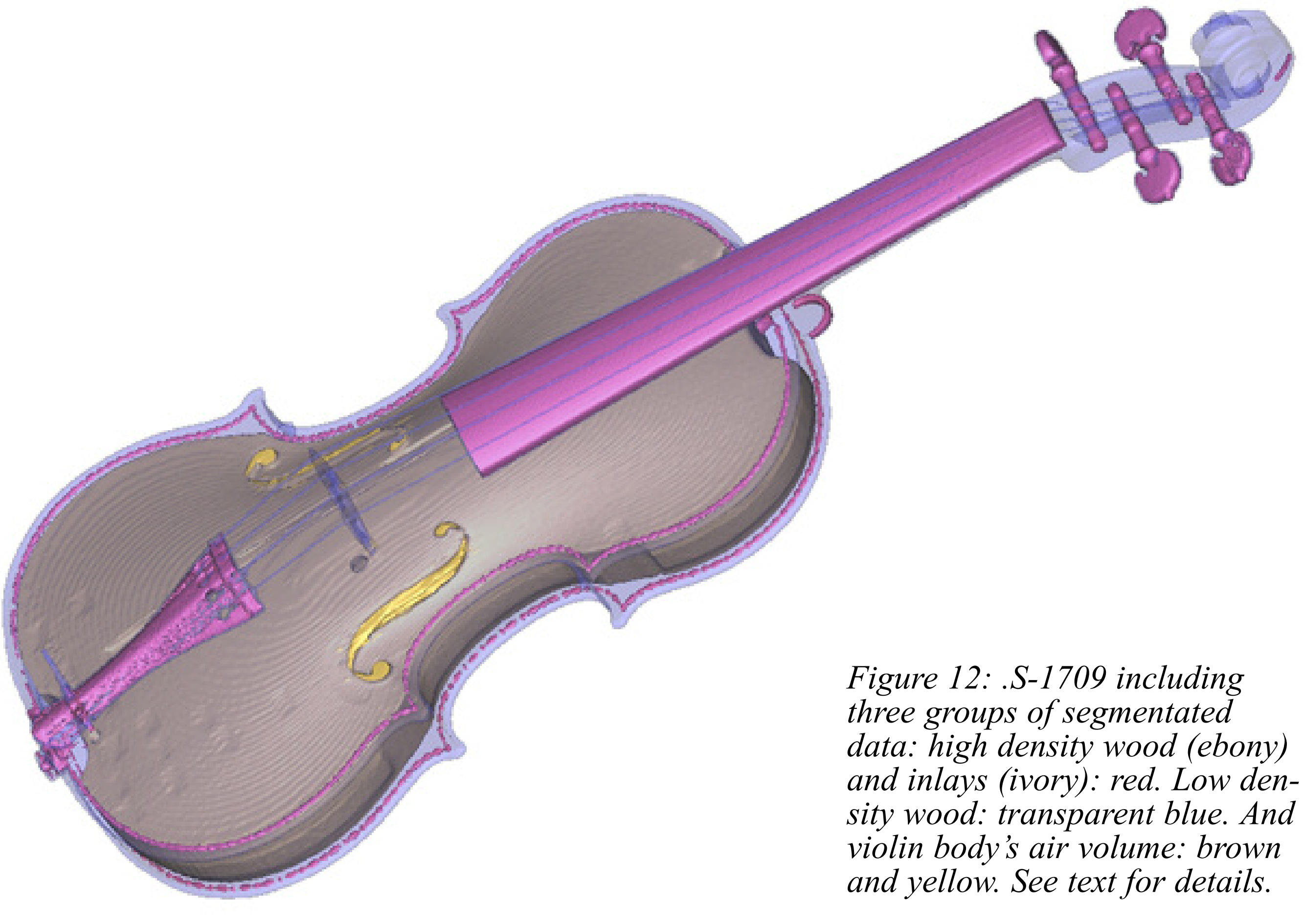


Figure 12: .S-1709 including three groups of segmentated data: high density wood (ebony) and inlays (ivory): red. Low density wood: transparent blue. And violin body's air volume: brown and yellow. See text for details.

Figures 13 and 14: S-1709 with the Stradivarius label visible through the f-hole and the ivory inlays set in a black varnish.

bility and possibly for enhancing the tone quality although the latter cannot be verified at this time. The smooth variation from thick to thin wood within each instrument is remarkable. Considering the fact that the lower board has been carved out of a solid piece of maple wood, and in some cases getting close to one millimeter in thickness is a reflection of Stradivari's excellent workmanship. The isolated red areas at the corners, the top and bottom represent areas reinforced with blocks of soft wood blocks filling in the space between the upper and lower boards (Figures 8a to 8g).

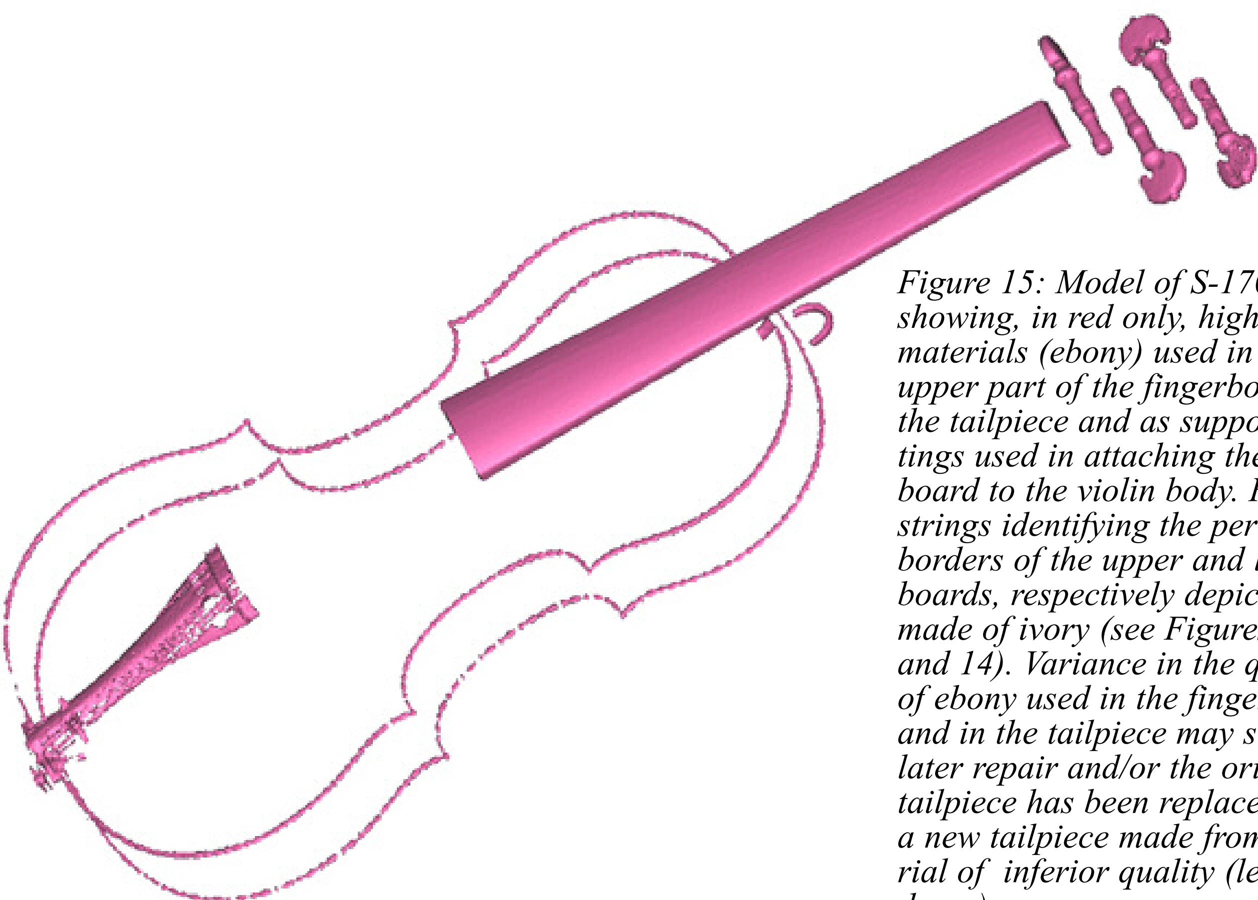


Figure 15: Model of S-1709 showing, in red only, high-density materials (ebony) used in pegs, upper part of the fingerboard, in the tailpiece and as support fittings used in attaching the fingerboard to the violin body. Red strings identifying the peripheral borders of the upper and lower boards, respectively depict inlays made of ivory (see Figures 13 and 14). Variance in the quality of ebony used in the fingerboard and in the tailpiece may suggest later repair and/or the original tailpiece has been replaced with a new tailpiece made from material of inferior quality (less dense).

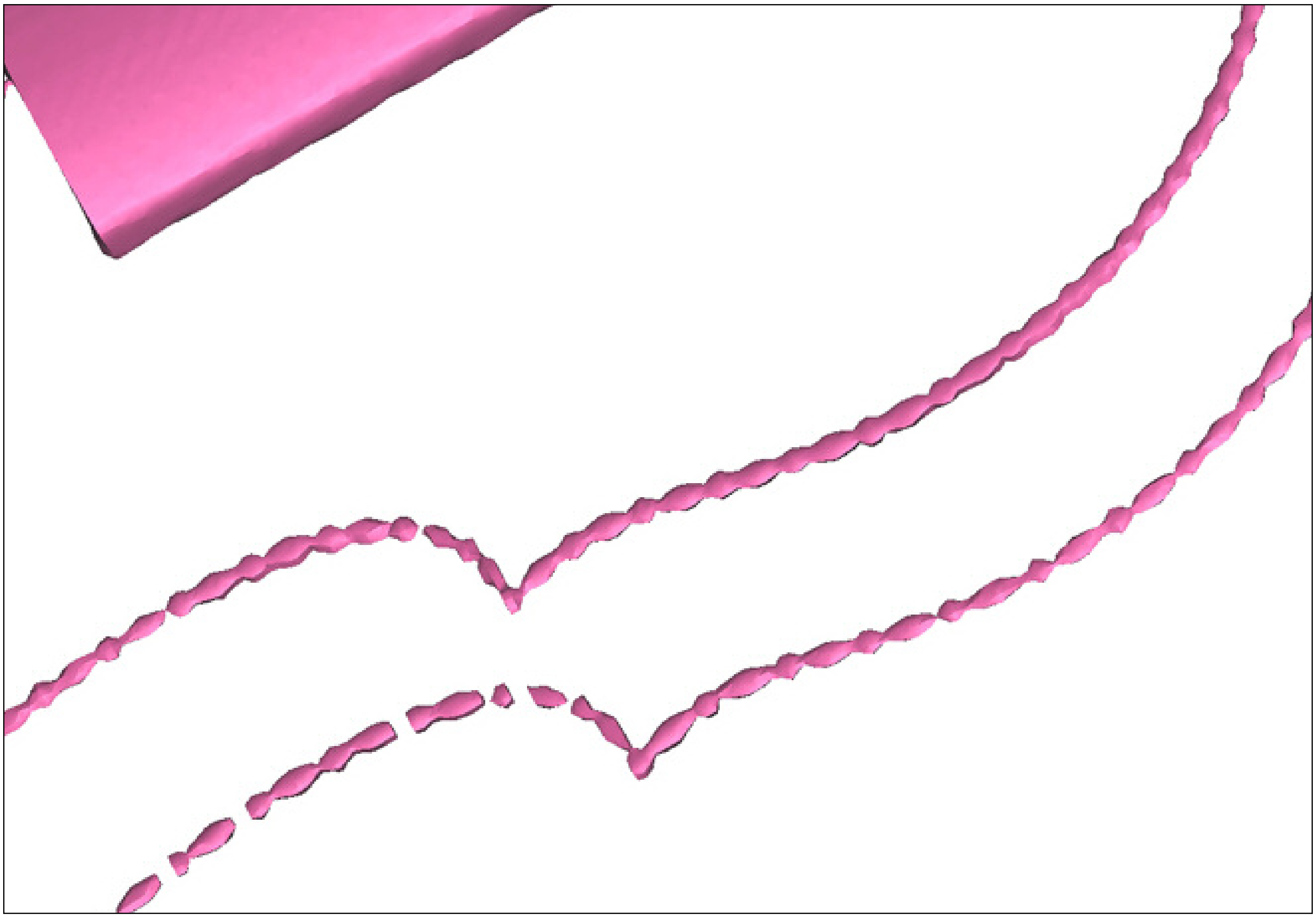


Figure 16: S-1709 showing close-up of high density material (ivory and ebony) in Figure 15. Note shape of diamond and circle shaped ivory inlays. See Figures 13 & 14.

The thickness study based on the upper boards displays similar trends as seen in the lower boards, i.e. older instruments appears to include thicker boards than the younger instruments (Figures 7 & 9a to 9g). Again we see a clear exception to this trend in the S-1677 and the S-1709 (Figures 9a and 9g). Also, the gradually and smooth thinning of the board seen in the lower boards is absent in the upper boards. We find areas of relative thin wood in some areas and not in others and except for a slightly higher wood thickness in the area where the sound post should be located, the trend appears to be random. At this time we believe that the variation in the general wood thickness in the upper boards may be correlated with the density or the strength of the wood. We are presently exploring the possibilities of displaying upper and lower boards with colors reflecting the density variation of the wood.

Some other visual trends are worth mentioning. The bass bars, located on the inside of the upper board, are in some cases depicted as red, which is explained by the wood thickness in this specific area would be recorded as more than the specified range (from two mm to four mm). In S-1677 and S-1704 (Figures 9a & 9f) the bass bar is depicted in yellow compared to the green colored board, thus the combined thickness of the bass bar and the upper board would be less than four mm. Also, patches used for repairing the upper board and glued to the interior surface will show up as a reflection of added thickness (Figures 9b, 9e & 9g). Patches are most often found in areas where the wood is exposed to added mechanical stress which would include the location of the sound post (where the patch would be large so that the instrument can be effectively tuned by changing the location of the sound post), at the top and bottom part of the f-holes and in areas where the wood may have become too thin. The latter example is seen in the upper board of the S-1709 (Figure 9g) where the lower left area is relative thin (green) and it may have been repaired at a later time by adding two patches (Figure 9g).

The S-1677 and S-1709 are examples on instruments changed at a later time. The S-1677 has most likely been repaired and 'thinned' by an unknown instrument maker. This may be supported by the fact that the upper board between the inner ribs and at the centerline is thinner than in the areas adjacent to the f-holes. All other studied instruments made by Stradivari depict the opposite trend; thus, being thicker at the center and getting slightly thinner toward the f-holes (Figure 9a). The S-1709 was most likely manufactured at an earlier date, possibly between 1679 and 1687 based on how the color variation for the lower board fits into the order of the rest of the lower boards. Stradivari may have repaired the instrument around 1709 and added a new label covering the old one. Significant repairs are evident by the presence of more than fifteen repair patches. Curators, who are studying and playing the instruments, have more recently supported this interpretation.

We have described some of the features in Mimics and 3-matic, which were used in our pilot study. The software has opened up a multitude of applicable application, which will benefit our non-destructive studies of millions of objects in our collections. Some of the features not specifically used in the pilot study, but which will be included in the study of all 47 instruments have been tested out and produced excellent results. This includes the ability to identify, display and, analyze materials with various values on the Hounsfield Unit scale. This does not only produce fascinating images, but also becomes a powerful tool in showing how different material is related and distributed. Segmentation of the instrument into different groups based on density values can produce color-coded images displaying various sections and/or materials. Figure 10 shows the Stradivari 1679 violin (Greffuhle) with the fingerboard, scroll, bridge, strings and tailpiece colored yellow and the body of the violin colored blue. Note the yellow sound post partly visible through the f-hole (Figure 10). The same instrument with the lower board sectioned away displays the inside surface of the upper board, made from spruce, including about twenty repair patches (Figure 11). The six patches at the centerline, also known as 'cleats', are used to reinforce the joints between the two pieces of wood making up the upper board (Figure 11). The ability to change the transparency independently allows for the display of transparent features in combination with features, which are displayed as non-transparent (Figure 12). Three 'volumes' are displayed: high density wood (bony) and inlays (ivory) with densities above 0 HU (red and non-transparent), the spruce and maple wood making up the body of the violin, the underside of the fingerboard and the scroll with HU values between –850 and –100 (blue and transparent), and a 3D model of the air within the body of the violin with HU values between –1024 and –900 (yellow and not transparent). The 'yellow colored' air mass appears as brown mass because it is viewed through the transparent blue wood mass of the body. The true yellow color of the air mass can be observed though the f-holes (Figure 12).

Stradivari and other instrument makers used small pieces of ivory and black lacquers to decorate the upper and lower boards and sometimes the ribs (Figures 1, 13 & 14). Some of these are sophisticated art pieces as observed on the Stradivari decorated instruments (Figures 1, 13 & 14) (Yokoyama 1986 & 2002). The S-1709 (Greffuhle) violin includes inlays on the upper and lower boards, which consists of a beautiful combination of circular and diamond shaped pieces of ivory (Figures 13 & 14). The inlays are seen in Figure 12 (red) and as a separate entity in Figure 15. Finally, an enlargement of one corner depicted in Figure 15 is seen in Figure 16. The Mimics software produces a clear graphic display of the inlays, with sizes and shapes, all true reflections of what is observed on the original violin (Figures 1, 13 & 14).

Conclusion:

The use of high resolution CT scanning and the application of advanced software for the analysis and display of CT data have significantly improved our access to research data which otherwise would be inaccessible. The creation of a digital copy based on the original object and the ability to retrieve information from the digital copy, which is compatible and a true reflection of the original object is one of the most powerful developments in the field of non-destructive and non-invasive research.

Our pilot study using seven violins manufactured by Antonio Stradivari has shown that it is possible to collect data from a true digital copy of the original instrument, based on CT data and the application of relevant and well-designed software.

In this pilot study, we have used few of many features available in Mimics and 3-matic. We have, however touched base with some of the more advanced opportunities, but are still not fully experienced in mastering the entire range of the many analytical features. We see the application of Mimics and 3-matic as an important tool in the study of the 47 stringed instruments, which have been scanned so far and which will allow us to obtain a much better understanding of the Stradivari instruments and how they compare both in time and space.

Acknowledgement:

This work could not have been completed without the wonderful support we have received over the years from Siemens Medical Solutions. Our newly acquired relationship with biomedical engineers at Materialise USA in Ann Arbor, Michigan has also helped us understanding and appreciating the great research potential of their software as related to our studies of objects most often found in museums. We appreciate editorial assistance and help from Marie T. Frohlich. Finally, we appreciate the never ending support we have received over the years from our respective departments at the Smithsonian Institution's National Museum of American History and National Museum of Natural History in Washington DC.

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