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# Neutrons and music: Imaging investigation of ancient wind musical instruments

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ABSTRACT

A set of seven musical instruments and two instruments cares from the '*Fondo Antico della Biblioteca del Sacro Convento*' in *Assisi*, Italy, were investigated through neutron and X-ray imaging techniques. Historical and scientific interests around ancient musical instruments motivate an intense research effort for their characterization using non-destructive and non-invasive techniques. X-ray and neutron tomography/radiography were applied to the study of composite material samples containing wood, hide and metals. The study was carried out at the NEUTRA beamline, PSI (Paul Scherrer Institute, Switzerland). Results of the measurements provided new information on the composite and multi-scale structure, such as: the internal structure of the samples, position of added materials like metals, wood fiber displays, deformations, presence of adhesives and their spatial distribution and novel insight about construction methods to guide the instruments' restoration process.



## 1. Introduction

The library of the '*Fondo Antico della Biblioteca del Sacro Convento*' in *Assisi*, Italy includes a small collection with a relevant historical interest, recently discovered in the Sacred Convent of *Assisi*, made of seven wind wooden instruments that can be dated between the second half of XVI century and the end of XVII century. It consists of a *dulciana*, a traverse flute, a bass recorder and four cornetts. The collection, although of undeniable historic interest, is poorly known to scholars. Recently discovered documents [1] shed new light on the provenance of the instruments (this is of particular relevance since all the instruments are anonymous) and supply information about instrumental practice between 1620 and 1720 in the Sacred Convent of *Assisi*, allowing us to put forward some hypotheses about the specific use of the instruments in the musical activity of the Franciscan community; music production and execution had a central role in the *Assisi* organization. The documents confirm the historical events by way of which the collection of instruments came into the possession of the Holy Convent, allowing us to establish a definite date regarding their arrival in *Assisi*, as well as to provide estimates of the dating of the instruments themselves [2].

The historical and scientific interests in the knowledge of this precious collection of ancient instruments motivate an intense research effort for their characterization and modeling [3]. The musical instruments were restored in Basel after the measurements presented in this work, and are now preserved in the Treasure Museum of *Assisi Basilica*. X-ray and neutron tomography/radiography were applied to the study of composite material samples containing wood, hide and metals. The study was carried out at the NEUTRA thermal neutron radiography facility [4], located at the Paul Scherrer Institute (PSI), Switzerland. Aim of the measurements was to characterize: the internal structure of the samples, the position of composite and added materials like metals, wood fiber displays and deformations. These measurements provided information about construction methods and were used to guide the instruments' restoration processes.

## 2. Methods

### 2.1. Instrumentation

The imaging measurements were carried out at NEUTRA beam line at the spallation neutron source SINQ, Paul Scherrer Institute,

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Switzerland [5]. NEUTRA, an instrument for neutron radiography and tomography images of medium to large size objects, uses a thermal neutron energy spectrum (see Fig. 1). A 320 kV X-ray tube and related acquisition system is also available on the beamline to perform X-ray imaging with identical geometry to the neutron measurements in the closed neutron shutter configuration. In both neutron and X-ray set-ups signals are detected by a scintillator-CCD camera system with field of view of 220 × 260 mm and 2160 × 2560 pixels. For neutrons, $^6$LiF:ZnS scintillators (thickness 100 μm) were used while for X-rays green-emitting converter foils (CAWO™ OG 8) were used. The scintillation foil was changed from a neutron and X-ray configurations. X-ray acquisition time was of 20 s while neutron acquisition time was of 40 s for each radiography and the effective pixel size for both techniques was 100 μm.

The 3D structure is reconstructed based on a set of 2D projections, recorded at different angles by rotating the sample around a defined axis [4,6]. When the neutron or X-ray beam is transmitted through a sample, part of the radiation is attenuated by the sample material. The change in beam intensity is related to the material attenuation for the particular probe. Absorption and scattering processes are the interactions that contribute to beam attenuation. In conventional radiography the attenuation on incident beam by the sample, under the assumption of "narrow-beam geometry", can be described by an exponential function:

$$I(x,y) = I_0(x,y)e^{\int_{path}\mu(x,y,z)dz}$$

where $I(x,y)$ and $I_0(x,y)$ are the intensity of transmitted and incident beam in a plane $(x,y)$ perpendicular to the propagation direction $z$. The linear attenuation coefficient, $\mu$ quantifies the fraction of the beam that is absorbed or scattered per unit thickness of the attenuating material. The charge-free neutrons interact with the atomic nuclei, while in contrast, X-rays interact with the charge distribution of the electronic shell. X-ray imaging is a well-established non-invasive method for investigation of wood materials, while more recently neutron imaging was used to study wood materials [7–11].

### 2.2. Samples

A total of nine samples were investigated: (A) four cornetts, length ∼40 cm, max diameter ∼5 cm, wall thickness ∼4 mm. These were made of wood and leather joined with an unspecified adhesive and suffered modifications such as opening and closure of holes, addition of metal extensions, addition of metal insertions in some areas along the tubes. (B) One bass recorder, length ∼65 cm, max diameter ∼7 cm, wall thickness ∼5 mm. This sample was made of maple wood and divided in three parts, with a brass clef. The central part was modified by adding two hand-worked pieces of boxwood. (C) One transverse flute, length ∼33 cm, max diameter ∼5 cm, wall thickness ∼4 mm. This sample was made of 3 boxwood pieces and a brass clef. (D) One *dulciana*, length ∼70 cm, max diameter ∼10 cm, wall thickness ∼10 mm and had a metal unidentified piece blocked inside the tube. Internal structure of the instrument, position and possibly material of this metal piece were investigated. (E) Five renaissance recorder care and one cornett care (XVI century). The cornet care (CC) had a max length ∼70 cm, a max diameter ∼6 cm and wall thickness of ∼3 mm. The renaissance recorder cares were made of five tubes connected together with the external dimensions ∼20 × 20 × 30 cm, and wall thickness of each tube of ∼3–4 mm. All these samples were made of wood.

### 2.3. Measurements

Neutron and X-ray radiographies at frontal and lateral views were performed for each instrument through the two set ups. A complete neutron and X-ray tomography on the transverse flute were also performed. The combination of the neutron and X-ray techniques, thanks to their complementary penetration powers, allowed quantitative measurements of specific properties of the instruments. In particular through a combination of X-ray and neutron radiographies the analysis of the internal diameters allowed to investigate wood deformations. The pixel-size, indeed, is 100 μm per pixel in both cases (X-ray and neutrons) and structures are definitely resolved because of are three-times larger than the pixel-size. The neutron characterization provided the wood fiber displacement. Morphological information deduced by radiographic-tomographic results plays a fundamental role in the identification of the construction methods, internal morphology to guide the restoration process, attribution and state of conservation.

## 3. Results and discussion

### 3.1. Study of the internal shape

X-ray and neutron radiographic images are reported in Fig. 2 for each instrument analyzed. Internal features in wood and metal parts are shown trough the complementarity of the two probes. The bore-holes structure of all instruments is entirely distinguishable. X-ray are used to identify portions in the wood parts while neutrons along the metal areas. Frontal and lateral views of X-ray and neutron radiographies of the four cornetts are shown in Fig. 2. Closed and opened holes are clearly visible in the radiographies. Radiographies of the *dulciana* present the typical U bore-hole closed in the lower part with a piece of wood. Two unexpected parts are found in the *dulciana*: a conical metal part in the center area and an organic finding, a dry-out bat, that were subsequently extracted during the restoration process. Transverse and bass

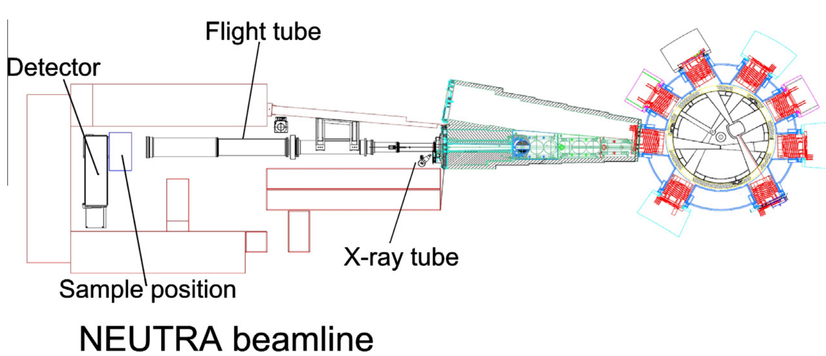


**Fig. 1.** Drawing of NEUTRA facility at Paul Scherrer Institute, Villigen, Switzerland. Distance from the sample position and the detector (1–3 cm), distance from the neutron target center to sample position ∼13 m, distance from the X-ray tube to sample position ∼7 m.


**Fig. 2.** Investigated musical instruments and radiographic images. From left to right for each instrument photograph, X-ray radiographies and neutron radiographies are reported. (i) Cornett – A and B are the frontal and lateral view respectively, (j) cornett – A and B are the frontal and lateral view respectively, (k) cornett – A and B are the frontal and lateral view respectively, (l) cornett – A and B are the frontal and lateral view respectively, (m) dulciana – a bat was discovered inside the bore hole, (n) transverse flute, (o) bass recorder, (p) cornett and flutes cares.

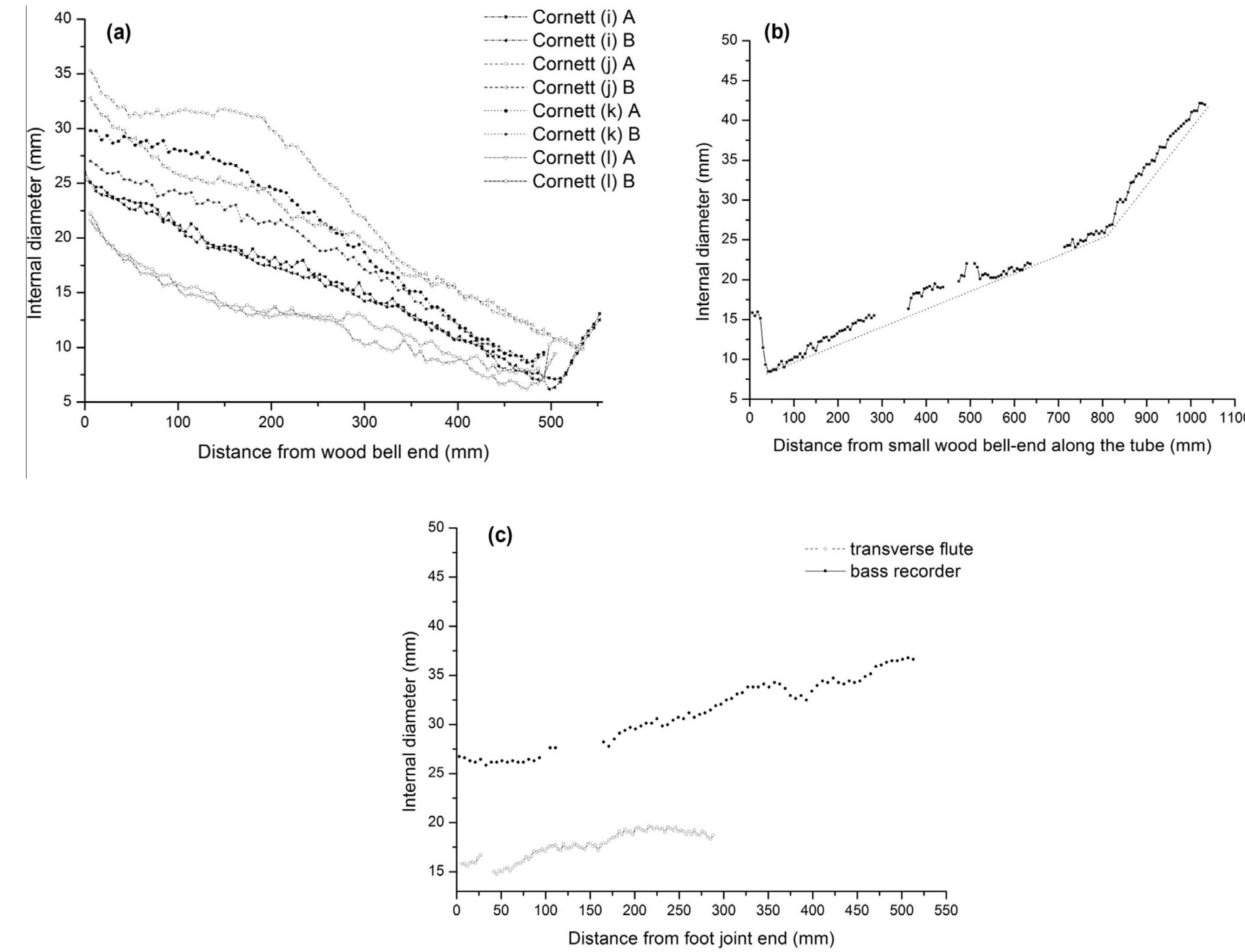


**Fig. 3.** Dimensional diagram of bore diameter along the longitudinal direction. Measurement points are spaced by 6 mm. (a) Cornetts bore diameters as function of distance from wood bell end. A and B are the frontal and lateral view respectively; (b) *dulciana* bore diameters as function of distance from small wood bell-end along the tube; (c) transverse flute and bass recorder bore diameters as function of distance from foot joint end.

recorded bore-holes are visible in Fig. 2. Neutron radiographies of the cornett and flutes care show leather and adhesive layers in the cornett care and woodworm cavities inside the flutes care. The bore-hole of wood wind instruments can be roughly described as cylinder or cone. Small perturbation in the shape of idealized instrument geometry are present and some of these perturbations could be used to adjust the instrument shape during construction process, in order to properly align or displace instrument resonances [12]. Dimensional diagrams of diameters along the longitudinal directions were produced, for all the set of instruments, to evaluate the divergence of the tube from circular geometry. Measurement points are spaced, for all instruments, by 6 mm. These are shown in Fig. 2.

Cornetts are made of two wooden half bounded together with leather. Measurements of internal diameters were taken normally to the right surfaces. In Fig. 2a the cornetts bore diameters as function of distance from wood bell end is reported; frontal (A) and lateral (B) views for each cornett are reported. The trend is decreasing index (angle with the *x*-axis is negative) of a conical internal shape. Cornett (i) borehole has the most regular conical shape and is similar for the A and B views; a small cavity around the position at 250 mm from the wood bell end is interpreted as a working-correction performed from the constructor for the adjustment of timbre and intonation. This musical instrument, made by fruit tree wood that is softer than other woods such as boxwood, results more stable with stress fields confined in small areas. Cornett (j) is the largest among the instruments under study. The two views show an elliptical shape in correspondence of the curvature. In that region, at a distance from the bell end of 200 mm, a large peak is shown in both views, and more clearly in view A; this is interpreted as strain effect. The cornetts, indeed as made of two halves and the ligneous fiber, as it will be shown before, are oriented along the longitudinal direction. The halves underwent forces that tend to broaden the diameters of the two halves. This effect is most noticeable in the frontal views instead of the lateral view. Cornett (j) is made of boxwood, that is a hard wood, and for this reason more susceptible to stress forces and more unstable. The cornett (k) was constructed with boxwood. The two views of the instrument show the same trend but shifted up to 350 mm from the wood bell end; this effect is interpreted as the enlargement of the diameter due to the relaxing of ligneous fibers. Cornett (l) is the most rough-worked. The internal bore-hole presents an irregular shape in the region between 250 and 500 mm from the wood bell end. Working marks made by hand tools are also visible and produce irregularity in the bore-hole shape. The dulciana bore-hole has a conical shape and presents two trends: the first from the small wood bell-end to the position at 850 mm along the tube and the other from that position to the large bell-end; this

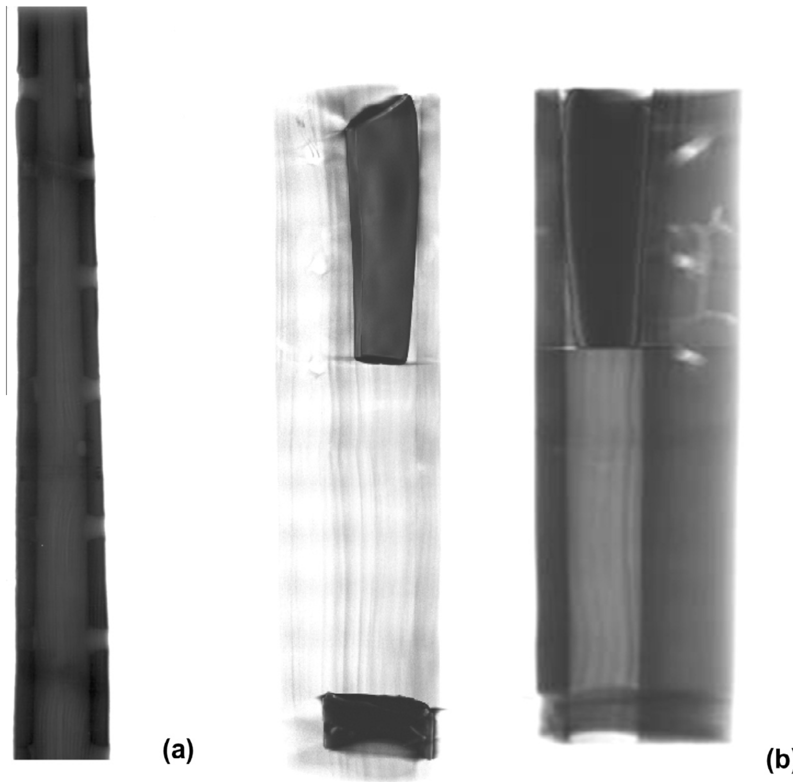


**Fig. 4.** Wood fiber displacement in (a) cornett (i) and (b) *dulciana*.

enlargement corresponds with the bell aperture of the bore-hole. In the region from 350 to 600 mm a cavity is shown. This region corresponds with the lower part of the instrument and results are interpreted as a machining performed from the lower part of the instrument. The *dulciana*, indeed, is composed by two tubes closed in the bottom part to a piece of wood as shown in the radiographies; hand working with tools was possible from the bottom to up regions. Transverse flute and bass recorder bore-holes measurements are reported in the Fig. 3c. Before the Baroque period, flutes were generally cylindrical, but this shape was revised in the late Seventeenth century. At the same time the Renaissance recorder developed into the baroque one. The Baroque flute, like the recorder, has a slightly tapered conical main bore and was divided into two or more pieces, the head being nearly cylindrical. It has six main finger-holes and an extra hole for the right-hand little finger. Renaissance recorders have a nearly cylindrical bore while instruments of the baroque period have a conical shape bore-hole, two or more sections and decorative elements near the head and foot of the instrument [12]. The bore-holes of the two instruments have a slight tapering and, for this reason, could be attributed, as in agreement to the historical sources, to the baroque period. The structure and placement of ligneous fibers was also evaluated by neutron radiographies and tomographies. Fig. 4 reports the radiography of one cornett (cornett (i)) and tomographic reconstruction of a section of *dulciana*. Ligneous fibers are displaced along the longitudinal direction of all the instruments. This gives direct information for the interpretation of ligneous movements due to stress forces.

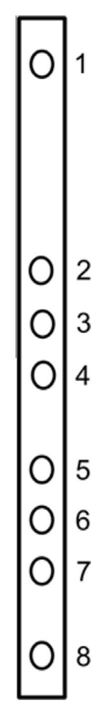


**Fig. 5.** Transverse flute hole chart. Hole nomenclature is reported.

### 3.2. Transverse flute study

The transverse flute morphology was studied through neutron and X-ray radiographies. The note played by a wood-wind instrument is changed by opening one or more finger holes thus changing the acoustic length of the air column. Tuning imperfections are adjusted during construction by undercutting certain holes and making slight enlargements to various sections of the bore. Construction information about transverse flute can also be obtained through the structure and dimensions of the holes reported in Figs. 6 and 7 and in Tables 1 and 2, respectively.

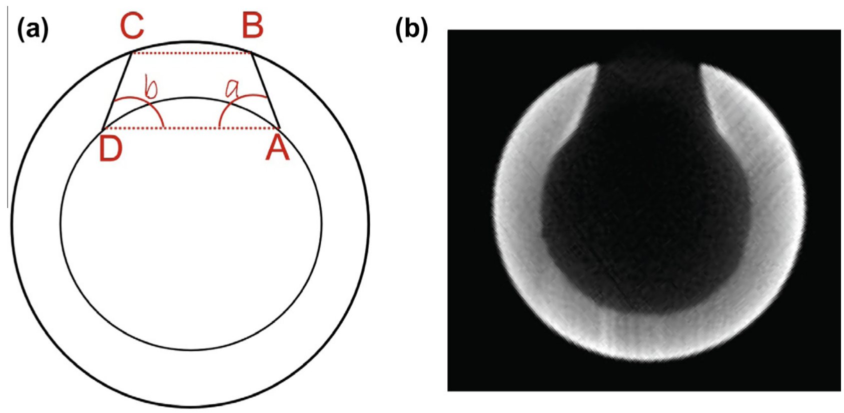


**Fig. 6.** Drawing of transverse flute hole dimensions in transverse direction (a) and neutron tomographic slice of transverse flute.

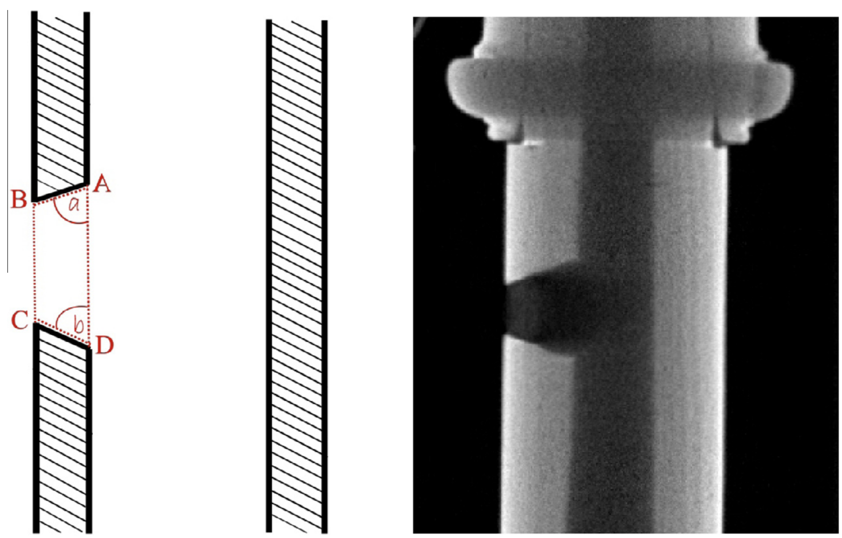


**Fig. 7.** Drawing of transverse flute hole dimensions in longitudinal direction (a) and neutron tomographic slice of transverse flute.

The musical instrument construction process is obtained through the equilibrium of factors that determines the sound of the instrument, namely: the shape and dimensions of the bore hole, the position of the finger-holes in the longitudinal direction with respect to the embouchure hole, and the dimensions of the holes. The internal shape of the bore hole of the flute has a different conicity from the wood pieces, and can be observed in Fig. 3c. This 'step' structure, typical of the baroque period, was a choice of construction used to balance the harmonic series for all octaves. From this primary structure the equilibrium and determination of fundamental frequency and harmonics of each note was obtained through the bore holes structure and position. Constructor interventions on the holes shape have been evaluated through the analysis of the deviation from the geometrical shape (truncated cone). The positions of the finger-holes in the transversal direction with respect to the embouchure hole act mostly on the harmonics rather than the quality of sound, while the widths of the holes (longitudinal direction) act on the fundamental frequency and harmonics in the same way and this influences the intonation. Tables 1 and 2 show that in longitudinal direction the geometrical shape is more regular as compared with the transversal direction. This indicates a good initial project of the instrument: a stable design of the instrument that did not need further adjustments.

**Table 1**
Table reported the transverse flute hole dimensions in the transverse direction (Fig. 6). Hole number corresponds with the nomenclature in Fig. 5. All measurements are reported in mm, angles are reported in degrees (errors on measurements are ±0.1 mm).

| | Hole 1 | Hole 2 | Hole 3 | Hole 4 | Hole 5 | Hole 6 | Hole 7 | Hole 8 |
|---|---|---|---|---|---|---|---|---|
| AB | 6.3 | 4.9 | 4.7 | 3.4 | 4.7 | 6.2 | 6.1 | 8.7 |
| BC | 8.8 | 7.5 | 7.4 | 6.5 | 6.1 | 6.7 | 6.2 | 8.1 |
| CD | 5.8 | 4.9 | 3.9 | 3.1 | 4.1 | 4.8 | 5.7 | 11.0 |
| DA | 12.3 | 10.8 | 9.9 | 7.9 | 8.8 | 10.1 | 8.8 | 15.5 |
| a | 73.9 | 74.7 | 68.2 | 81.1 | 64.0 | 60.5 | 74.1 | 76.5 |
| b | 69.6 | 71.0 | 83.9 | 80.7 | 82.7 | 87.3 | 84.1 | 58.8 |

**Table 2**
Table reported the transverse flute hole dimensions in the longitudinal direction (Fig. 7). Hole number corresponds with the nomenclature in Fig. 5. All measurements are reported in mm, angles are reported in degrees (errors on measurements are ±0.1 mm).

| | Hole 1 | Hole 2 | Hole 3 | Hole 4 | Hole 5 | Hole 6 | Hole 7 | Hole 8 |
|---|---|---|---|---|---|---|---|---|
| AB | 5.8 | 5.3 | 4.9 | 4.1 | 5.3 | 6.5 | 7.4 | 6.3 |
| BC | 7.2 | 6.8 | 6.8 | 5.9 | 6.2 | 5.7 | 4.5 | 4.5 |
| CD | 6.1 | 5.9 | 4.8 | 4.1 | 5.2 | 6.0 | 7.0 | 7.2 |
| DA | 10.7 | 10.8 | 11.5 | 7.9 | 9.3 | 11.1 | 9.6 | 12.1 |
| a | 67.5 | 63.0 | 62.1 | 71.1 | 61.8 | 57.1 | 69.2 | 56.3 |
| b | 67.6 | 64.7 | 57.1 | 84.3 | 61.2 | 65.5 | 70.3 | 45.7 |

## 4. Conclusions

A set of musical instruments from the '*Fondo Antico della Biblioteca del Sacro Convento*' were characterized by non-invasive neutron and X-ray radiographies and tomographies. The results obtained on internal structure of wood and metal parts provided new conformational information on the artefacts. Internal diameter trends, studied using radiographies, provided information on construction techniques and borehole design, of main relevance for the determination of sound quality. Wood fiber displacements were also determined. These results show that the geometrical shape of the holes in the longitudinal direction is more regular as compared with the transversal direction and indicates a good initial project of the instrument. This piece of information was used for the restoration process and to verify attribution. The present work shows that the combined use of neutron and X-ray techniques provide unique information on the conformation of historical musical instruments and to better define restoration techniques.

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