Recommendations for the Three-Dimensional Computed Tomography of Musical Instruments

and Other Cultural Artefacts

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Content

Introductory Remarks

The recommendations for the three-dimensional tomography of musical instruments presented in this document were drawn up within the framework of the DFG-project (DFG = the self-governing organization for science and research in Germany) MUSICES (Musical Instrument Computed Tomography Examination Standard) from 2014 to 2017. During the course of this project, it became evident that it would be more practical to develop a communication matrix to enable a target-oriented dialogue between the involved museum- and X-ray experts instead of using fixed numerical values for X-ray parameters for each individual type of testing and instrument.

As a result, these recommendations including the other elements set out herein should continue to be relevant even after further technological developments have been made. Furthermore, it should basically also be possible to apply them to other types of objects of cultural heritage, provided that these are not excessively large and/or their material composition permits examination by X-ray so the possibility of testing with this technology is not precluded from the start.

Thus, the technical values acquired during the MUSICES-project can be considered to be the currently recommended and proven reference values which are accessible in two ways: On the one hand, in the table of key data in chapter 21 of this document which enables an X-ray institute to assess the feasibility of a request for testing of cultural artefacts – especially musical instruments – with regard to the technical equipment available.

On the other hand, all process steps, materials, settings, devices etc. and most importantly, detailed documentation of an evaluation of the measuring procedure, are available on the website of the MUSICES-project (musices.gnm.de) to ensure that the best possible result is achieved while the musical instrument is examined in the best possible way to ensure its conservation. As parameters such as material combination, material thicknesses and sizes relevant to X-ray examination of various objects are described here, due to the very varied characteristics of musical instruments, in principle these recommendations can also be applied to other types of object.

For the sake of completeness, we would like to point out that this document and the related website are not technical standards in line with ISO-regulations despite the fact that they contain documentation of a precise nature and irrespective of the above mentioned project acronym. They constitute a recommendation, which should provide a long-term contribution for a more efficient, better accessible and last but not least less expensive access to the invaluable method of three-dimensional computed tomography for musical instruments and other cultural artefacts for research purposes and also didactic applications.

Introduction

1 Three-Dimensional Computed Tomography

Three-Dimensional Computer Tomography (3D-CT) creates three-dimensional images and enables numerous different views which can be selected by the user to suit the particular area of research, e.g. cross-sections, top views, separation of materials and construction elements as desired. This method gives important insight into groups of objects, whose inner construction or shape is of great relevance and is difficult or impossible to access using conventional testing methods and when there is a combination of different materials, some of which are permanently joined. Examples of such objects include sculptures, scientific instruments or musical instruments.

The 3D-CT is particularly suitable for use with musical instruments as

- most of them have an artificial hollow space the shape and construction of which is of fundamental importance for their function: such as a resonator for string instruments and some percussion instruments or for the spatial limitation of the air column in wind instruments,
- the inner construction is often either completely inaccessible as in the case of plucked instruments with roses or it is difficult to access or not sufficiently accessible (key instruments, string instruments) or testing with conventional methods which necessitate fixed contact with sensitive surfaces involves risks (bore gauging for wind instruments),
- hardly any other type of object is made of such a wide variety of materials: many different types of wood and metal, ivory, horn, tortoiseshell, mother of pearl, leather, textiles and many other materials occur in a wide variety of different combinations.

Unlike conventional X-ray imaging which is afflicted with geometrical errors, imaging of musical instruments with 3D-CT has particular value because it provides a high quality digital representation which allows conducting precise measurements in most cases.

Within the framework of the MUSICES project, 251 measurements of 105 instruments of as wide as possible a range of sizes and combinations of materials were carried out. From a technical point of view, this is hitherto probably the most comprehensive and representative testing of its kind. The experience gained thus should allow proposals for future CT scans.

1.1 Medical 3D-CT

The first 3D-CT-tests carried out on musical instruments in the 1980s, the devices used were predominantly in medical facilities and are still present in more advanced version today. The indisputable advantages of medical 3D-CTs are:

- their widespread use,
- their high speed,
- their uncomplicated operation using fixed parameters which are based on human physiology,

- their normally low costs.

The disadvantages of this parametrization are:

- a spatial resolution which is sufficient for medical use but whose precision is insufficient for measurements on musical instruments,
- radiation levels in a range which causes as little damage as possible to human tissue but is often not sufficient for many materials of which cultural artefacts are made,
- object sizes limited by the dimensions of the human body,
- the possible necessity of the protection of operating secrets of the CT-machine used which may mean a lack of transparency with regard to the recording of technical parameters.

For these reasons using a medical 3D-CT to examine cultural artefacts can make sense if:

- the test only requires results of a purely qualitative character,
- exact measuring does not have to be carried out and if a high level of precision is not demanded in the evaluation of the test e.g. for rapid prototyping,
- solely materials with a low density are to be radiated,
- the dimensions of the test object are compatible with the testing equipment.

However, when a medical CT-test is carried out, these recommendations with regard to scientific questioning, conservational requirements and the documentation of all relevant and collectable data in metadata model must be observed in the same way.

1.2 Industrial 3D-CT

While the basic physical principle of industrial 3D-CT is identical to the medical X-ray computed tomography, in the practical realization there are several elementary differences. Firstly, in the industrial CT the object is rotated in the beam of the X-ray radiation, whereas the radiation source (in most cases an X-ray tube) and the receiver (these days mostly a flat panel detector) are geometrically mounted with high precision and remain stationary during the measurement.

As a rule industrial CT-machines are operated at high X-ray voltages of up to 600 kV, whereby at the same time very small focal spots, which can measure 1 µm or less for high resolution images, are effective. As the objects tested on an industrial CT are very varied as far as size, shape and material are concerned, unlike those tested on a medical CT, industrial CTs are designed to be very flexible and can be geometrically configured in a wide range using mechanical axes.

One of the most essential components in the industrial CT is the rotary table on which the object is placed and which rotates around the axis of rotation during measurement. The focal spot of the X-ray tube moves on a circular- or helical path seen from the perspective of the test object. In the case of the helical path, in addition to the rotation, the object is moved in a straight line in the direction of the axis of rotation (translation).

Another difference to a medical CT in which mostly multi-row detectors (e.g. 64 x 1200 channels) are used to avoid scatter radiation, so-called flat panel detectors which can show large image details with up to 4096 x 4096 pixels on a 40 x 40 cm surface have established themselves in industrial X-ray imaging.

With regard to three-dimensional imaging of historically significant objects such as musical instruments the industrial CT has several advantages:

- The machine configuration is very flexible and can be adapted to suit the various sizes of objects to be tested
- The X-ray parameters can be carefully selected especially in the presence of metallic components to suit any materials inside them.
- The high spatial resolution which can be obtained (< 0.1 mm, in details also 0.01 mm).
- Most commercially available systems enable full access to primary data, insight into correction- and reconstruction methods and data export for the further processing and visualization of 3D-volume data.

A larger measuring volume with higher spatial resolution means, as a consequence, longer measuring times and very high volumes of data.

2 Practical Advice

When musical instruments and other objects from cultural heritage institutions undergo 3D-CT-testing, various, mostly highly specialized and often barely related research- and applied disciplines are forced together: Musicology and/or other cultural sciences, art technology and conservation science, X-ray- and information technology. A more detailed presentation of these disciplines is not possible within the framework of this study.

The interdisciplinary dialogue is of decisive importance for an efficient work sequence with which high-quality results can be obtained. This dialogue is of primordial importance due to the different methodologies, approaches and last but not least language regimes of the disciplines involved. It is illustrated generically in the practically tested communication matrix in chapter 7, although not all areas are mentioned in detail. Therefore, we strongly recommend all persons involved for the first time in testing cultural artefacts using 3D-CT and also for subsequent tests, to read this complete document to gain knowledge relating to their own area as well as a basic understanding of the other disciplines involved. For this purpose the glossary in chapter 23 should also be of use.

Best Practice Guide

3 Preliminary Considerations

Testing of cultural artefacts using 3D-CT usually involves transport of the object to be tested to the institute at which the tests are to be carried out. This alone poses a range of conservational, logistical and technical challenges. The suggested work sequence shown here in its three main areas has proved itself within the project MUSICES (Figure 1). Although this description applies to musical instruments, it could be used for most other types of cultural artefact if suitable modifications are made.

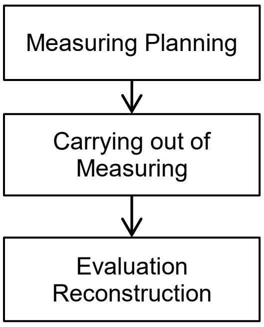

Figure 1: Schematic work sequence

Before any practical planning for such testing is undertaken, it is advisable to make some general preliminary considerations based on the specific characteristics of the test method and taking into account the museological requirements, as factors such as size and material characteristics have a significant influence on planning and process.

- The attenuation of X-rays is depending on the density and chemical composition of a material.
- Large objects require longer scan durations at the same spatial resolution and generate a correspondingly high volume of data in particular at high resolutions.
- Scans of objects made of homogenous materials with a low density often result in images with a higher quality than those of objects which are composed of various materials with different densities (e.g. wood and metal).
- Musical instruments made of dense materials with high material thickness (e.g. brass instruments) can only be radiated using high energies.

4 Measuring Planning

4.1 Suitability of the Objects

The factors size (including mounting elements), materials (including the emplacement within the object), geometry and weight should be discussed at an early stage with the operator of the CT-system in order to ensure the fundamental feasibility of the examination (size of the measuring chamber, maximum scanner range etc.).

In addition to this an important requirement is the conservational examination of the object to establish whether it can be transported and mounted. Another important consideration is the risk assessment of the possible damage which could occur as a consequence of X-ray radiation (see below 4.4).

4.2 Scientific Question

The concrete scientific question, which is the reason for carrying out the examination, influences the fixing of technical parameters. Typical questions from the area of historical musical instruments are e.g.:

- investigation into manufacturing/construction techniques
- examination of repairs and modifications
- assessment of conservational state
- volumetric analyses
- acoustic simulation
- dendrochronological dating using sectional images
- reproduction of the object or parts of it e.g. using 3D-printing or CNC-milling
- animation, visualization

In order to provide answers to a question with regard to the resolution amongst other things a certain image quality must be obtained. As a rule of thumb when musical instruments are examined, a spatial resolution of 100 µm voxel size or better must be reached. In the case of special questions (e.g. dendrochronological dating) higher resolutions may be required. In order to improve image quality and avoid image faults (artefacts), when instruments made of materials with a relative low density (wood, ivory) are to be examined, before measuring any metal parts should be removed if required for the question and only if justifiable under conservational aspects. Examples of this include removing keys, metal clips and -clamps from woodwind instruments and also removing the mechanics from key instruments. If possible metal strings on string- or plucked instruments should be removed and/or replaced with nylon strings.

Furthermore, it is necessary to clarify pre-emptively whether the instrument as a complete object or only one or several parts of it (volume of interest), such as the base of the neck in the case of string instruments, should be scanned. As a rule, higher resolutions are usually obtained if smaller objects or parts are scanned. It can also be possible to scan several parts together, if a number of small objects are to be examined. This saves scan time and money (cluster-measuring).

In case several scans of partial volumes are to be combined, it should be noted that an undesirable border between these volumes can occur as a result of the combination and perturb the interpretation of data. Therefore, during measuring planning it must be ensured that those parts of the instrument which are of most importance for the test do not extend beyond this border.

4.3 Sub Volume Measuring (Volume of Interest: VOI)

The scanning of individual sub volumes of an object lends itself well to objects which are too large for a complete scan, if the scientific question can also be answered with a detail scan or if the answering of a question necessitates a higher resolution than that which could be obtained with a complete scan. Detail scans often require a shorter scan time. Various areas for a detail scan come into consideration depending on the instrument:

String- and plucked instruments:

- body without neck, if the neck is not of interest [1]
- detail of the soundboard in higher resolution for dendrochronological age determination [2]

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[1] Cf. Lute DNgnm_MIR902_VOI3, Metal Violin DNgnm_MIR2033_VOI1

[2] Cf. Violin DNgnm_MI419_VOI2, Viola Pomposa DNgnm_MIR836_VOI1

- pegbox, so the connection with the neck (e.g. neck graft) becomes visible [3]
- top block, so the neck connection becomes visible [4]

Wind instruments:

- subarea of a wind instrument, so the surface structure of the bore becomes visible [5]
- individual connection pieces, e.g. for assembled joints [6]
- bend of a crumhorn to assess the manufacturing technique [7]
- box of a basset horn in order to expose its structure [8]

Key instruments:

- wrestplank for examining cracks [9]
- connection between wrestplank and frame to assess stability [10]
- area of a ravalement [11]

Further questions can justify detailed testing of all types of instrument, e.g.:

- high quality images of technical details [12]
- tool traces
- assessment of conservational state [13]
- repairs [14]
- modifications [15]
- improved images of areas composed of several materials with very different densities, use of dual-energy-methods [16]

4.4 Conservation Aspects

Before testing the object must undergo an examination to assess its physical state. This examination is done to establish whether the object can be transported and whether it can be guaranteed that its mounting on the rotary table would not result in deterioration and consequential damage. Furthermore, cleaning of the surface and if necessary fixing- and securing of loose parts are also recommended.

For transport and mounting, instructions relevant to conservation of and specifically pertaining to the particular object must be formulated in order to ensure its safe handling. Information about the disassembly of the complete object as well as the dismantling of

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[3] Cf. Violin DNgnm_MI577_VOI1, Viola da Gamba DNgnm_MIR789_VOI1, Lute DNgnm_MIR902_VOI2

[4] Cf. Viola da Gamba DNgnm_MIR789_VOI2

[5] Cf. Great bass pommer DBim_0289_VOI2

[6] Cf. Threading of cornetto DNgnm_MI119_VOI1, Joints of a serpent DNgnm_MI148_VOI1

[7] Cf. Krummhorn DNgnm_MIR423_VOI1

[8] Cf. DNgnm_MIR465_VOI4

[9] Cf. Square piano DNgnm_MI954_VOI3, Harpsichord DNgnm_MINe85_VOI2

[10] Cf. DNgnm_MINe85_VOI5

[11] Cf. DNgnm_MINe85_VOI6

[12] Cf. Functional mechanism of a pocket metronome DNgnm_MI934_VOI1

[13] Cf. Wood structure in cornetto DNgnm_MI119_VOI1, Boreholes of wood borer in square piano DNgnm_MI954_VOI1

[14] Cf. Repair at bell of great bass pommer DBim_0289_VOI4

[15] Cf. Extension of hitch pins (bass) of a dulcimer DNgnm_MI249_VOI1

[16] Cf. Keys of a clarinet DNgnm_MI149_VOI2

individual parts for collecting parameters relevant to X-ray examination are also of importance

During the complete measuring campaign climatic conditions complying with the conservation guidelines must be guaranteed (see section 5.1).

Determining of the various materials of composition is also relevant to avoid radiation damage. Detailed studies as to whether and to what extent radiation damage can occur have not yet been carried out. However, evidence exists stating that exposure to X-ray radiations leads to an interaction of ionizing radiation with the matter [1]. The extent and durability of these changes depends on the applied dose of radiation and effects have been observed even at low X-ray energy levels of below 200 keV. Resulting effects such as photodegradation, chain scissions and subsequent modification of molecules or DNA-structures are to be expected. As a consequence, long term radiation exposure of organic materials such as synthetics or paints can have degradation effects such as embrittlement and in the case of cellulose yellowing. Browning (solarisation) of glass and precious stones (silicate-based rubies, emeralds) can occur. It is sometimes possible to reverse this effect by heating and/or further radiation [2].

To obtain an estimation of the dose an object receives during a single CT scan, a simple procedure was used during the MUSICES project. For details on the method see section 5.5. The obtained dose values were between 0.1 Gy and 73 Gy with a median of around 1.6 Gy. The values are documented in the data base [3].

Most instruments were subject to more than one scan resulting in a higher overall dose. To facilitate an assessment of the dose that can be expected in future scans, the overall dose absorbed by each instrument was determined und plotted in a histogram (Figure 2). Instruments holding several organological questions were investigated more thoroughly and thus contribute higher values. The median dose per instrument is 7 Gy. For comparison, the dose absorbed due to natural radiation amounts to approximately 2.1 mGy per year.

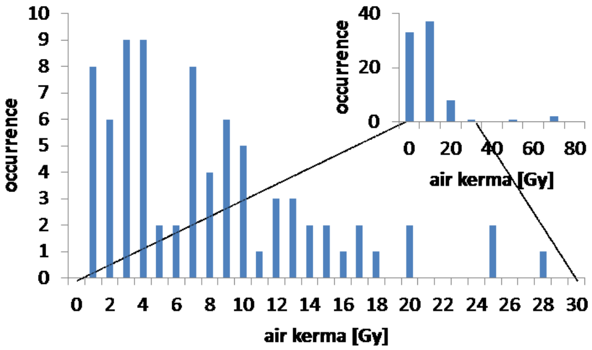

Figure 2: Histogram of the dose absorbed by instruments during the MUSICES project.

As the atomic nucleus is untouched by X-ray radiation, a radio carbon dating is still possible after X-ray testing. However, results of other methods which are based on an interaction with the electron shell (e.g. thermoluminescence), could be influenced [4].

It was not possible to carry out systematic investigations into the possible damaging effects of measuring campaigns within the framework of the MUSICES-project. However, the applied radiation dose for each measurement was determined (see section 5.5) and recorded in the metadata structure. No visible changes to varnish, paint, wood, glass or any other materials were observed.

4.5 Collecting of the Object Data Relevant to Measuring

Data about the materials and sizes are decisive for planning the measuring duration, calculating the costs incurred and judging whether the project is feasible. Based on a description of the object, measuring parameters and the optimum positioning of the object in the beam path can be determined. Therefore, this information should be provided during the initial communication with the testing institute and ideally should comprise the following:

Figure 3: Example for Total-Object Dimensions and Dimensions for Subarea Measurements (VOI)

- A list of all materials including information about the location in the object. As a rule of thumb, when the density of a material is larger than 4 g/cm^3 (metals) also small parts should be mentioned. Special attention should be payed to lead (also in white lead). The metals aluminium, brass and lead should be mentioned separately as they differ in X-ray attenuation. While small decorative inlays of low density materials, like tortoise shell, are not highly relevant, small metallic nails should be mentioned if possible. With respect to X-ray physics, an object consisting of paper, cloth, pine and beech is regarded as made of one material. Also brass and German silver are similar.
- Dimensions: Determine the size of the bounding box (or a bounding cylinder) around the object including the mounting.
- Wall thicknesses, material thicknesses – also approximately if these cannot be measured using conventional methods.
- Extended planar structures: If the object contains extended planar structures, their extensions and locations should be specified. Examples are the flat back of a guitar or the plane formed by metallic strings in a grand piano.
- Maximum transmitted length: Set up the instrument in the orientation it will assume during the measurement. For each material that contributes considerably to X-ray attenuation, find the largest distance that a ray can travel through this material. For instance, for a guitar with a flat back this is not the thickness of the ribs, but the width of the back.
- Variations in object geometry (shape and density): If the overall shape of an instrument varies, more detailed measures are required additionally. For a crumhorn, for instance, the dimensions of the straight tube and the lower bend

should be provided. Also for a double bass it can be useful to determine the size of the corpus and the neck. Locations, where the density differs strongly from the rest of the instrument, such as the area of the valves in a trumpet, should be indicated.

- Information about possibility of disassembly and if necessary about removable parts.
- Stability of the object: If an object is not stable and can also not be stabilized by the mounting system, this should be communicated to the operator of the CT facility. Cases in which parts of an object could change their position with respect to other parts during one scan or between two scans, for instance when manipulating the object position in the mounting system, should be indicated. Examples are partially loose joints of woodwind instruments or the keys in a keyboard instrument.
- Weight: The weight of the object including the mounting should be provided especially for heavier objects like pianos.
- For sub volume measuring (VOI, see section 4.3) the dimensions of the section and its exact position on the object (Figure 3)
- Basic data from the museum such as designation, inventory number, manufacturer, date and place of manufacture, owner/proprietor.
- Brief description (shape and function)
- Photo of the complete object
- For subarea measurements: Photos of the requested areas

An example of an object description including data relevant to X-ray testing can be found in chapter 19.

4.6 Assembly Planning

Using the object description the CT-system operator can plan the preferred position of the object (standing, lying, tilted) in the beam path. This and three other criteria determine the assembly planning.

A mounting system should

- be stable, i.e. the object must be firmly fixed. If it vibrates or oscillates during measuring, image quality will be impaired. Loose elements (keys, cloths or bands) should be fixed during the measuring duration,
- be designed so that as little as possible additional material is brought into the beam path,
- be as small as possible. Mounting materials can increase the total measuring diameter and thus increase the total measuring time as well as reducing the resolution due to a lower magnification.

The following recommendation is valid for mounting- and packing material:

- pressure stability
- preferably low density
- Mounting materials in direct contact with the object should not be made of the same material as the object and should be of a different density to enable a

clear identification and differentiation of the material characteristics on the X-ray images.

- No metals, if necessary aluminium can be used.

4.7 Mounting of the Object

A trial mounting in the museum is strongly recommended. Practical instructions for this as well as corresponding documentation of a multifunctional mounting system can be found in section 11. The trial set-up should be documented with photos, the set-up dimensions recorded and this information passed on to the X-ray technician. To this end, the horizontal distance between the rotational axis and the point of the object and mounting furthest away from it must be determined. This value multiplied by a factor of two is the diameter of the setup. Besides the possible magnification it also determines the minimum distance between object and X-ray source and detector that can be realized without causing a crash. These dimensions are completed with the height of the total set-up.

4.8 Transport

For transport purposes the instrument must be packed securely and climate-stable in compliance with conservation guidelines. The taking out of corresponding insurance to cover the duration of the complete measuring campaign including transport times is strongly recommended.

5 CT-Measuring

5.1 Climate

During transport and the total duration of the measuring campaign the climate should be documented constantly (Figure 4) and if necessary regulated to prevent climate-induced damage such as cracks in wood caused by dryness For this purpose wooden objects can be packed with sealed polyethylene foil together witch preconditioned moisture regulating silica gel-boxes[17] and/or by using air humidifiers in the CT-system. To further ensure climate-regulatory measures the seasonal climatic conditions can also be taken into consideration when planning the measuring campaign (wooden objects in summer, metal objects in winter).

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[17] During the planning it has to be considered that this can increase the dimensions of the whole assembly.

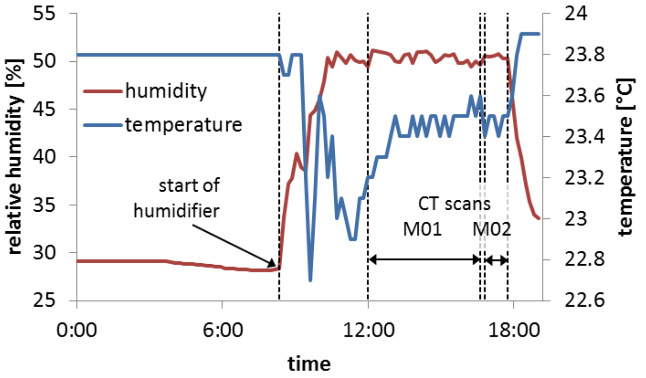

Figure 4: Climate protocol of a CT-measuring chamber. For the measurements M01 and M02 of musical instruments the relative humidity (red) was regulated to the required conservational value of approx. 50 % using humidifier units.

5.2 Set-Up

The object is mounted in the CT-system based on the mounting trial carried out previously in the museum. It is advisable to have additional mounting material available to be able to react flexibly if modifications are necessary.

When the measuring set-up in the CT-system is completed, this should also be documented with photographs.

Before measuring is started the configuration of the system and if necessary the travel paths must be checked to eliminate the risk of a collision between parts of the object and parts of the X-ray unit. This step must be monitored with particular care. If a walk-in CT-system is being used, the previous step can be carried out according to four-eyes-principle: After set-up has been completed, the person responsible for the test object observes movement next to the set-up and communicates via telephone with the X-ray technician at the control panel outside the measuring chamber. For more details also see chapter 12.

5.3 Items to Be Scanned with the Object

If one aim of the CT is to identify materials or to determine the density of a part of the instrument, it is useful to place reference samples in the CT. For instance, to determine the density of the maple back of a violin, wooden samples with different known densities should be scanned with the instrument (see also section 15.2).

One recurrent aim of CTs of historical musical instruments is to measure various dimensions like the thickness of the top plate of a stringed instrument or the diameter of a bore in a wind instrument. It is thus useful to add a calibrated scale to the scanned volume. Ball bars are suitable for this purpose. They consist of two or three balls of ceramics or ruby, which are connected by a carbon fibre bar (Figure 5). The distance between the balls is known. A ball bar should be placed close to the object to be scanned, but not in contact with it. It should not be attached to locations, where artefacts, for instance from metal parts or due to a large cone beam angle, are expected. Furthermore, it should not increase the dimensions of the setup.

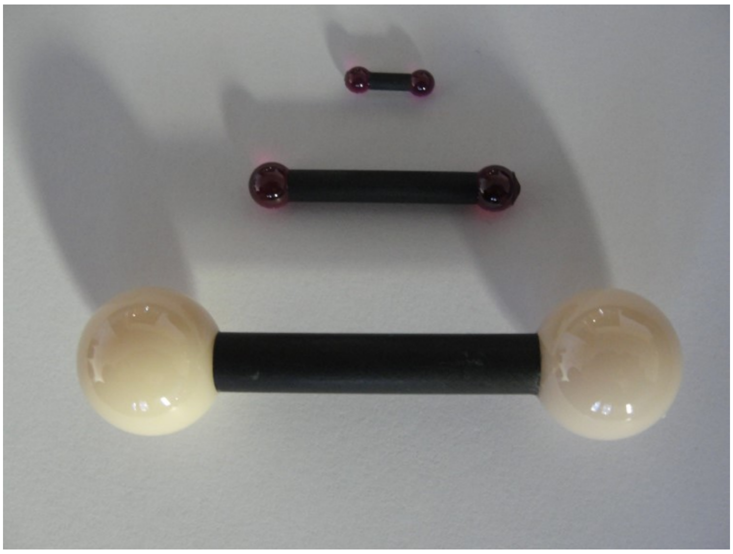

Figure 5: Examples of ball bars that can be used as calibrated scales.

Depending on the organological question, also other image quality indicators might be useful. For instance, when looking for cavities in brass instruments duplex wires can be used to quantify spatial resolution.

5.4 Vertical Combination of CT Scans

When the vertical extension of an object cannot be covered in one scan, it is possible to stack several measurements. Scans can be performed at well-defined vertical positions that allow concatenating the reconstructed volumes. Alternatively an overlap of the volumes can be used for a later registration of the volumes. When objects are too long for the CT facility to be used, it can be considered whether they should be turned upside-down to scan the upper and the lower end. This increases the maximum length that can be scanned by nearly a factor of two. In this case an overlap is needed for registration.

If a registration has to be done it should be checked whether the overlap region of the object contains suitable structures for this procedure. It should be taken into account that this might not be the case for metal structures if they cause strong artefacts. If the object itself does not provide suitable structures, they have to be added. A combination of plastic beads embedded in Ethafoam® and mounted to the object has proven to be beneficial for this purpose. If the object is moved with respect to the mounting between two scans, it has to be ensured that the structures are fixed to the object, not to the mounting.

Assembling two reconstructed volumes can cause a visible transition between them. This transition should not be at a position where it could hamper answering any organological questions. A clear communication between object owner and CT operator about the places where junctions should be avoided is thus crucial.

5.5 Dosimetry

The dose absorbed by a historic object during a CT scan should be measured and documented. For easy comparison to the dose received due to natural radiation, air kerma is preferred as measurand.

There are different ways to obtain the absorbed dose. During the MUSICES project a simple dose estimation was used. The object was replaced by a dosimeter after the CT scan. After exposing the sensor to radiation with the same X-ray spectrum for some time, the dose absorbed during the scan could be extrapolated. The value obtained in this way corresponds to the dose received by an immobile object located on the axis of rotation in the central beam. In reality, during a CT scan each part of the instrument moves through the cone beam with its position dependent X-ray intensity and is shadowed by other portions of the objects on parts of its trajectory. The dose absorbed by a particular piece of instrument is thus lower than the estimated value.

Therefore, if the dose received by a specific component of the musical instrument is of interest, the dosimeter should be attached close to this component during the scan. In this case a tethered dosimeter might be unsuitable. An alternative could be thermoluminescent dosimeters.

5.6 Documentation

5.6.1 Check Lists

It is recommended that the complete working coordination and the course of movement of the object are systematically supported by using check lists (see chapter 20).

5.6.2 Photos

For the collection of object data relevant to measuring as well as for documentation purposes photographs must be taken of the trial set-up as well as of the object mounted in the CT-system. These photos must be saved and annotated with metadata, so that they can be permanently and unequivocally assigned to the corresponding measuring process. Ideally these should be permanently assigned to the scan data using a media administration system or a suitably configured virtual research environment such as WissKI (see section 5.7). As there is not yet a metadata standard for photographic documentation, a recommendation cannot be given for this. For the actual photos the following key values are recommended: Tiff, 24 Bit sRGB. The data size complies with the existing technical possibilities with the proviso that the complete set-up and all the relevant details, if necessary as detailed photos, must be clearly recognizable.

5.7 Collecting Metadata

The structured recording and permanent saving of metadata is the basis of the traceability of the measuring procedure and not least the prerequisite for a sustainable research infrastructure. Metadata provide information about the object and the framework conditions of a measurement, they also contain information about the technical equipment used, about the measuring parameters as well as the reconstruction method. Information regarding the data recorded can be found in the metadata model (chapters 8 and 9). There are several possibilities for saving and organization. In many applications used in the field of medicine and in several proprietary industrial systems some metadata are entered automatically in the header of the data set. However, these are often incomplete. All data necessary in the cultural sector can be recorded in a list and archived together with the data set.[18] If a database is being used to document the measurements 3D-CT-data sets can be linked to the related metadata. The consistent naming of the data sets (see chapter 17) is a precondition for guaranteeing an unambiguous assignment of the metadata to a data set. For this purpose, in the MUSICES-project a database was developed, which assigned all the necessary information to the corresponding data set. The open-source-software WissKI (www.Wiss-KI.eu) used is available in Open Access.

5.8 Data Processing

5.8.1 Data Format

CT-data can be saved and processed in several different formats. Many processing programs use proprietary storage formats most of which can only be opened using fee-based software. Therefore, for storage and processing the use of either the DICOM-format (Digital Imaging and Communications in Medicine)[19] used in the field of medicine or as an alternative the DICONDE-format (Digital Imaging and Communication in Nondestructive Evaluation) which is based on the DICOM is recommended. DICOM is an open standard for storage and exchange of image data. If required the metadata structure can be used and if necessary commercial storage solutions from the field of medicine (e.g. PACS, Picture Archiving and Communication System) can be considered for long term archival storage.

5.8.2 Data Transport

Before measuring takes place, the organization of data transport should be clarified. If measuring is carried out on a system from the field of medicine, the data are usually available immediately on a DVD. As a rule, the reconstruction of data sets requires more time on an industrial system and significantly larger volumes of data are generated. For this reason, the method of data transfer should be agreed upon before testing: e.g. physical transport per mass storage device or transmission by an FTP-server. To ensure sustainable use of the data (new reconstruction algorithms) not only the reconstructions but also the projections should be archived by the customer in their original data format (raw format).

5.8.3 Data Volume and Hardware

The size of a reconstructed CT-data set depends amongst other things on the volume of the object, taking into account the mounting, and the bit-depth. This means that CT-data sets can be very large which makes transport and processing difficult. The size of a high image quality scan data-set for a violin can be as high as 40 GB or more, the size of a scan of a tenor recorder around 8 GB. Before measuring, a check must be carried out to ensure that the available computer is sufficiently able to process the data sets in particular with regard to the working memory.

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[18] During the MUSICES-project it was proved to be of use to print the metadata tables out and to note interesting information on them during the measuring process.
[19] http://www.dicomstandard.org (as consulted online on 2 March 2018)

5.8.4 Software

If the reconstructions are saved in DICOM-format then many freely available software products can be used to view and process them. However, the range of functions of this software can be limited and often only allows viewing of the scan and simple operations such as measuring of distances. For more complex processing methods it is advisable to purchase special software – which can be very costly –or to consult an institution which possesses such equipment.[20]

5.8.5 File Names, Structure of Folder and Archiving

When choosing a name for files, it is recommended to adhere to the scheme depicted in chapter 17. The structure of the folder should be created in a clear and sustainably comprehensible manner und established security mechanisms must be installed.

6 Evaluation of Data

6.1 Assessment of Image Quality

Technical criteria apply in particular to the assessment of the image quality. If, however such technical procedures for the determination of image quality are not desired and a rapid, simple, visual assessment is preferred, the following criteria can be used as reference points for a rapid evaluation of the image quality:

- Resolution: Is it possible to distinguish small details?
- Noise: Is a clear divide between material and air or between different materials distinguishable?
- Contrast: Is the depiction e.g. the structure of wood sufficiently high-contrast?
- Artefacts: Are there disruptive image errors in the image e.g. close to metal parts? Can homogenous grey values also be seen on homogenous parts?
- Double contours: Are edges and e.g. annual growth rings in wood clearly depicted?
- Surface presentation: Is the 3D-presentation homogenous?
- Mounting: Does the fastening have a disruptive effect in the image?

For a quantitative evaluation of image quality various measures are available. Examples are:

- spatial resolution at high contrast measured using standardised resolution tests [5]
- contrast recognisability between attenuation coefficients in different materials
- signal to noise ratio (SNR) within a representative region of interest in the reconstructed volume
- homogeneity and isotropy of the attenuation coefficients in the reconstructed volume
- probing error form measured using calibrated spheres to describe distortions [6, 7]

Standardised procedures exist for the determination of some measures.

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[20] In the framework of the MUSICES-project amongst others the free software solutions „Image J“ for Windows^{TM}-systems „Horos“ for iOS^{TM}-systems were used. However this does is not an acquisition recommendation. Further freely available viewers from the field of medicine with strengths in various categories e.g. in 3D-presentation can be obtained from e.g. idoimaging.com.

6.2 Answering the Scientific Question

CT-measurements are requested to answer certain questions about an object (see also section 4.2). Therefore, a record should be made in the metadata structure as to whether it was possible to collect the desired information through the measurement.

6.3 Preparation of Tomograms

Stationary tomograms can give a first impression of the information content of a data set. By specifying the tomograph levels the aim is a comparability of the quality of data sets. In addition to this, like other two-dimensional images, they can provide information in the documentation system of the museum, in its website or in the MIMO-portal (www.mimo-international.com) and ultimately in Europeana (www.europeana.eu) about the existence of a 3D-scan. Therefore, their preparation is strongly recommended after the CT-measuring has been carried out. Details regarding the preparation of tomograms can be found in chapter 18.

Technical Guidelines

7 The Choice of Technical Parameters

Musical instruments have various properties that influence the choice of the CT parameters (Figure 6). Their shape may be elongated (flutes) or board-like (zither), they may consist of materials with low density or of metal and can even contain parts, which are at risk from radiation damage. At the same time, there are many CT parameters that have to be chosen, like the energy of the X-rays to be used or the trajectory of the scan.

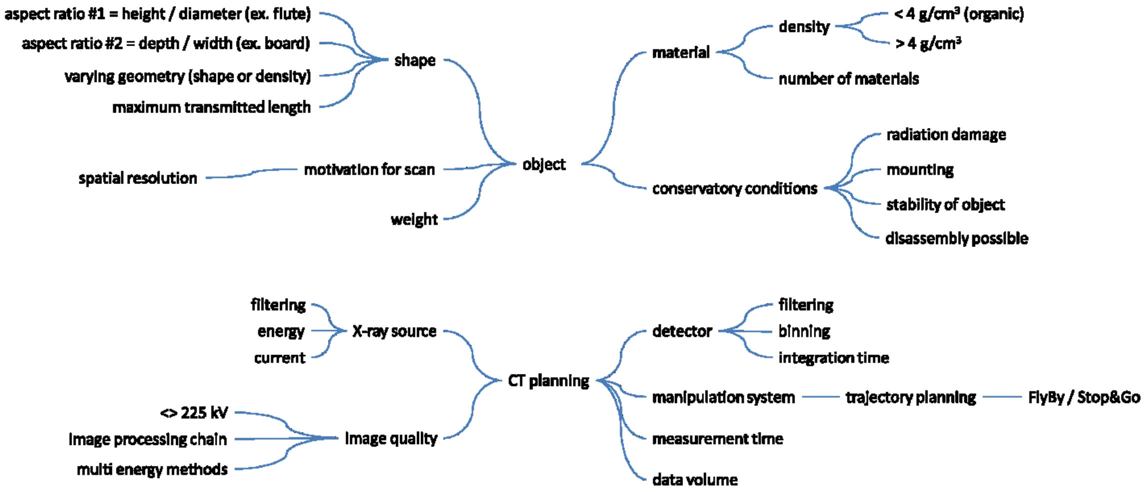

Figure 6: Properties of an object to be scanned, which influence CT conditions and scan parameters that have to be considered.

To identify suitable CT parameters, several historical musical instruments were scanned multiple times under varying conditions for comparative studies. In other cases contemporary instruments were used for this purpose. However, in most cases different instruments with similar properties were used to compare the effect of different CT parameters. The results of these comparisons are presented in chapter 14.

A database available on the MUSICES homepage [3] documents the parameters of all scans performed during the project. When planning a CT of an object, the database should be checked for CTs of a similar instrument, i.e. with similar form and made of materials with comparable X-ray attenuation. In this sense, a mute cornett is similar to a recorder and in some cases a guitar might resemble a viola da gamba. The database provides an evaluation of many of the scans. Also the reconstructed volume data sets can be found online [3]. If a documented scan allows the conclusion that a reconstruction of similar quality would answer the given question, the same parameters can be used for the CT.

For objects different from those in the database, a set of concise guidelines is provided in the following sections that should lead to useful CT conditions. For illustrations of the influence of the parameters on the resulting volume data the reader is referred to later chapters. The recommendations are based on the experience with the 251 scans of 105 instruments that were carried out in the MUSICES project. They apply not only to (historical) musical instruments, but may also be used for other objects from the field of cultural heritage.

7.1 The Communication Matrix

As historical objects are typically sensitive they should not remain in a CT facility longer than necessary due to climatic conditions. Also the absorbed dose should be kept as low as possible. It is therefore recommended to avoid trial and error experiments. Instead, as many parameters as possible should be defined based on information provided on the object before placing it into the CT machine. For instance, the focus object distance (FOD) and focus detector distance (FDD) can be calculated from the object diameter and the desired spatial resolution. Information regarding the present materials can be used to identify suitable tube voltage and prefilters.

The matrix in Table 1 lists information the operator of a CT machine has to request from a person interested in a scan of an instrument. It shows which object properties influence the selection of scan parameters. The instrument owner can thus understand why particular information is interesting for the operator and what consequences may arise from the given answers. The table thus demonstrates the necessity of communication between both parties. It also illustrates the complexity of the issue. It is not possible, for instance, to define an X-ray voltage for all board-like objects, because the X-ray energy is also influenced by several other object properties like density or the fear for radiation damage. Therefore, the following sections give guidelines for the selection of the parameters given in the rows depending on the answers given to the questions in the columns of Table 1.

Table 1: Communication matrix for facilitating the correspondence between object owner and operator of the CT facility. The markers indicate which object properties have an influence on the CT parameters.

	maximum transmitted length	density < > 4 g/cm^3	spatial resolution (→ question)	number of materials > 1	aspect ratio #1 (height / diameter, ex. flute)	extended planar structures? (ex. board)	varying object geometry (density as well as shape)	disassembly possible to reduce dimensions?	weight	mounting	stability of object	radiation damage
< > 225 keV	x	x	x	x		x	x	x				x
X-ray energy	x	x	x	x		x	x	x				x
source filtering	x	x	x	x		x	x	x				x
tube current	x	x	x	x		x	x	x				x
multi energy methods				x			x				x	x
FlyBy / Stop&Go			x	x						x	x	x
trajectory planning	x	x	x	x	x	x	x	x	x	x	x	x
image processing chain	x	x		x	x	x	x	x				
integration time (averaging, gain ...)	x	x	x	x		x	x					x
measurement time	x	x	x	x	x		x		x		x	x
data volume			x	x			x	x				

When answering questions about the instrument, some general assumptions are made:

- The mounting is stable enough to allow reproducible scans. It is not made of materials that cause artefacts. Further, it does not significantly increase the diameter of the object. Should the last point not be fulfilled, the diameter of object and mounting together will determine the scan parameters and are thus communicated to the CT operator.
- Components, especially those of metal, that are not relevant for answering the organological question are removed if it is possible from a conservatory point of view. This means, the given information concerns the object in the state in which it is scanned.
- All conservatory aspects, like additional packaging for stabilisation of climatic conditions, were taken into account when submitting information to the CT operator.
- When requesting a specific spatial resolution, it should be taken into account that the resolution depends on many parameters [8]. The discussion of this matter is not the scope of these recommendations. Here, the term spatial resolution will be used equivalently to the voxel size of the reconstruction, which is determined by the applied magnification

  $$M = \frac{FDD}{FOD} \tag{7.1}$$

  The useful magnification is given by

  $$M_{\mathrm{opt}} = \frac{p}{d} + 1 \tag{7.2}$$

  with p being the size of a detector pixel and d the diameter of the focal spot. No higher magnification than M_{opt} will be used.

There are also some assumptions regarding the CT facility:

- Gain and offset images are made and applied to all projections.
- Detector afterglow images are avoided.

7.1.1 X-Ray Energy, <> 225 keV

The X-Ray energy is determined by the applied tube voltage U. The choice of the voltage determines the dominating attenuation mechanism. While at low energies the photoeffect dominates, the Compton effect dominates for higher kV [8]. The transition energy between both regimes depends on the material. A voltage of 225 kV, a typical U_{max} for sources, can be considered as a reference. The choice of a suitable energy depends on various object properties:

- Maximum transmitted length and density: For large transmitted lengths or high density (metal) a higher X-ray energy is needed. The tube voltage should be chosen to result in a transmission of 10 % through the parts with highest absorption. A lower transmission increases noise, a higher transmission reduces contrast [9]. For an estimation of the transmission to be expected, the attenuation coefficients from NIST can be used [10]. If the X-ray spectrum emitted by the tube is not known, the effective energy (approximately $e \cdot ⅓ \cdot U_{\mathrm{max}}$) can be used for the calculation. See also the database for suitable values of the tube voltage.

- Spatial resolution: According to equation (7.2), small focal spots are needed when high resolutions are desired. Thus, microfocus sources have to be used, which limits the available X-ray energy.
- Multiple materials: A hard spectrum is preferable for scanning objects with materials of strongly differing density.
- Extended planar structures: If the object contains board like structures, for instance the top and back plates of guitars, the spectrum should be adapted to them even if these boards are thin. As mentioned above, a transmission of 10 % through the parts with strongest attenuation should be pursued.
- Varying object geometry: If the amount of material per volume varies strongly, the spectrum should be chosen hard enough to transmit the parts which contain the most material. For instance, a cornet has much material in its valves, but not so much in the bell.
- Disassembly: The disassembly of an object can result in pieces with decreased transmitted length. In this case, a lower energy can be chosen. However, disassembling an object also allows scans of a cluster of the pieces, which might reduce scan time, but increases the transmitted length and makes higher energy necessary.
- Radiation damage: For some materials, like gem stones, radiation damage can occur [11, 12]. Choose the X-ray spectrum accordingly, i.e. preferably hard.

7.1.2 Filtering of the Source

Placing a filter in front of the source makes the spectrum harder which reduces beam hardening artefacts. So in general the same rules apply as in section 7.1.1. However, a filter also decreases the detected intensity and thus increases scan time. Especially when using microfocus tubes with low photon flux, using filters might not be economically.

7.1.3 Tube Current

The tube current has to be adapted to the X-ray spectrum and the exposure time to ensure a sufficient signal on the detector. Typically, the unattenuated intensity should be about 70 % of the detectors dynamic range. For a 16 bit detector this corresponds to approximately 46000 grey values. When the chosen current is too high, the correlation between intensity and detected signal ceases to be linear [13]. Further, overexposure of the detector is risked. Choosing the current too low increases noise.

Raising the current at fixed tube voltage increases the tube power and thus the focal spot. As a rule of thumb, an increase of the focal spot diameter by 1 µm when increasing the tube power by 1 W can be assumed [13]. Accordingly, eq. (7.2) can set a limit to the possible tube current if a high spatial resolution is needed. Also the maximum permitted tube power has to be taken into account.

If the unattenuated intensity that can be reached with the maximum available current is too low, the exposure time has to be increased (see 7.1.8).

7.1.4 Multi Energy Methods

In some cases it can be useful to perform two or more scans with different X-ray spectra. These scans have to be combined afterwards to improve the image quality and thus increase post-processing time. Whether it is of advantage to choose such methods depends on different aspects of an object:

- Multiple materials: It is advisable to use multi energy methods for objects consisting of multiple materials with different X-ray attenuation properties, like wood and metal. The spectra should be chosen as different from each other as possible while still being hard enough to transmit the object [14]. See also sections 14.3, 15.1 and reference [15].
- Varying object geometry: Multi energy methods are recommendable for objects with strong variations of the amount of material per volume.
- Stability of object: Multi energy methods require multiple scans of an object, which increases the probability for damage. Further, the object has to be in the same state for every scan to allow a subsequent combination of the CTs. Objects that are fragile and potentially deform during a scan are not deemed suitable for these methods. If multiple scans shall still be performed, special care has to be taken to provide the necessary stability through a suitable mounting. These restrictions do not apply if both scans can be performed simultaneously with energy sensitive detectors or dual source/dual detector setups [16].
- Radiation damage: Due to the increased absorbed dose, multiple scans of radiation sensitive objects should be avoided.

7.1.5 FlyBy or Stop&Go

A CT can be performed in FlyBy or Stop&Go mode. In FlyBy, the projections are recorded while the object rotates. This method is faster but can lead to motion artefacts in the reconstruction that increase with distance from the axis of rotation. In a Stop&Go scan, the object stands still while the projection is recorded. This avoids motion artefacts and allows, for instance, to increase the SNR by averaging several projections, but it increases measurement time. There are conditions, where one of these methods should be preferred:

- Spatial resolution: If a high resolution is desired, Stop&Go should be chosen.
- Multiple materials: If multiple energy methods are used, Stop&Go should be used.
- Mounting: When the mounting cannot provide sufficient stability, for instance when dealing with large and heavy instruments like cembalos, FlyBy is of advantage since it reduces vibrations of the object.
- Stability of object: For fragile objects FlyBy is of advantage since it reduces vibrations.
- Radiation damage: FlyBy reduces the exposure to radiation and has to be preferred for radiation sensitive objects.

7.1.6 Trajectory Planning

The planning of a trajectory includes the movement of object, source and detector during the scan as well as the positioning of the object on the rotary table. For objects with complex shape an optimization of the trajectory by simulations can be of advantage [17]. This section provides a concise collection of recommendations. For more detailed examples on the influence of the trajectory on image quality see chapter 13. A good trajectory depends on several parameters:

- Maximum transmitted length and density: Especially for high density materials, the object should be positioned on the rotary table in an orientation that minimizes the transmitted length.
- Spatial resolution: When high resolution is demanded, helical scans are preferred over circular scans. For some objects it might be possible to find an orientation that reduces the diameter and therefore allows a higher magnification. If the diameter restricts the possible magnification, a scan with displaced detector is possible (see section 13.2). For even larger diameters measurement field extension (MFE) can be used. This increases the measurement time considerably. Another possibility is the scan of a volume of interest instead of the whole diameter. In this case handling of truncated projections is necessary.
- Multiple materials: Artefacts caused by the high density parts can be reduced through a skilful positioning of the object. In some cases, it is also possible to shift them to less interesting parts of the instrument, where they do not hinder the interpretation of the reconstructed volume data.
- Aspect ratio #1: Elongated objects like flutes or violins should be positioned with the elongated axis parallel to the axis of rotation. This balances the transmitted length for all projections. Helical trajectories are beneficial. Also the vertical stacking of measurements is possible. However, this requires the later combination of the reconstructed volumes.
- Extended planar structures: For CTs of instruments with planar structures it should be attempted to find an orientation that reduces the transmitted length. For very large objects (grand pianos, cembalos) that cannot be rotated by 360°, limited angle scans have to be considered. For planar structures laminography can also be an option (see 13.4 and [18]).
- Varying object geometry: When the amount of (dense) material varies within an object, as with brass instruments, it should be tried to find an orientation that minimizes the transmitted length. Objects with variable shape (crumhorn, viola da gamba), can be scanned in sections with trajectories adapted to different regions. For instance, corpus and neck of a viola da gamba can be scanned using MFE and helical scan, respectively. For details see also section 13.3.
- Disassembly: For instruments that can be disassembled, trajectories can be optimized for each part. It is also possible to arrange all parts into a cluster and find a trajectory that saves scan time.
- Weight: For heavy objects the centre of gravity should be kept close to the axis of rotation.
- Mounting: When the mounting is not able to stabilize a long object sufficiently, it is preferable to position the part to be scanned close to the rotary table. So if a long object is to be scanned in its whole length, it should be turned upside down after scanning half of its length if this is passable from a conservatory point of view.
- Radiation damage: Minimizing the transmitted length can reduce the needed energy and scan time. It can also help to record a larger part of the object with one scan. A good trajectory can thus reduce the absorbed dose.

7.1.7 Image Processing Chain

The processing after the measurement has to be considered before the CT. In some cases special requirements or additional scans are needed.

- Maximum transmitted length and density: When transmitted lengths are long or densities high, beam hardening and scattering have to be corrected. Depending on the chosen procedure, this might require additional calibration scans.
- Multiple materials: While beam hardening correction is simple for mono-material objects, it is difficult for multiple materials. If multi energy methods are used to improve image quality, the scans have to be combined. Some methods require additional calibration measurements for this purpose. Also the increased demand of computational resources (memory, time…) should be taken into account.
- Aspect ratio #1: When objects are too long to be recorded in a single scan, the reconstructed volumes have to be combined afterwards. The vertically displaced scans thus either have to match seamlessly or have to overlap enough to allow registration of the volume.
- Extended planar structures: Extended planar structures can require beam hardening correction. In extreme cases projections from particular directions may not contain useable information due to the large transmitted lengths. It can be considered to exclude these projections from the reconstruction process.
- Variable object geometry: If the trajectory has been adapted to the different regions of an instrument as suggested in section 7.1.6, the reconstructed volumes have to be combined.

7.1.8 Integration Time

The integration time and the detector gain have to be chosen according to the X-ray spectrum and the tube current. Therefore, if a sufficient signal, as defined in section 7.1.3, cannot be realized by increasing the current, the integration time has to be raised. However, the measurement time should be kept short enough to ensure the stability of the CT facility during the scan. This may mean that a smaller than optimal intensity has to be accepted.

When a high spatial resolution is required, high integration times are expected because small detector pixels and a microfocus source with low photon flux are needed. It is also of advantage to increase the number of averaged projections to improve the SNR.

7.1.9 Measurement Time

It is desired to keep the overall scan time as low as possible for conservatory and economic reasons. However, several conditions increase the required time:

- Maximum transmitted length and density: When transmitted lengths are long or densities high, long integration times and averaging of projections is needed to achieve a good SNR. Also potentially used prefilters make longer integration times necessary. The measurement time will thus be long.
- Spatial resolution: A high spatial resolution requires long exposure times and a large number of projections per 360°. This leads to long measurement times as well.
- Multiple materials: If multiple energy methods are used, the measurement time will be increased.
- Aspect ratio #1: Scanning an elongated object using a helical trajectory can decrease the measurement time in comparison to the vertical stacking of scans with circular trajectories.

- Variable object geometry: Trajectories adapted to different parts of an object as suggested in section 7.1.6 can save measurement time.
- Weight: For very heavy objects, controlling the object manipulation axis can be more time consuming.
- Stability of object: Reducing the measurement time lowers possible influences on fragile objects. It also reduces the risk, that the instability of the object deteriorates the scan.
- Radiation damage: The measurement time should be kept as low as possible for radiation sensitive objects.

7.1.10 Data Volume

The scan parameters influence the volume of reconstructed data that has to be handled. It is desired to keep it low. Several aspects have an influence:

- Spatial resolution: High spatial resolution leads to a large amount of data. Dividing the voxel size by a factor of two increases the data volume by a factor of eight.
- Multiple materials: The use of multiple energy methods increases the data volume.
- Variable object geometry: Trajectories adapted to different parts of an object as suggested in section 7.1.6 reduce the amount of data because less empty volume is scanned.
- Disassembly: When an object is disassembled and the parts are scanned separately, the data volume is increased. However, if the pieces are collected into a cluster that allows to scan a larger part of the object with fewer measurements, the data volume can be decreased.

7.2 Further Considerations

7.2.1 Number of Recorded Projections

The number of recorded projections is also an important factor influencing the quality of the reconstruction. It is, however, not depending on the object properties. Thus, it was not mentioned in the matrix Table 1.

It is found from sampling theory that the number of projections should approximately equal the number of pixels the object (including the mounting) covers on the detector in lateral direction [8]. Accordingly, when virtually increasing the detector width by MFE, the number of projections per 360° has to be increased too.

In general, a large number of projections should be used when a high spatial resolution is required especially for structures far from the axis of rotation. However, recording more projections means longer scan times. To provide an indication for the influence of the number of projections on the image quality, some examples are presented in section 14.1.

7.2.2 On the Relevance of Communication

The statements made in this chapter demonstrate that there are several object properties or demands that can lead to contradictions from an X-ray physics point of view. For instance:

- The material composition might require a high energy. The facility that can provide the hard X-ray spectrum might, however, not allow the desired voxel size.

- The operator of a CT facility might suggest a way to mount the object that reduces the transmitted length or decreases a particular dimension of the object in an attempt to reduce scan time. This suggestion might, however, be rejected by the object owner due to conservatory reasons.

In such cases the communication between object owner and CT operator is important to find out what the priorities are. Ideally, an agreement should be found before further planning of the scan. In some cases more than one CT under different conditions might be required to facilitate an answer to all organological questions.

Metadata Model

8 Introduction

Examining musical instruments and other cultural heritage assets through 3D-CT creates large amounts of metadata that must be stored in a sustainable way, as it is of fundamental importance for the understanding and future research that is based on the generated data. The model proposed describes relevant metadata for CT examination of cultural heritage.

In this context, the focus is on the examination of musical instruments using industrial X-ray-CT. However, the model can be transferred to the examination of other objects of cultural heritage using other irradiation methods (neutron CT, medical CT).

The acquisition of metadata can be carried out in different ways. In some of the data formats used in 3D-imaging the storage of metadata is already implemented. In the medical format DICOM (Digital Imaging and Communications in Medicine) some acquisition fields are already provided in the structure of the header and can be filled automatically in some cases. To ensure a persistent storage of metadata of cultural objects a more detailed structure is necessary. The data can be acquired using e.g. spread sheets, tables or a data base. All metadata has to be connected to the object and the corresponding 3D-data set. Therefore, a consistent continuous naming of the object and the 3D-data set using an identifier is essential (see also chapter 17).

8.1 Metadata Structure

The metadata structure corresponds to the connections within the work flow. Thereby the single sections are divided according to the operations performed by the different institutions or persons. Hereby a chain of activities (work areas) is created that reflects the actual workflow.

8.2 Setup of the Metadata Structure Based on the Workflow

From the perspective of metadata acquisition the work areas of a 3D-CT scan of an object can be grouped into three main sections:

- Object description: The first step concerns the planning of the measurement (see chapter 4) and includes the formulation of a scientific issue, the acquisition of the basis data of the object (size, material, weight, etc.) and the determination of the conservational requirements.
- Measurement: The actual CT-scan follows (see chapter 5). Here the metadata concerning the technical parameters of the X-ray facility and the applied settings (current, voltage, exposure time, etc.) as well as the organizational details of the scanning process are recorded.
- Reconstruction and Evaluation: After scanning the recorded images are reconstructed using appropriate algorithms in order to provide the final 3D-vizualisation. In this third step all metadata is recorded that concerns the generation of the 3D-data set and the evaluation of the whole workflow (see chapter 6).

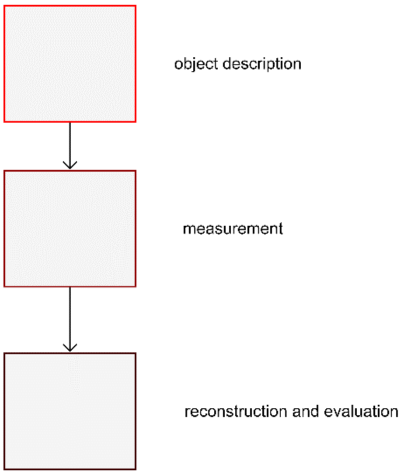

Figure 7: Basic structure of a workflow

The single acquisition areas of the three work areas are represented by the metadata model and are connected to each other (Figure 7). These relations can be represented in an accordingly structured database displaying the workflow of the CT-measurement.

For every object a dedicated three-part workflow is created, consisting of “object description”, “measurement”, and “reconstruction and evaluation”. The chronology is given in Figure 7.

Each of the work areas is displayed through several entry forms which are linked by a semantic structure. At content level, they are connected by defined identifiers (workflow numbers).

Apart from this basic structure further possible workflows exist:

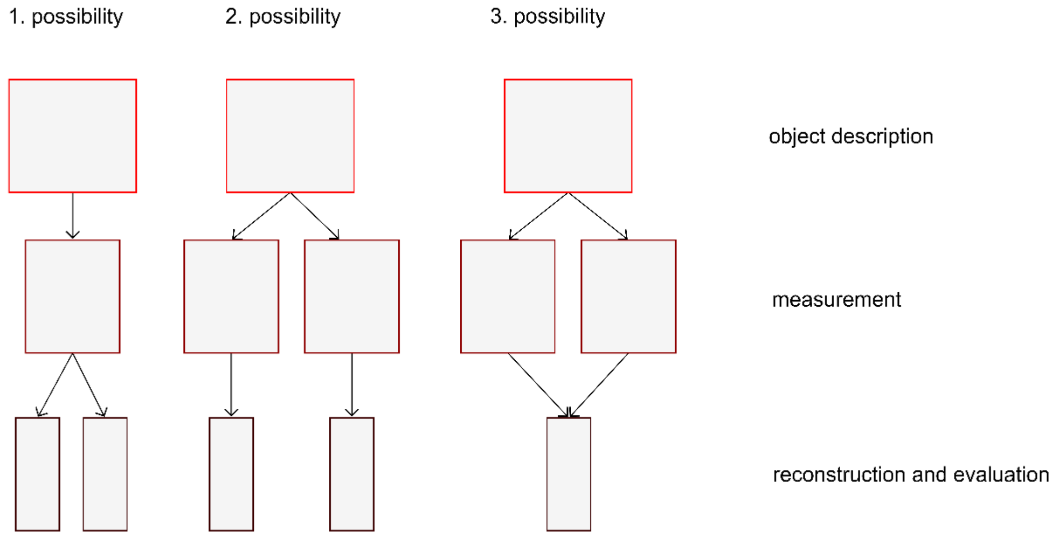

Figure 8: Examples for possible workflows

In the simplest case, only one measurement follows the object description and only one reconstruction is made (Figure 7). However, based on an object description and on a single measurement, several reconstructions can be computed with different algorithms (Figure 8) to evaluate their variation (quality, artefacts, calculations, etc.). A tree structure of the workflow is created, which is divided at the end (1st possibility). One object can also be scanned several times. Then, the work area „object description“ is followed by several work areas „measurement“ (2nd possibility). How many measurements of one object are made depends on different factors. Often the scientific issue requires more scans with different goals. The various measurements and reconstructions have to be linked to each other and numbered consecutively. In case a reconstructed data set consists of a combination of several distinct measurements, only the final data set needs to be evaluated (3rd possibility). Further combinations of the sketched options are possible and can be represented by the metadata model.

In case of a cluster measurement, i.e. when several objects are scanned together, the metadata of the single objects are acquired separately. The respective technical parameters for the measurements are then identical in the work area “measurement” for all objects of the cluster.

8.3 Acquisition Areas within the Single Work Areas

All three work areas are split into different acquisition areas. In the following the superordinate structure is explained first and later the single acquisition fields are presented.

8.3.1 Work Area 1: Object Description

The features of the objects, which include relevant information for a CT examination like its materiality and size, are structured in the following acquisition areas:

- object description – identification
- definition of a volume of interest (VOI)
- X-ray-relevant features – entire object or VOI
- conservational requirements
- scientific issue

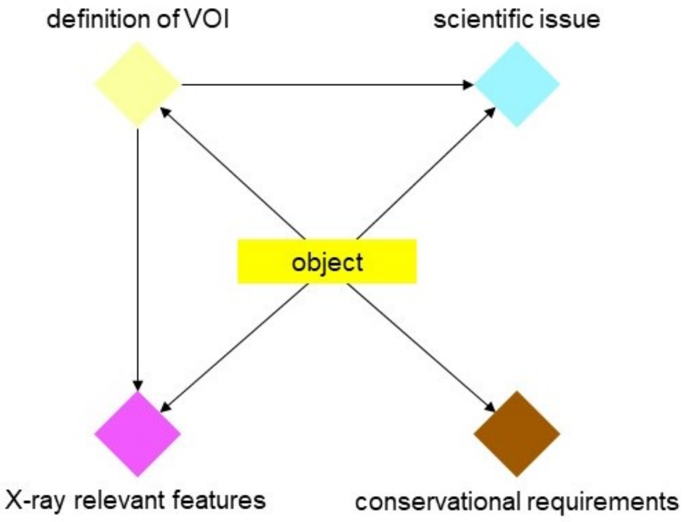

Figure 9: Graphical representation of interdependencies within the work area “object description”

These acquisition areas cover the characteristics that are directly connected to the object (**Fehler! Verweisquelle konnte nicht gefunden werden.**). The area “object description–identification” gives a short overview of the object properties, classification, the owner, the material and the approximate size.

If only a small area and not the whole instrument is to be scanned (or the object and a smaller area with a higher resolution) this will be indicated under „definition of a volume of interest“. The area “X-ray-relevant features” contains more specific information concerning object size, material, wall thicknesses respectively irradiation length, which is relevant for the choice of X-ray parameters of the CT-facility. In the area “conservational requirements” all important conditions can be defined to provide a safe transport, handling and examination of the object. The goal of the examination is outlined in the area “scientific issue” and has essential influence on the technical parameters applied by the CT-operator and finally on the evaluation.

8.3.2 Work Area 2: Measurement

The second work area especially produces metadata concerning the technical parameters of the scan (Figure 10). These are structured in the following acquisition areas:

- documentation of the object measurement
- constellation of the CT-facility (CT-facility, X-ray-detector, X-ray-source)
- documentation of the measurement process
- parameters of the projection data set
- archiving of projections

The chosen CT-facility is equipped with different components. The scan parameters are adjusted according to the requirements based on the object description and the scientific issue. In the group “documentation of the object measurement” organizational information is collected, as: which CT-facility was chosen, when the object was transported, how were the climatic conditions during the scan etc. The particular information on the single components is captured in the group “constellation of the CT-facility”. In case an image quality indicator is used, it is also documented. All technical parameters are collected in the group “parameters of the measurement process”. Here, information on current, voltage, focal spot, exposure time, filter and more data on the setting of the X-ray-facility are recorded. The “documentation of the measurement process” collects all information concerning the applied radiation dose, the person who operated the CT-facility and the size of the projection data set. Finally the storage location and parameters are indicated in the group “archiving of projections”.

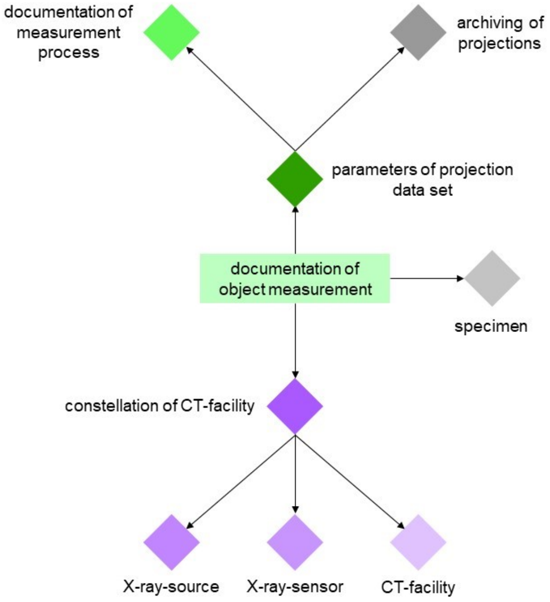

Figure 10: Graphical representation of interdependencies within the work area “measurement”

8.3.3 Work Area 3: Reconstruction and Evaluation

When all measurements of the object are done the single projections have to be computed into a 3D volume data set. All details concerning the reconstruction and the evaluation of the data sets (Figure 11) are recorded in the following categories:

- reconstruction
- post-processed reconstruction
- evaluation and visualization

In the area “reconstruction” all parameters are recorded which are important for the generation of a 3D data set: important corrections, the used reconstruction procedure and information on the achieved spatial resolution. Subsequently, further processing can follow. In order to reduce the data volume, the empty area around the object can be deleted or the data format can be converted. The result of these processes is called “post-processed reconstruction”. Both reconstructions can be evaluated in the third step. Here, it can be recorded if the scientific issue was answered and if the achieved spatial resolution is sufficient. Disturbances or image errors can be reported here.

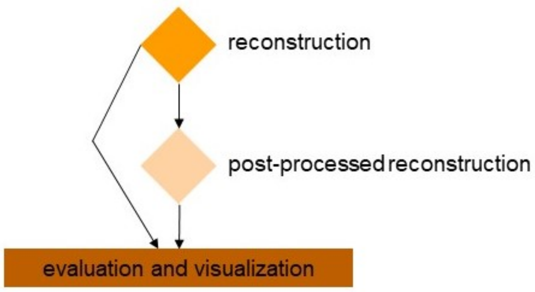

Figure 11: Graphical representation of interdependencies within the work area “reconstruction and evaluation”

8.3.4 Overview of Work Areas

As described above, all three work areas are correlated within in a workflow consisting of several smaller areas (Figure 12):

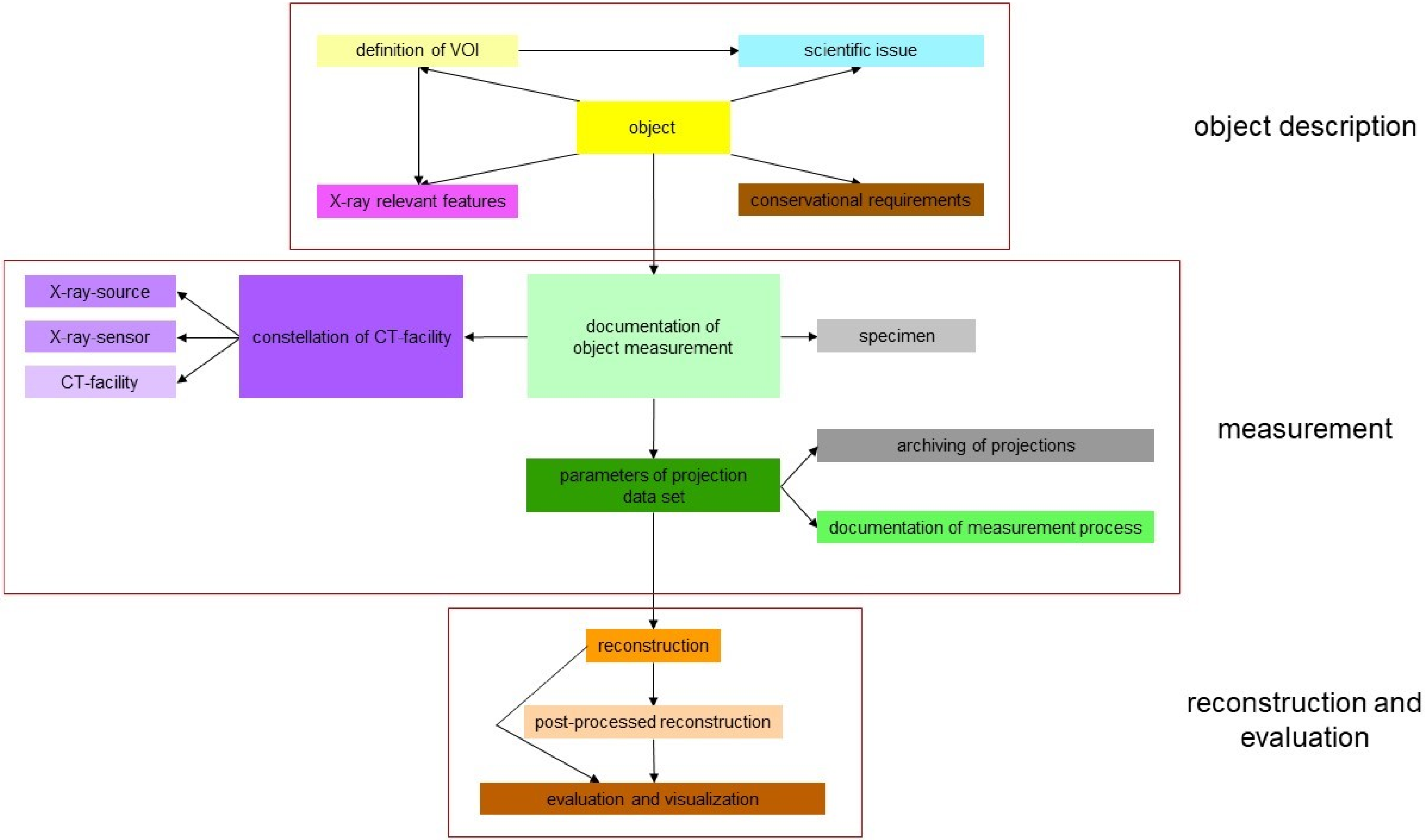

Figure 12: Structure of Work Areas within the Workflow

9 The Acquisition Fields of the Work Areas in Detail

In the following, the metadata which has to be documented is summarized in tables including annotated examples. In relevant cases, the form of the content is explained. An indentation in the table indicates a grouping of a selection of different fields. In the following example (Figure 13) the fields "dimension", "value" and "unit" belong to the group "size" which can be duplicated. The possibility of duplication is shown by the (+)-symbol and can be applied to a single field or a whole group.

Size (+)	←	Dimension	Text	*Height*
	←	Value	Integer (in mm)	*96*
	←	Unit	Text	mm

Figure 13: Example for a group of fields which can be multiplied

In some cases only one of two fields "A" or "B" can be filled (A XOR B). This can be the case e.g. when a measurement is connected either with the whole object or just with a volume of interest. These fields are marked by the symbol "(A↔B)".

Recommendations for entry formats:

- a dot is used to separate decimal floating-point numbers
- a date is written according to the scheme YYYY_MM_DD
- a time is written according to ISO 8601 as hh:mm:ss
- for more information on the generation of work flow numbers and IDs see chapter 17.

Please note: The acquisition fields of the metadata model are representing a pool for a detailed description. The particular fields should be used according to the context of the current measurement campaign.

The presented version of the metadata model can be extended if necessary. For example in the area "X-ray-relevant features" some fields could be added to describe irradiation lengths[21] or different aspect ratios for planar or tubular objects. For special methods which can be useful according to the scientific issue, a more complex correlation of the different workflow IDs are necessary. Examples are:

- the simultaneous association of a measurement or reconstruction with several objects and/or volumes of interest in case of cluster scans
- the computation of reconstructions out of the projections of several object measurements (3rd possibility in Figure 8), e.g. in case of a
  - basis material decomposition (see 15.1 and [19])
  - tomosynthesis of laminography scans with several circles (see section 13.4)

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[21] To determine the irradiated length is not trivial for inexperienced users and is therefore not part of the basis version of the metadata model.

9.1 Acquisition Fields of the Work Area „Object Description“

9.1.1 Object Description - Identification

Name		**Type**	***Example* / Explanation**
Workflownumber		Text	*DNgnm_MI1234*
Object-ID		Text	*DNgnm_MI1234*
Common Name		Text	*box trumpet*
Classification (MIMO_HS)[22]		Text	*321.322-71*
Inventory number		Text	*MI1234*
Owner (Institution)		Text	*Germanisches Nationalmuseum, Nürnberg*
Owner (Person)		Text	*Max Müller*
Proprietor (Institution)		Text	*Germanisches Nationalmuseum, Nürnberg*
Proprietor (Person)		Text	*Max Müller*
Department		Text	*collection of musical instruments*
Manufacture	Maker (+)	Text	*Denner, Jakob*
	Place of manufacture (+)	Text	*Nürnberg*
	Date of manufacture	Text	*1804 or 1744-1755 or around 1900*
	Material (+)	Text	*brass* (Only one material per field, in case of more materials, duplicate fields)
Size (+)	Dimension	Text	*height*
	Value	Integer (in mm)	*96*
	Unit	Text	mm
Attachment (+)		Link	
MIMO		Link	
Literature (+)		Text	

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[22] MIMO-Hornbostel-Sachs-Klassifikation. Cf. www.mimo-international.com bzw. www.mimo-db.eu (6.2.2018).

9.1.2 Definition of a Volume of Interest (VOI)

Name		**Type**	***Example* / Explanation**
Workflownumber		Text	*DNgnm_MI1234*
VOI-ID		Text	*DNgnm_MI1234_VOI6*
Description		Text	*mouthpiece*
Location at the Object		Text	*upper third*
Part of Object (Object-ID)		Text	*DNgnm_MI1234*
Material/Technique	Material (+)	Text	*brass*
	Technique (+)	Text	*casting*
Size (+)	Dimension	Text	*height*
	Value	Integer (in mm)	*96*
	Unit	Text	mm
Picture-URL (+)		Link	

9.1.3 X-Ray-Relevant Features – Entire Object or VOI

Name		**Type**	***Example* / Explanation**
Workflownumber		Text	*DNgnm_MI1234*
Object-ID		Text (A↔B)	*DNgnm_MI1234*
VOI-ID		Text (A↔B)	*DNgnm_MI1234_VOI6*
Technological Description (+)	Shape	Text	*tube, bell, hollow, massive*
	Description of Materials	Text	*…wrapped thread, and covered with leather*
	Other description	Text	*flexible, loose parts, (keys, hammer…)*
Existing scientific examination		Text	*dendrochronology, X-ray images*
Technical Drawing		Selection: yes/no	*yes*
Simulation Results		Text	*tilt angle 8°; instrument has to be turned upside down.*
Size (+)	Dimension	Text	*height*

	Value	Integer (in mm)	*210*
	Unit	Text	mm
Object plus Package and Mounting(+)	Dimension	Text	*height*
	Value	Integer (in mm)	*350*
	Unit	Text	mm
Picture URL (+)		Link	

9.1.4 Conservational Requirements

Name		**Type**	***Example* / Explanation**
Workflownumber		Text	*DNgnm_MI1234*
Object-ID		Text	*DNgnm_MI1234*
	Climatic conditions	Text	*relative humidity between 45 % and 55 %*
	Directions for Object Handling	Text	*fix loose parts, at least two people for transport*
	Positioning during the measurement	Text	*lying on the rotary table*
Transportpackaging		Text	*in wooden box, cushioned, in polyethylene foil with silica-gel-pads*
Picture-URL		Link	

9.1.5 Scientific Issue (per Object or VOI)

Name		**Type**	***Example* / Explanation**
Workflownumber		Text	*DNgnm_MI1234*
Object-ID		Text (A↔B)	*DNgnm_MI1234*
VOI-ID		Text (A↔B)	*DNgnm_MI1234_VOI6*
Question (+)	Keyword	Text	*E.g. Manufacture technique, 3D-print* (for generating new keywords, see also last table of the meta data model 9.4.3)

	Description of Scientific issue	Text	Free text in case a suitable keyword is missing *The back plate seems to be doubled, can this be made visible?* *How is the neck joint constructed?*
	Required spatial resolution	Text	*min. 100* µm
Orientation of Reconstruction	Orientation	Text	*Neck and pegbox in z-axis, top plate parallel to frontal plane*
	Attachment (+)	Link	E.g. picture / sketch

9.2 Acquisition Fields of the Work Area „Measurement“

9.2.1 Documentation of the Object Measurement

Name		**Type**	***Example* / Explanation**
Workflownumber		Text	*DNgnm_MI1234-M08*
ID of object measurement		Text	*DNgnm_MI1234_20170905_FUERTH_FHGEZRT_M08_VOI6*
Measured Object (ID)		Text (A↔B)	*DNgnm_MI1234*
Measured VOI (ID)		Text (A↔B)	*DNgnm_MI1234_VOI6*
Used CT-facility		Text	*ID of CT-combination*
Date of delivery		Date	*2017_09_01*
Date of return transport		Date	*2017_09_07*
Modification on the Object		Text	*keys were dismantled; strings were removed*
	Climatic conditions	Text	*50* °C, *19,8* % *relative humidity*
	Climate measures	Text	*50* l *humidifier in the CT-facility*
Test Specimens (+)	ID	Text	*ballbar_XS*
	Location at the Object	Text	*between back plate and carbon fibre tube at the position of the middle bout*
ID of Measurement (projection data set) (+)		Text	*DNgnm_MI1234_20170905_FUERTH_FHGEZRT_M08_VOI6_V1of5* *DNgnm_MI1234_20170905_FUERTH_FHGEZRT_M08_VOI6_V2of5* *DNgnm_MI1234_20170905_FUERTH_FHGEZRT_M08_VOI6_V3of5*

		DNgnm_MI1234_20170905_FUERTH_FHGEZRT_M08_VOI6_V4of5 *DNgnm_MI1234_20170905_FUERTH_FHGEZRT_M08_VOI6_V5of5*
Attachment (+)	Link	

9.2.2 Parameters of the Projection Data Set

Name		**Type**	***Example* / Explanation**
Workflownumber		Text	*DNgnm_MI1234-M08*
ID of Measurement		Text	*DNgnm_MI1234_20170905_FUERTH_FHGEZRT_M08_VOI6_V1of5*
Measured Object (ID)		Text (A↔B)	*DNgnm_MI1234*
Measured VOI (ID)		Text (A↔B)	*DNgnm_MI1234_VOI6*
X-ray tube voltage	Value	Integer (in kV)	*225*
	Unit	Text	kV
X-ray tube current	Value	Floating-point number (in mA, two decimals)	*0.65*
	Unit	Text	mA
Prefilter (+)	Filter element	Text	*Cu*
	Value	Floating-point number (in mm, two decimals)	*2.05*
	Unit	Text	mm
Chosen focal spot		Text	*High Power*
Nominal focal spot size	Value	Floating-point number (in µm, two decimals)	*15.2*
	Unit	Text	µm

Exposure Time	Value		Integer (in ms)	*199*
	Unit		Text	ms
Number of averaged frames			Integer	*2*
Number of skipped frames			Integer	*1*
Acquisition mode			Text	*Stop&Go*
Positioning of Object in beam path	Distance (Focus-Object)	Value	Floating-point number (in mm, one decimal)	*1225.2*
		Unit	Text	mm
	Distance (Focus-Detector)	Value	Floating-point number (in mm, one decimal)	*2450.8*
		Unit	Text	mm
	Orientation		Text	*upright*
Size of object (incl. mounting and spatial positioning) (+)		Dimension	Text	*height*
		Value	Integer (in mm)	*12*
		Unit	Text	mm
Rotation for circular CT (A↔B)	Angular range of scan	Value	Floating-point number (in degree, three decimals)	*209.250*
		Unit	Text	*degree*
	Number of angles per 360°		Floating-point number	*2400*
Rotation for helical CT (A↔B)	Angular range of scan	Value	Floating-point number (in degree, three decimals)	*650.475*
		Unit	Text	*degree*
	Number of angles per 360°		Floating-point number	*2400*
	Helical pitch in z-direction per 360°	Unit	Floating-point number (in mm, one decimal)	*258.4*
		Value	Text	mm
Trajectory			Text	Circle

Measurement Field Extension	Number of Measurement Field Extensions	Integer	*3*
	Overlap in pixels	Integer	*16*
Picture-URL (+)		Link	

9.2.3 Archiving of Projections

Name		**Type**	***Example* / Explanation**
ID of Measurement		Text	*DNgnm_MIN1234_20170905_FUERTH_FHGEZRT_M08_VOI6_V1of5*
Media storage		Text	*tar-zip*
	Format of projection data set	Text	*DICOM* *Fraunhofer raw*
	Link/Folder	Link	

9.2.4 Documentation of the Measurement Process

Name			**Type**	***Example* / Explanation**
Workflownumber			Text	*DNgnm_MI1234-M01*
	ID of Measurement		Text	*DNgnm_MI1234_20170905_FUERTH_FHGEZRT_M08_VOI6_V1of5*
	Date of Measurement		Date	*2017_09_05*
	Time of Start of Measurement		Time	*08:14:30*
	Duration of Measurement	Value	Floating-point number (in h, one decimal)	*1.2*
		Unit	Text	h

	Applied radiation dose (air kerma)	Value	Floating-point number (in Gy, one decimal)	*40.1*
		Unit	Text	Gy
	operating personnel of facility (+)		Text	*Max Müller*
Measured Object (ID)			Text (Object-ID) (A↔B)	*DNgnm_MI1234*
Measured VOI (ID)			Text (VOI-ID) (A↔B)	*DNgnm_MI1234_VOI6*
Data volume of projection data		Value	Floating-point number (in GB, one decimal)	*28.1*
		Unit	Text	GB
Picture-URL (+)			Link	

9.3 Acquisition Fields of the Work Area „Reconstruction and Evaluation“

9.3.1 Reconstruction

Name	**Type**	***Example* / Explanation**
Workflownumber	Text	*DNgnm_MI1234-M08-R01*
ID of Reconstruction	Text	*DNgnm_MI1234_20170905_FUERTH_FHGEZRT_M08_VOI6_V1of5_R01*
ID of Measurement	Text	*DNgnm_MI1234_20170905_FUERTH_FHGEZRT_M08_VOI6_V1of5*
Reconstructed Object (ID)	Text (A↔B)	*DNgnm_MI1234*
Reconstructed VOI (ID)	Text (A↔B)	*DNgnm_MI1234_VOI6*
Number of reconstruction	Integer	*1*
Image balancing for measurement field extension	Text	*Median*
Important corrections (+)	Text	*horizontal detector shift = -5.5* px *= -2199.67* µm
Comment	Text	*two projections too dark*

Selection criterion for reconstruction method (+)			Text	*standard reconstruction*
Method			Text	*filtered backprojection FBP*
	Reconstructionsoftware		Text	*Volex*
	Number of Version		Text	*revision189316*
Reconstruction parameter (+)	Convolution kernel (+)		Text	*Shepp-Logan*
	Other filters (+)		Text	*3x1 median*
	Number of iterations		Integer	
Padding	Padding		Text	*cosine*
	Padding length per side	Value	Integer	*1432*
		Unit	Text	*Pixel*
Binning			Integer	*2*
Voxel number		Nx	Integer	*2016*
		Ny	Integer	*2016*
		Nz	Integer	*1494*
Voxel edge length (+)		Wx	Floating-point number(in µm, one decimal)	*101.1*
		Wy	Floating-point number (in µm, one decimal)	*101.1*
		Wz	Floating-point number (in µm, one decimal)	*101.1*
		Unit	Text	µm
Type of reconstructed values			Text	*float, µ in 1/*cm
Backup	Format of the reconstructed data set		Text	*rek-volume (FHG)*

	Size of reconstruction	Floating-point number (in GB, one decimal)	*17.5*
	Unit	Text	GB
Link volume data set (+)		Link	

9.3.2 Post-Processed Reconstruction

Name		**Type**	***Example* / Explanation**
Workflownumber		Text	*DNgnm_MI1234-M08-R01*
ID of post-processed reconstruction		Text	*DNgnm_MI1234_20170905_FUERTH_FHGEZRT_M07_R01_M08_VOI6_R01*
ID of underlying reconstruction (+)		Text	*DNgnm_MI1234_20170905_FUERTH_FHGEZRT_M07_R01* *DNgnm_MI1234_20170905_FUERTH_FHGEZRT_M08_VOI6_R01*
ID of underlying post-processed reconstruction (+)		Text	*DNgnm_MIR823_20170905_FUERTH_FHGEZRT_M07_R01_M08_VOI6_R01*
Combination method		Selection field: assembly to larger volume computation of congruent volumes	*computation of congruent volumes*
	Type of computation	Text	*Addition*
Comment		Text	*Due to double structures caused by a movement of the object, only the upper par (from the end of the mouthpieces) was exported as DICOM*

Voxel number	Nx	Integer	*535*
	Ny	Integer	*460*
	Nz	Integer	*1444*

Voxel edge length	Wx		Floating-point number (in µm. one decimal)	*83.7*
	Wy		Floating-point number (in µm. one decimal)	*83.7*
	Wz		Floating-point number (in µm. one decimal)	*83.7*
	Unit		Text	µm
Backup	Format of reconstructed data set		Text	*DICOM*
	Size of reconstruction	Value	Floating-point number (in GB, one decimal)	*59.1*
		Unit	Text	GB
Arrival of the reconstructed data set in the museum	Date		Date	*2018_01_18*
	arrived		Selection field: Yes / no	*Yes*
Link volume data set (+)			Link	

9.3.3 Evaluation and Visualization

Name				**Type**	***Example*** / **Explanation**
Workflownumber				Text	*DNgnm_MI1234-M01-R01*
ID of reconstruction (+)				Text	*DNgnm_MI1234_20170905_FUERTH_FHGEZRT_M08_VOI6_R01*
ID of edited reconstruction (+)				Text	*DNgnm_MI1234_20170905_FUERTH_FHGEZRT_M07_R01_M08_VOI6_R01*
Specimen	Specimen ID			Text	*ballbar_XS*
	Fitting	fitted length of ball bar	Unit	Floating-point number (in mm, three decimals)	*15.458*

			Value	Text	mm
		deviation of ball bar length	Unit	Floating-point number (in %, three decimals)	*0.024*
			Value	Text	%
Evaluation of the entire workflow				Text	*The reconstruction is perfect.*
Attachment				Link	e.g. Cross Section

9.4 Common Acquisition Fields

9.4.1 CT-Facility

The IDs of the different devices are combined from the single constructive elements. In the case of a CT-facility, the institution, the place and the name of the facility are recorded. The manufacturer, type and number (serial number) are added to identify the X-ray source and the detector.

9.4.1.1 Constellation of the CT-Facility

Name	**Type**	***Example*** **/ Explanation**
ID of constellation of the CT-facility	Text	*Mue-YXLON_Direkt-PerkinElmer_ab201701*
CT-facility (facility-ID)	Text	*FHGEZRT_FUERTH_MueCT_ab201606*
X-Ray-source (ID)	Text	*FXE-225.99 TwinHead - Mue*
X-Ray-sensor (ID)	Text	*XRD 1611 xP*

9.4.1.2 CT-Facility

Name		**Type**	***Example* / Explanation**
Facility-ID		Text	*FHGEZRT_FUERTH_TOMOSYNTHESE*
Operator		Text	*Fraunhofer EZRT*
Place		Text	*Fürth/Atzenhof*
Type		Text	*„v|tom|ex“, „own construction“*
Manufacturer		Text	*YXLON*
Name of the facility		Text	*„Mikro-CT“, „Nr. 4“*
Axes system	Number of axes	Integer	*5*
	Special features	Text	*rotation source*

9.4.1.3 X-Ray-Source

Name		**Type**	***Example* / Explanation**
ID		Text	*FXE-225.99 TwinHead - 11078691*
Name		Text	*transmission-target tube, open*
Manufacturer		Text	*Yxlon*
Type		Text	*FXE225.51*
Serial number		Text	*11078691*
Min. focal spot size	Value	Floating-point number (in µm, one decimal)	*5.2*
	Unit	Text	µm
Max. tube voltage	Value	Integer (in kV)	*225*
	Unit	Text	kV

9.4.1.4 X-Ray Sensor

Name		**Type**	***Example*** **/ Explanation**
ID		Text	*Pixium RF 4343 - 131185*
Name		Text	*flat panel matrix detector*
Manufacturer		Text	*Thales*
Type		Text	*Pixium RF 4343*
Serial number		Text	*131185*
Pixel matrix	Nx	Integer	*2874*
	Ny	Integer	*2840*
Pixel size	Value x-axis	Floating-point number	*0.148*
	Value y-axis	Floating-point number	*0.148*
	Unit	Text	mm
	Dynamic (Bits/Pixel)	Integer	*16*

9.4.2 Test Specimen

Name		**Type**	***Example*** **/ Explanation**
Type name		Text	*ball bar*
ID		Text	*ballbar_M*
Marking		Text	*H5 FE EN*
Calibration		Text	*286 DKD-K-13601 2008-12*
Certificate		Text	*S1E0074 C*
Measurements (+)	Dimension	Text	diameter
	Value	Floating-point number	*15.50*
	Unit	Text	mm

Picture-URL (+)	Link	*Picture-URL*

9.4.3 Scientific Issue Keyword

Name	**Type**	***Example / Explanation***
Keyword	Text	*Density*
Definition	Text	*The density of the different materials in the object has to be determined*

Remark: This table shows how to create a new keyword in the area „Scientific Issue“ (9.1.5).

10 LIDO Specification

LIDO was designed to exchange data describing Museum works. It is not suitable to handle a complex and specific data model such as MUSICES data model.

For a given instrument, its MIMO-LIDO record contains the data allowing to be aware of the fact that a 3D-CT representation is available on the dedicated website, e.g. the MUSICES project website.

This information has to be structured following these specifications:

Contributor's metadata element	LIDO element	Example
the name of the local file containing a preview of the 3D resource.	lido:resourceID	FileName.png ; FileName.pdf
URL to the full 3D resource on the contributor’s website.	lido:linkResource	www.gnm.de/resources/ 123.3DCT
the type of the resource: MIMO values = "image", "movie", "sound", "3D"	lido:resourceType	3D
the name of the institution/person holding the rights attached to the resource.	lido:rightsResource	Copyright GNM
resource creation or last modification date	lido:resourceDateTaken	01/01/2018
a description of the resource	lido:resourceDescription	MUSICES 3DCT Representation

Appendices

11 Mounting of Objects for CT-Scanning

11.1 Multifunctional Mounting System

During the MUSICES-project a multifunctional mounting system was developed in the Institute for Art Technology and Conservation of Germanisches Nationalmuseum in Nuremberg. This system is described below and can be copied and adjusted to individual needs (Figure 14).

Base

A circular wooden base is provided with bores and can be screwed on the rotation table of the CT-facility. It consists of two wooden plates (19 mm thick) which are connected through wooden spacers. The plates provide bores in which a tube of acrylic glass or carbon (Ø 40 mm) can be fastened vertically. The position of the tube can be varied due to several bores at different locations. The carbon tube (wall thickness 2 mm) is more stable compared to the acrylic glass (wall thickness 5 mm).

To this tube, objects with different geometries can be fastened by using a spacer made of foam (e.g. Styrodur®) and cotton strap, tape, paper or Tyvek®.

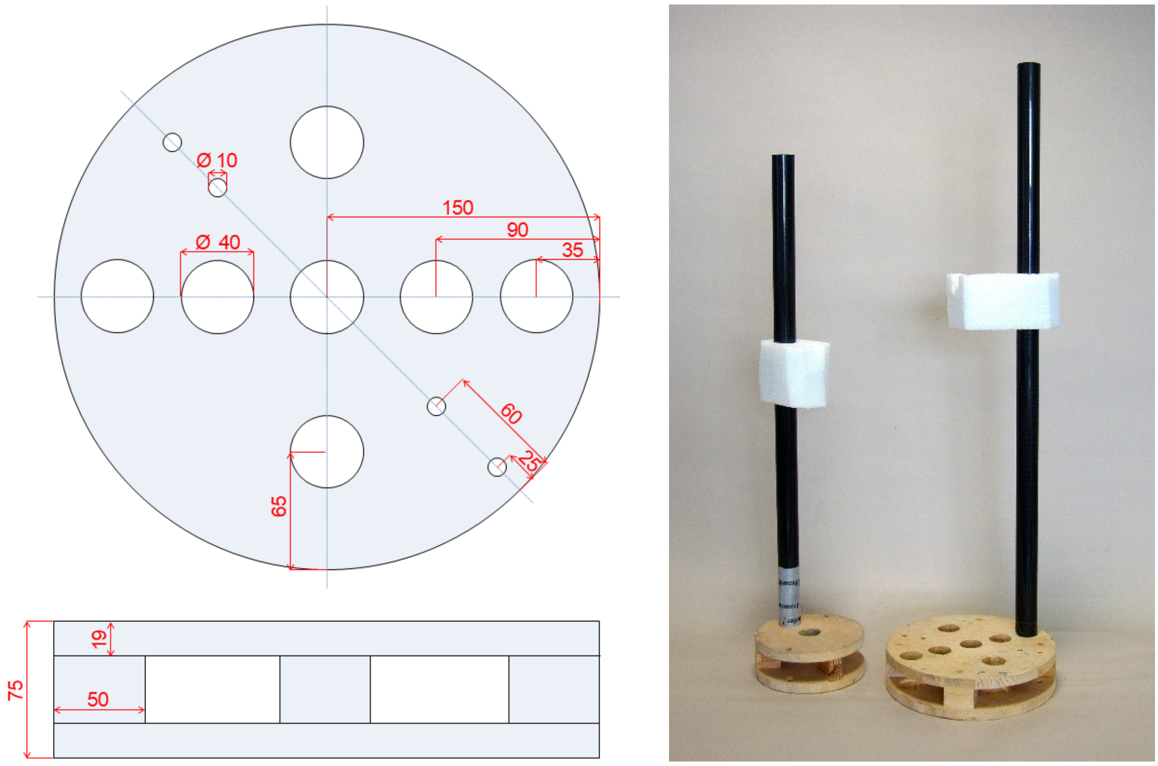

Figure 14: Multifunctional mounting system: Schematic sketch with top- und lateral view. All dimensions in mm (left). Two versions with carbon tubes and foam spacers (right)

Fixing Objects

For the stabilization of objects with round or complex geometries a medical vacuum pillow has proved to be a useful item. This X-ray safe pillow is adaptable to every shape and is reusable.

Also pieces of hard foam (Styrodur®) can be shaped individually to build a stable base for the object. This synthetic foam is characterized by stability against pressure. Pieces of Ethafoam® are not recommended due to the fact that they can deform during long scans by the weight of the instrument. The individually shaped foam basis can be fastened with double-sided adhesive tape or synthetic modelling clay at the wooden base. In case of a helical scan it can be required that the foam basis is slightly higher. Ethafoam® can be used for stabilization and supporting structures when there is no high pressure loading.

Positioning

When positioning the object on the rotary table it has to be considered that the instrument or the volume of interest (VOI) is placed in the centre, over the axis of rotation. In case of a VOI located at the edge of an object, the whole instrument should be positioned in a way that this area is in the centre over the axis of rotation. If the centre of mass of the object then lies beyond the rotary table, additional stabilization measures have to be undertaken.

In case the object has to be fixed in a tilted position (e.g. to achieve a minimization of the irradiated length) the stabilization construction has to be adapted accordingly (cf. 11.2).

In the following, a couple of proved mounting possibilities are presented:

Stringed plucked instruments/stringed bowed instruments (cf. Figure 15)

- vertical position
- remove metal strings or change them into nylon strings
- for the basis use either the vacuum pad or an individually fitted block of Styrodur®
- fix the instrument to the tube using an Ethafoam®-spacer and a thin Tyvek®-cuff or strong thread

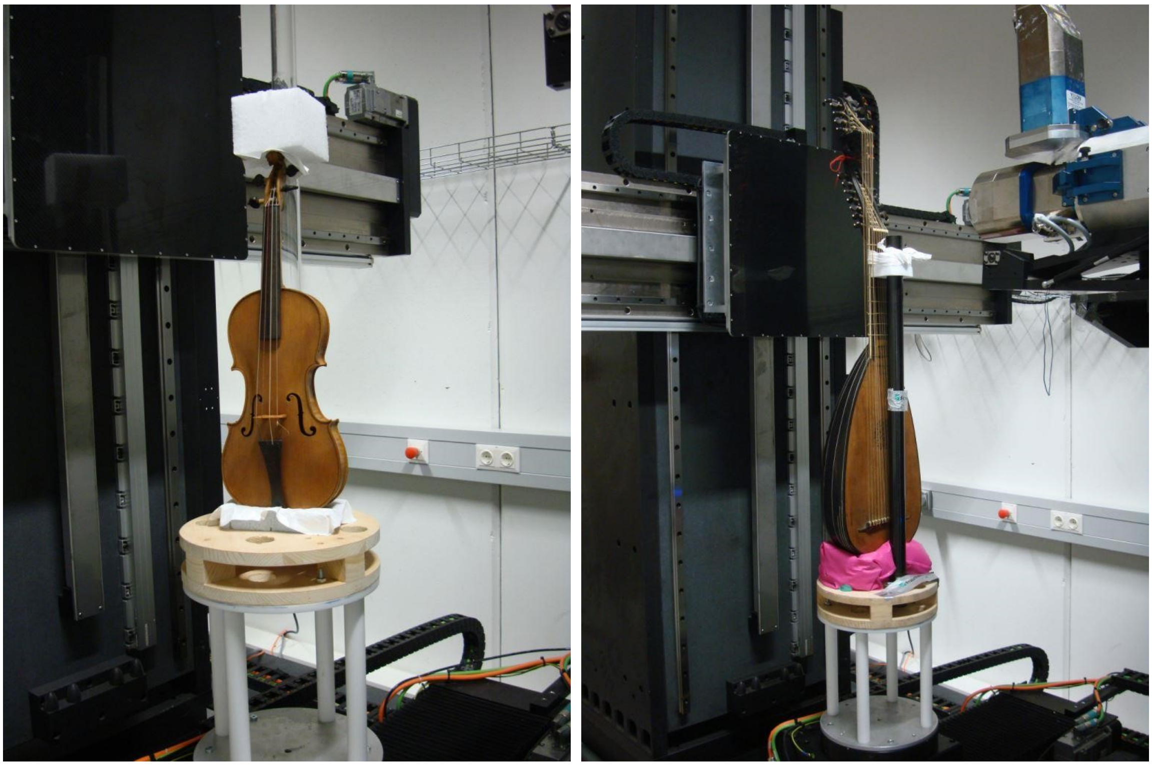

Figure 15: Mounting of a violin and a lute on the rotary table

The bigger an object is, the more difficult it can be to build a stable structure for the entire height. In addition to a fixation at the pegbox, another cuff, e.g. at the location of the waist, can provide additional stability.

A foam block that presses slightly from above is increasing the solidity. The pegbox can be inserted ca. 1 cm into the foam block.

Wind instruments with straight geometry (Figure 16)

- vertical position next to the carbon tube
- a foam block with a little cavity presses slightly from above
- individually shaped basis of Styrodur® when necessary
- several attachments at the tube increase stability in case of big, heavy or multi-part objects

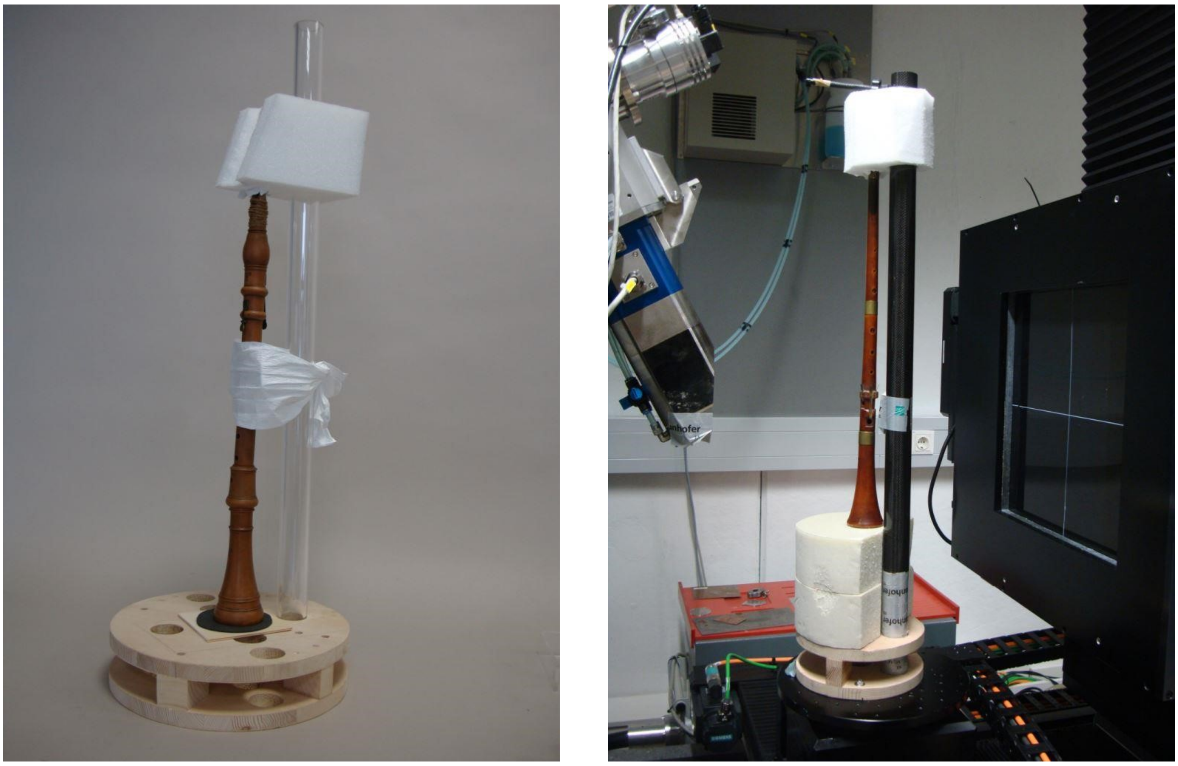

Figure 16: Mounting of a clarinet and oboe on the rotary table

Wind instruments with curved shape (Figure 17)

- individual foam construction to be fastened to the carbon tube
- fix the whole structure at the tube using an Ethafoam®-spacer and a thin Tyvek®-cuff or strong cord (e.g. crumb horn, English horn)
- optional: insert the whole instrument in a block of Ethafoam® or Styrodur® and fix it with tape at the carbon tube (e.g. cornetto)

Figure 17: left: English horn with individual supporting foam structure; middle: cornetto in foam block; right: fixed foam block with two cornettos on the rotary table.

11.2 Individual Solutions

For certain groups of instruments with specific sizes or shapes individual mounting solutions were found which are documented here. However, it is necessary to assure that only conservationally approved materials are in contact with the objects

a. Keyboard instruments (cf. Figure 18)
   - Dismantle the legs, the pedestal, the lyre etc.
   - Light keyboard instruments like early square pianos or harpsichords can be placed upright and attached to a rotary table with fixed aluminium rails or a wooden scaffold. Adequate cushioning is required.

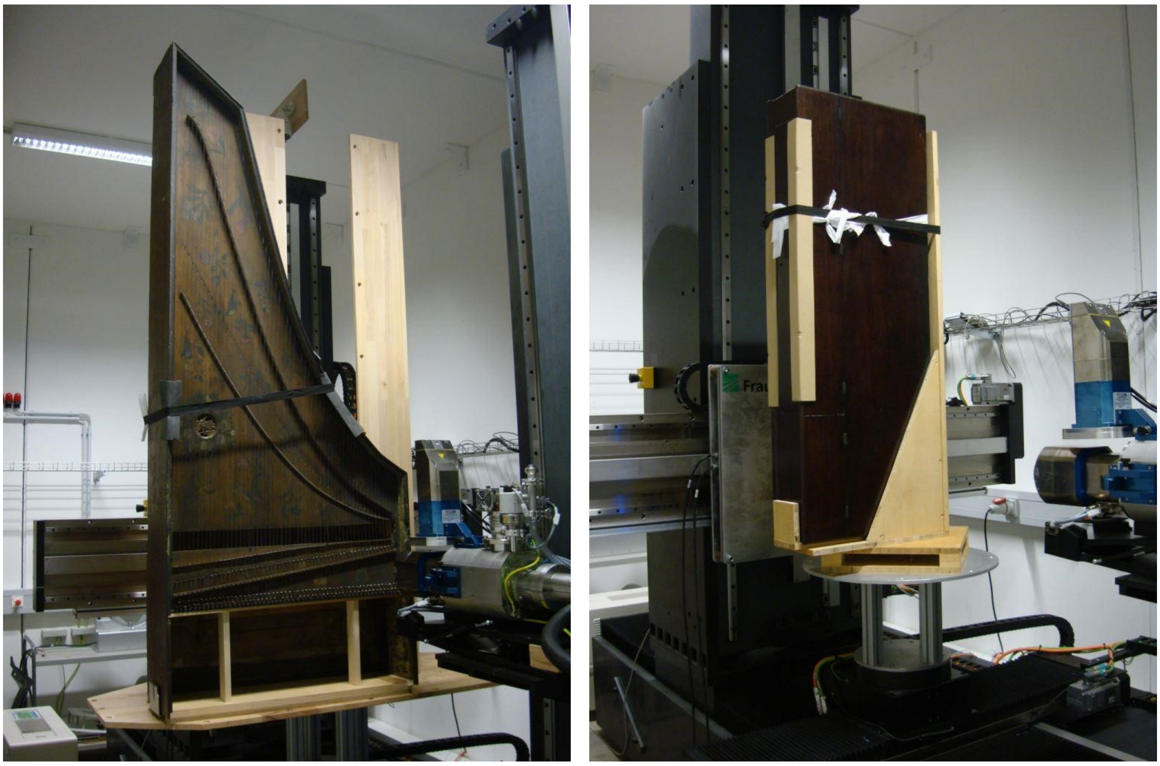

Figure 18: Upright mounting of a harpsichord (left) and a square piano on the rotary plate (right)

b. Unspecific und other geometries
    - Individually shaped base of Styrodur® or surgical vacuum cushion. (e.g. French horn, small objects; Figure 19, Figure 20). If the own weight of the object is not sufficient for the stability of the setup, stretched tapes above the object (with Tyvek® as intermediate layer) will be stabilizing it.
- In case an object has to be turned around between two scans, the fixation can be made within a wooden box (e.g. Figure 20 right) or between two wooden bases (Figure 21)

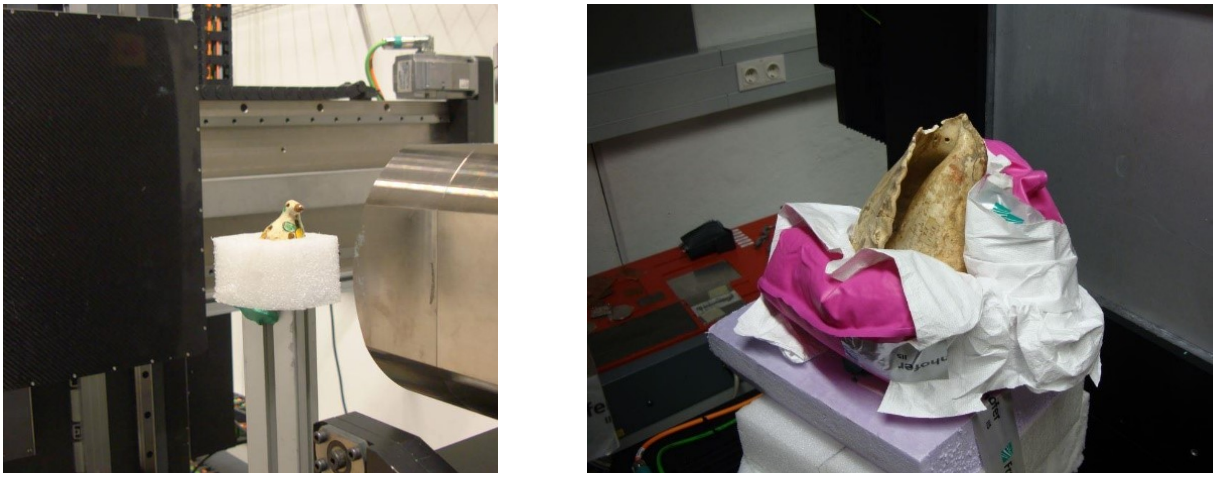

Figure 19: Ocarina in a purpose-made base of foam (left) and horn of shell fixed on a surgical cushion with Tyvek® as intermediate layer (right)

Figure 20: French horn tilted on an individual mold of Ethafoamblocks (left) and a bass tuba fixed with foam and surgical cushions in a wooden box (right)

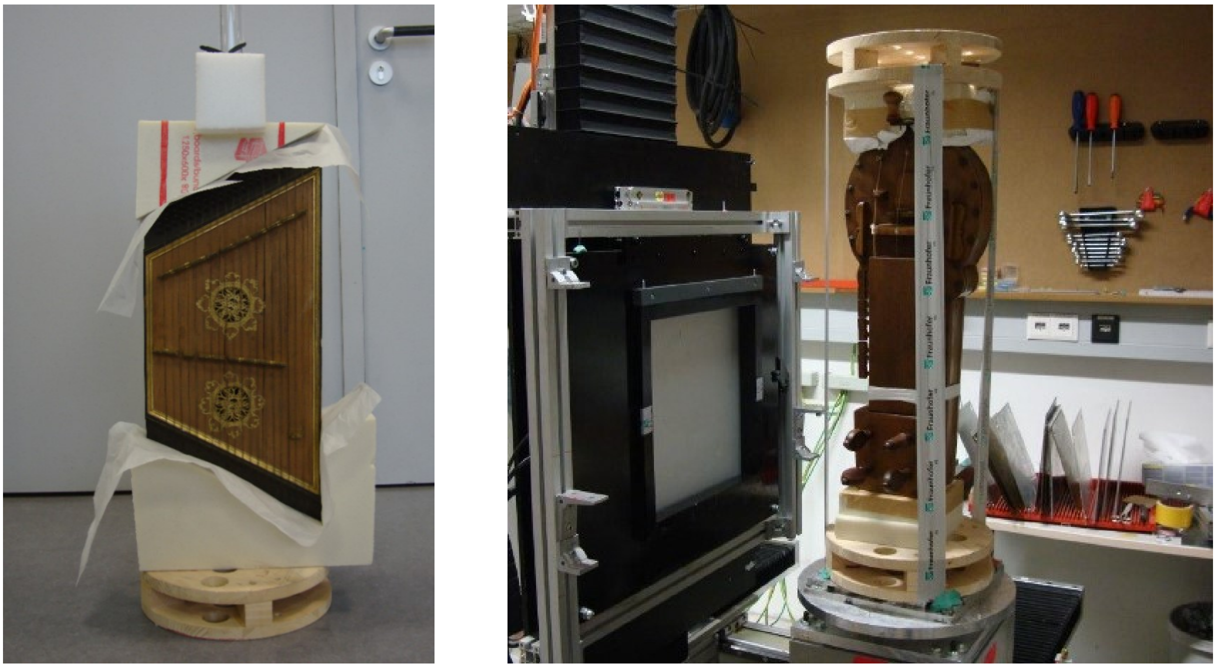

Figure 21 Dulcimer on an individual mold of foam on the wooden base (left); hurdy-gurdy between two base elements, additionally fixed with tape (right)

c. Cluster or multi-part objects (Figure 22 and Figure 23)
  - Several objects or parts of one object can be mounted on one base. A certain distance between the objects has to be ensured.
  - Watch out for metal parts. In order to reduce artefacts, the objects have to be positioned in an offset arrangement or with enough distance.

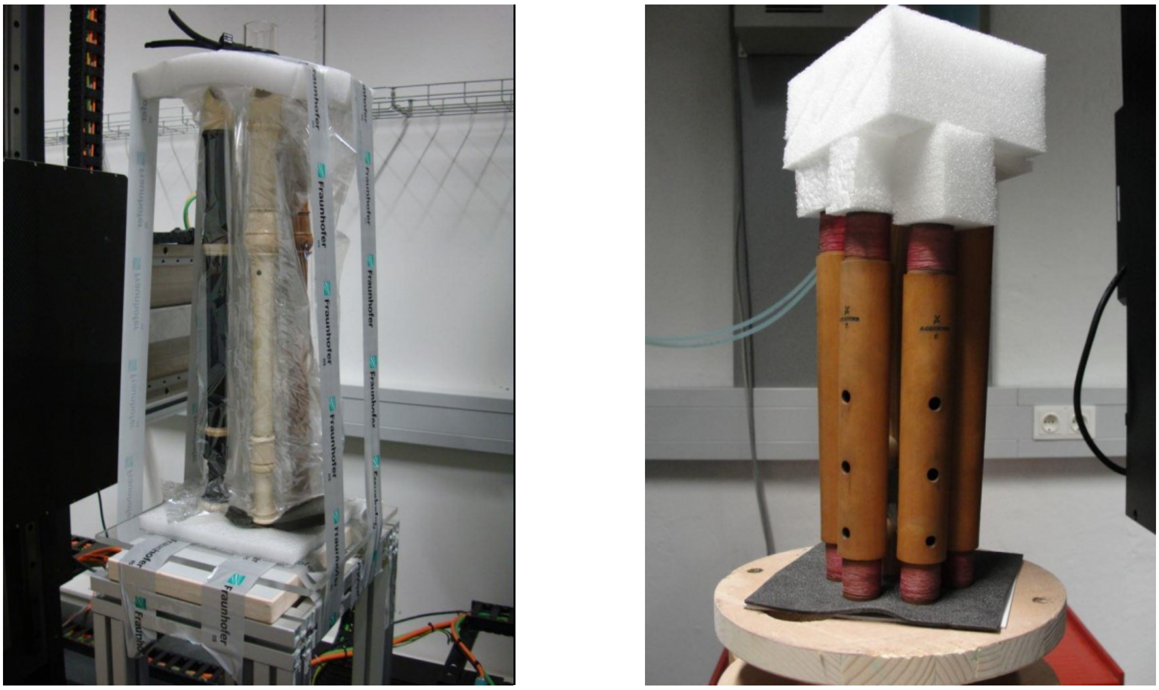

Figure 22: Cluster scan of four recorders (left) and different parts of one flute (right)

Figure 23: Cluster scan of parts of a segmented bass pommer (left) and a cluster scan of a flute and a pochette (right)

The test mounting should be documented with photos and the dimensions of the entire construction should be recorded and forwarded to the X-ray engineers. For the CT-scan the most important dimensions are the maximum diameter and the height of the complete mounting.

12 Manipulation of Objects in a CT Facility

Industrial CT machines contain several axes to manipulate investigated object, X-ray source and detector. Each movement during a CT scan or its preparation implies the risk of a collision between object and machine components. The risk increases when the distance between object and source and/or detector decreases. Miscalculation of distances to move, confusion of the axes or typing errors can lead to accidents, which can not only cause damage to an expensive machine, but also to an invaluable historical object.

In this context viola da gamba DNgnm_MI5[23] was an exceptionally critical object during the project. With a diameter of 60 cm it had to be scanned with threefold MFE in horizontal direction. To record gain images without removing the object from the rotary table required a complex manipulation as shown in Figure 25.

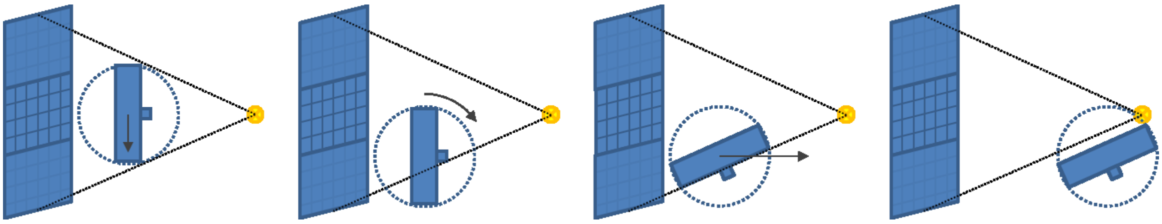

Figure 24: The viola da gamba DNgnm_MI5 was moved in a complex pattern to exclude its projection from the detector before recording gain images. It was first shifted parallel to the detector as far as possible. Then it had to be rotated before moving it closer to the source. Without this prior rotation the last shift would have led to a collision.

When tolerances for manipulation of sensitive objects are small it is advisable to use a dummy for a dry run to try all planned manipulations and trajectories. Parameters found in this way should be recorded in a checklist and can then be used for the real object.

It is generally recommended to follow the four-eyes principle. Two persons should agree on the next manipulation step and observe its correct execution.

All critical manipulations should be tested before a real scan. It is highly recommended that at least one person should watch these tests. Cameras are useful for this purpose. However, the perspective can lead to a misinterpretation of the available space. A camera as only security measure is therefore not sufficient. At the very least, cameras from different directions should be used to monitor the space between the object and both source and detector. Observing everything from within the facility is a better option. One option is to operate the axes system from within the facility. If this is not possible, one person should remain inside the facility to watch and communicate, for instance by telephone, with the manipulator outside. Every movement should be agreed upon prior to its execution. When deviations from the plan occur, the manipulation should be aborted immediately. In critical situations also an emergency shutdown can be applied.

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[23] To improve readability, the object-ID (see section 17.1.1) is used to refer to particular objects instead of the correct description in the pattern: viola da gamba, Germanisches Nationalmuseum, Nuremberg, Inv. No. MI 5.

13 Recommendations for Choosing Trajectories

During the project several CT trajectories were tested. This chapter presents some examples to illustrate different options and when they are useful.

13.1 Comparison of Circular and Helical Scan Trajectories

In most cases the trajectory chosen for a CT scan will be circular or helical. Both have advantages and disadvantages:

- Using helical trajectories, objects longer than the size of the detector in vertical direction can be scanned. The composition of several circular scans to one volume can be omitted.
- The Tuy-Smith sufficiency condition states that an exact reconstruction is possible if all surfaces intersecting the object also intersect the trajectory of the X-ray source [8]. When using circular scan trajectories, this condition is only fulfilled for the central plane. In the reconstructed volume this leads to deviations of the form and a loss of spatial resolution in vertical direction. With increasing distance from the central plane the contrast and resolution decrease further while distortions increase [6, 7, 20]. When using a helical trajectory, the form is reproduced correctly independent of the position in vertical direction [6].
- In comparison to circular trajectories, helical scans require an additional vertical movement of either source and detector or the object. This adds a potential source of artefacts. Further, the technical capability is not available in each facility.
- Helical scans require projections above and below the actually interesting part of an object. A sufficient travelling distance in vertical direction is thus needed also beneath the musical instrument. Therefore, the object may have to be placed on a raised pedestal, which can lead to stability issues.
- The reconstruction of helical scans is more time consuming.

To evaluate the influence on image quality some instruments were scanned with helical and circular trajectories. The harmonica DNgnm_MIR1041 consists of a tube, which is divided into compartments by thin semi-circular metal sheets. These sheets were oriented perpendicular to the axis of rotation during the CT scan. Figure 26 illustrates that these thin horizontal structures are well resolved in a helical scan. When a circular trajectory is used, only those sheets close to the central plane can be recognised due to the cone beam artefacts. As the sheets constitute a considerable length to be transmitted, they cause artefacts in the surrounding material. The shape of these artefacts is influenced by the trajectory, too (Figure 26, c).

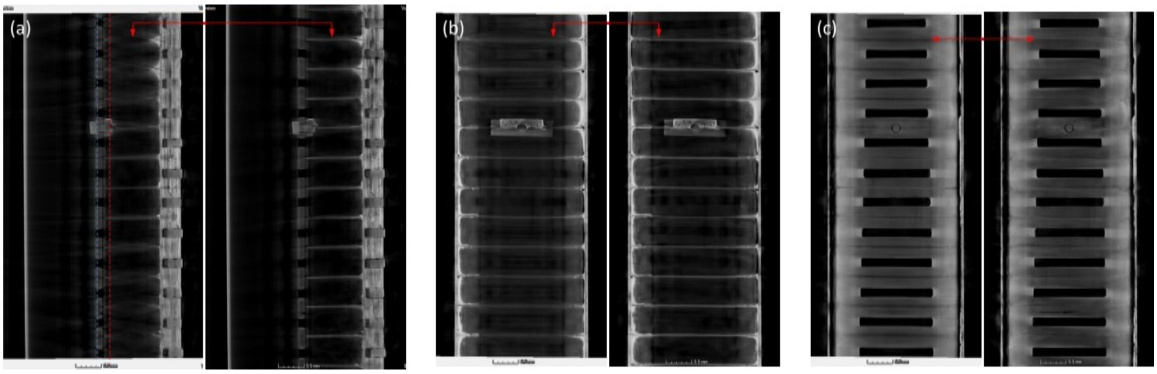

Figure 25: Different vertical cross sections through the reconstructions of harmonica DNgnm_MIR1041. Images (b) and (c) correspond to the dashed red and blue lines in (a), respectively. For all images, the left side depicts the circular and the right side the helical scan trajectory. (a, b) For the circular scan trajectory the thin, horizontal metal plates (arrows) are visible only close to the central reconstruction plane. In the helical scan they are visible throughout the whole volume. (c) Also the streak artefacts caused by the metal plates depend on the scan trajectory as indicated by the arrows.

Also the membrane of a drum represents a thin horizontal structure. As shown in Figure 27 they are visible only incompletely in circular scans, whereas they are well distinguished when applying a helical trajectory.

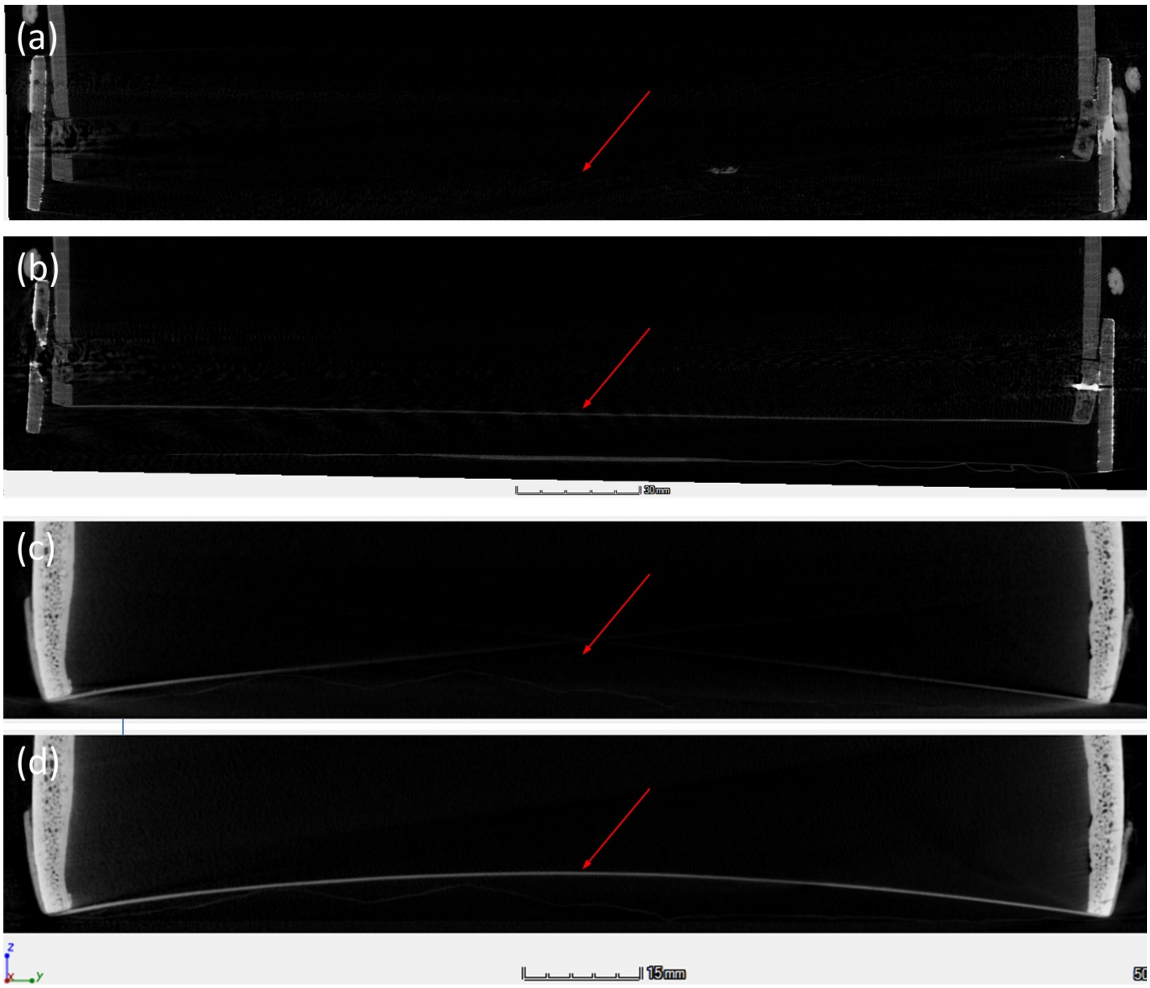

Figure 26: Vertical cross sections through the reconstructions of snare drum DNgnm_MIR635 (a, b) and damaru DLEu_2310 (c,d). Arrows indicate the membrane, which is not visible completely for circular trajectory (a, c) but can be well distinguished for a helical trajectory (b, d).

Consequently, when the object to be scanned contains thin structures perpendicular to the axis of rotation, a helical scan should be preferred even if the height of the object does not require it. If a circular scan has to be used for any reason, cone-beam artefacts could be reduced by positioning the object in a way ensuring that the critical parts are imaged close to the central plane of the detector. Decreasing the cone-beam opening angle at the same magnification by increasing FOD and FDD also helps, but requires longer exposure times. Also when aiming at measuring dimensions or attenuation coefficients a helical trajectory should be preferred.

13.2 CT of Objects with Diameters Just Exceeding the Detector Width

In general it is of advantage when the whole diameter of an object can be imaged onto the detector. This is not always possible due to the object size or the required magnification. Two options are commonly used in this case:

- If the organological question does not concern the whole instrument, it is possible to scan a smaller region of interest. In this case at least some projections are truncated on both sides, which can lead to artefacts in the reconstructed volume. However, these can be avoided using suitable reconstruction algorithms as demonstrated in section 14.2.

- To capture the whole object diameter, MFE can be applied. The number of projections per 360° has to be chosen according to the size of the object. This number has to be recorded for each detector position.

Another option is a scan with horizontally displaced detector. This method can be chosen if the detector has to be shifted horizontally by less than half of its width to image the object completely on one side. Projections on the other side are truncated.

The hurdy-gurdy DLEu_3505 (Figure 28) has a diameter of approximately 34 cm including the mounting. It was thus not possible to image it completely onto the detector, but using MFE did not seem appropriate. A displacement of the detector by 12 % permitted the scan of the object without the need for a horizontal MFE. Despite the truncation of the projections on one side, the whole object could be reconstructed with sufficient image quality even for the largest distances from the rotation axis. In vertical direction four scans were executed and combined to a dataset of the whole instrument.

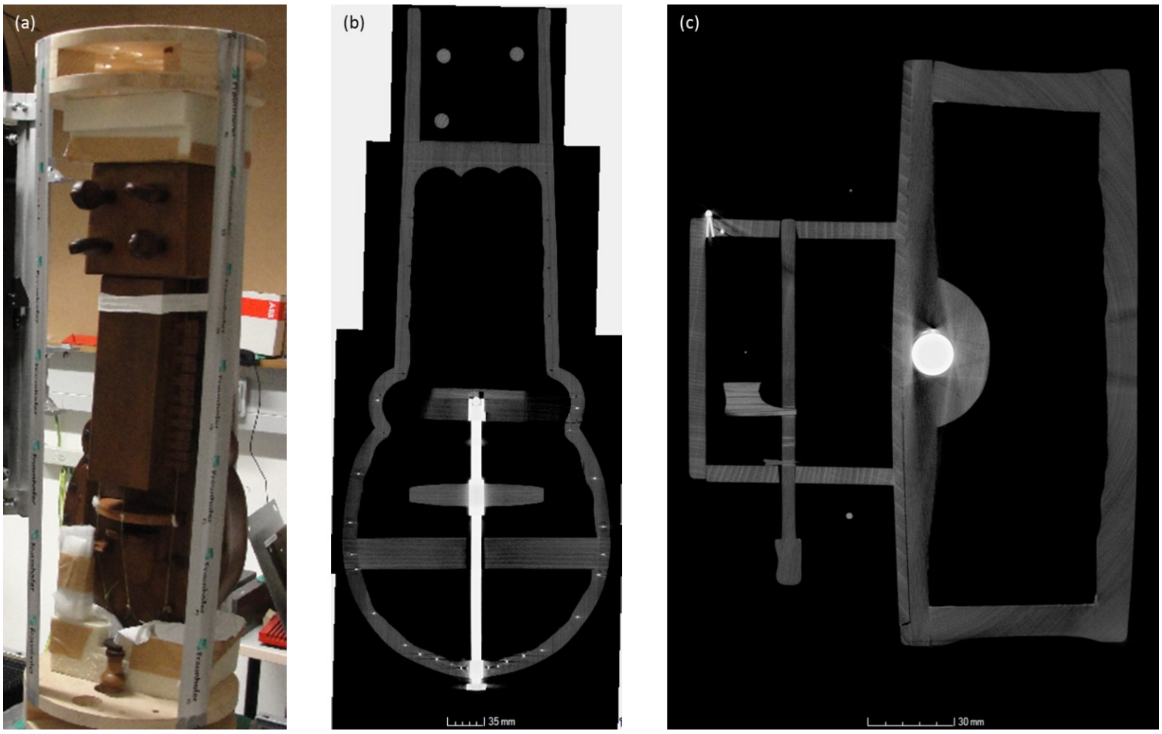

Figure 27: (a) Photograph of hurdy-gurdy DLEu_3505 in its mount for the CT scan. (b) Vertical and (c) horizontal cross section through the reconstructed volume data set.

The same number of projections was chosen, that would have been required when projecting the whole object onto a sufficiently large detector. This is the same number that would be needed for MFE. However, detector displacement uses only one detector position, whereas MFE would use two. Hence the scan time and dose would be doubled when using MFE.

13.3 CT of Objects with Varying Radius along the Longitudinal Axis

Objects with diameters exceeding the width of the detector have to be scanned using MFE. If the object is also too long to fit the height of the detector, it has to be scanned either with a helical-MFE (as done for instance with zither DLEu_0463) or by vertically stacking several circular MFE scans.

The diameter of some instruments changes along the vertical axis. For instance, the corpus of stringed instruments is wider than the neck. Also the width of the lower bend of a crumhorn exceeds the diameter of the tube (Figure 29).

Figure 28: Viola da gamba (DNgnm_MI5, left) and crumhorn (DNgnm_MIR423, right) are examples of instruments with varying object radius along the longitudinal direction.

When scanning instruments of this type using MFE along their whole length, the narrow parts are likely to fill only a small portion of each projection. The unnecessary “tomography of air” leads to an increased dose received by the object, a longer scan time and a larger data volume of projection and reconstruction data. Adapting the trajectory to the shape of an object can thus be of advantage.

The corpus of viola da gamba DNgnm_MI5 required a threefold MFE in horizontal direction. Seven scans had to be stacked vertically. For the neck a twofold MFE and the stacking of four scans was sufficient. The smaller diameter also allowed to reduce the number of projections per 360°. Choosing twofold instead of threefold MFE reduced the data volume, the scan time and the dose by 56 %.

The width of the crumhorn DNgnm_MIR423 at its lower end also made a twofold MFE necessary. To this end the instrument was placed centrally on the rotary table (Figure 30, a). For the scan of the long tube with a diameter of 5 cm the object was shifted to bring the tube closer to the rotational axis. This allowed a helical scan for this part of the crumhorn (Figure 30, b). As both scans were supposed to be consistent in all other parameters, the shift made between both scans required careful considerations. On the one hand, the object had to be close enough to the detector during the first scan to avoid truncated projections. On the other hand it had to be far enough to prevent a crash during the second scan.

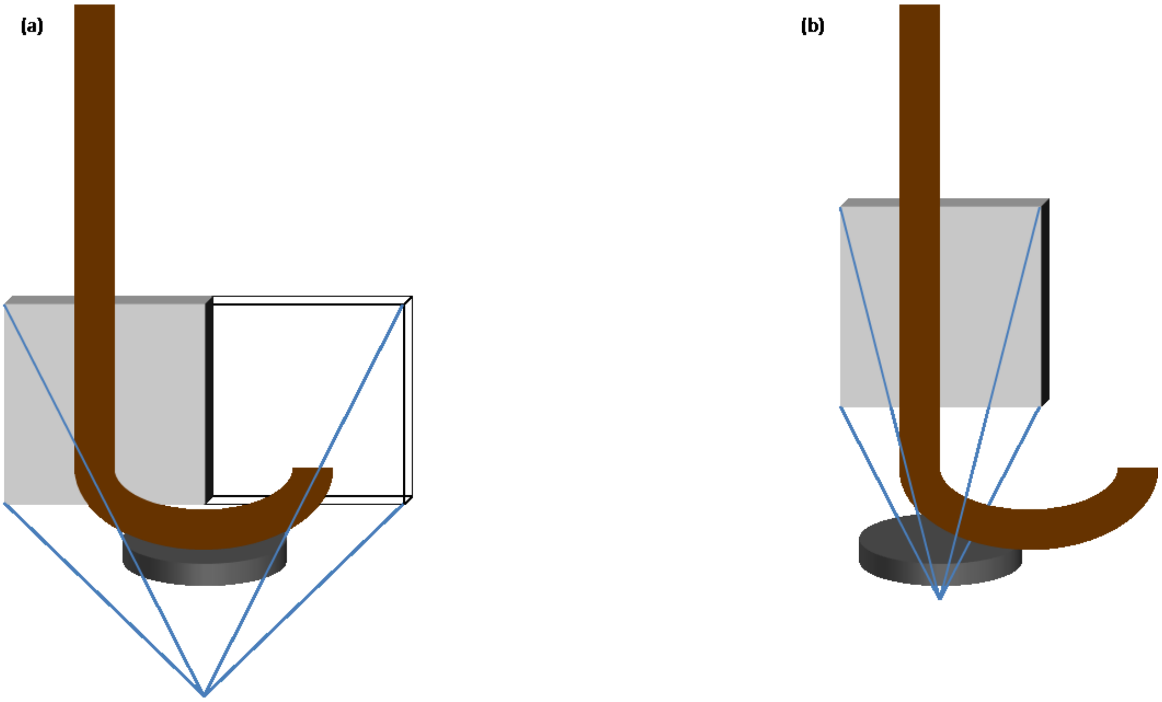

Figure 29: (a) Sketched position of crumhorn DNgnm_MIR423 on the rotary table during the MFE scan of the lower part. (b) Sketched position of the crumhorn on the rotary table during helical scan of tube.

Following from these examples it is recommended to consider whether MFE is necessary over the whole volume. For this decision it has to be taken into account if the scans have to be combined to a large reconstructed data volume afterwards. Combining volume data acquired by different procedures typically requires the registration of the volumes. This applies in particular when the objects positioning changes between scans, as in the example of the crumhorn. Registration of volumes usually makes it necessary to load them into the RAM of the computer. When using identical parameters for all scans it may be possible to simply concatenate volumes without registration.

13.4 Handling of Large Objects

Some musical instruments like grand pianos or cembalos are too large to be scanned completely using typical industrial CT systems. Different approaches are possible for such objects.

As a “proof of principle” two grand pianos (DNgnm_MIR1119 and DNgnm_MIR1126) were scanned in the EZRT XXL-CT facility. A linear accelerator produces X-rays with energies up to 9 MeV, allowing to transmit also metallic struts or cast iron plates. While this machine allows to scan the whole objects, it comprises some drawbacks: The resolution is limited to about 300 µm in lateral direction, the scan time extends over several days and the costs amount to a low five-digit number in €. The last two factors improve considerably, when the scan comprises not the whole instrument but only layers of a limited height, like the pinblock.

Common facilities that do not allow scans of the whole object might still permit a CT of a smaller volume of interest. A cembalo (DNgnm_MINe85) was used to demonstrate different options. One question concerned the condition of the pinblock and its connection to the frame (Figure 31). Although the location of this volume of interest increased the diameter of the mounted object to approximately 1.5 m, it was possible to rotate it by 360°. For even larger objects or facilities with smaller distance between source and detector a limited angle scan would be an alternative. This option increases the risk of a collision of the instrument with components of the CT system and requires exceptional attention (see also chapter 12)!

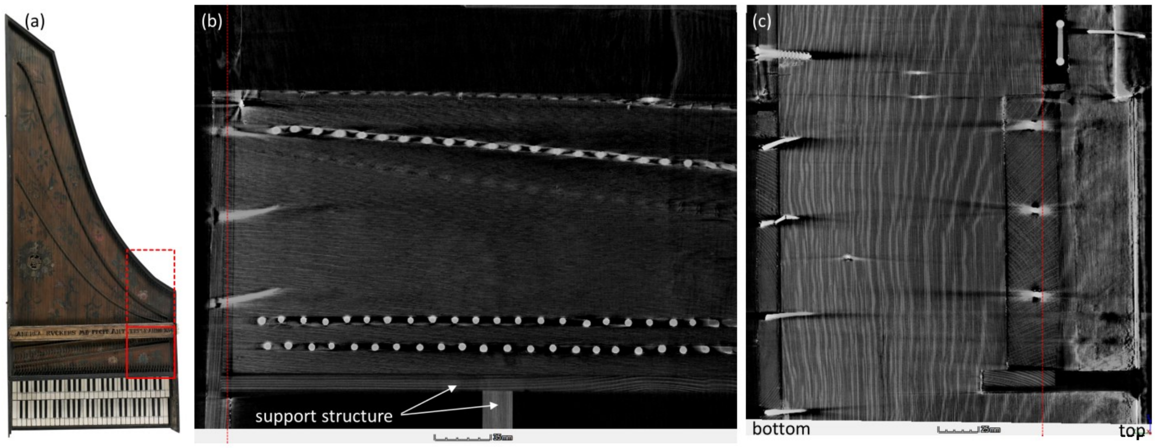

Figure 30: (a) Photograph of cembalo DNgnm_MINe85 with the scanned region of interest indicated in red. The solid line corresponds to the area shown in (b, c). The keys were removed prior to the scan and a support system was placed under the pinblock. (b) Cross section through the reconstructed volume along the pinblock. (c) Cross section along the outer rim. The vertical dashed lines in (b, c) indicate the position of the respective other image.

As the pinblock of this cembalo is a flat structure with a thickness of approximately 3 cm thickness, laminography represents an alternative to a CT scan [18]. One advantage of this method is that it does not require the rotation of the object. As source and detector move in planes parallel to the object, the risk of collisions is minimized. Furthermore, laminography allows high spatial resolutions. However, using tomosynthesis as the typical reconstruction method, resolution is not isotropic due to blurring of details in the direction perpendicular to the detector plane. Since projections are recorded only from a limited range of angles, interfaces perpendicular to the detector plane are distinct, those parallel to the detector appear blurred. This also applies for tree rings, the visibility of which depends on their orientation and on the tilt angle of the trajectory (Figure 32).

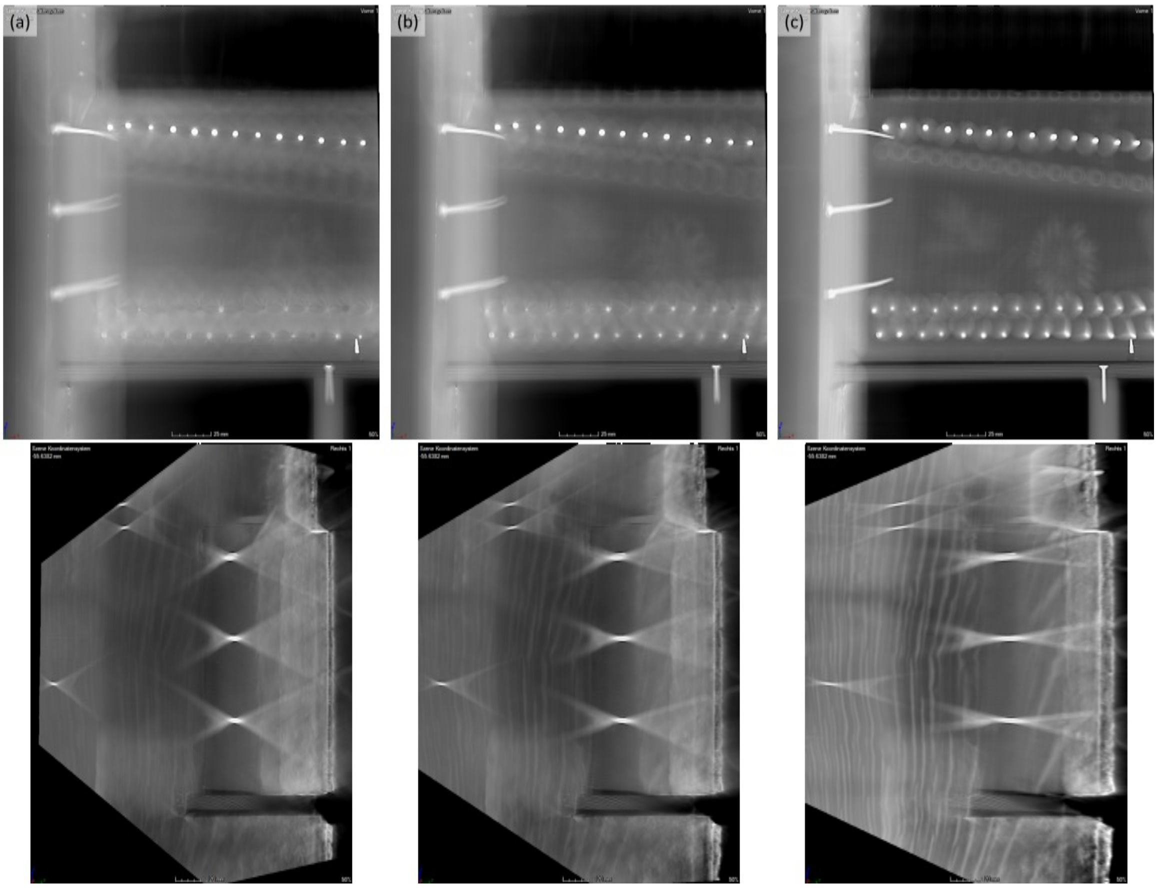

Figure 31: Cross sections through reconstructed volumes obtained by tomosynthesis. The structures shown correspond to those in Figure 30. In the top and bottom row the cross sections are oriented parallel and perpendicular to the detector plane respectively. (a) Tomosynthesis with tilt angle* 28°*, (b) with* 20° *and (c) with* 10°*. The visibility of the tree rings depends on their orientation with respect to the tilt angle. While they are visible in the support structure, they cannot be discerned in the pinblock.

When using tomosynthesis it is of advantage to combine several trajectories with different tilt angles. The additional information reduces artefacts (Figure 33). As a consequence, identification and interpretation of real structures in the reconstructed volume is facilitated.

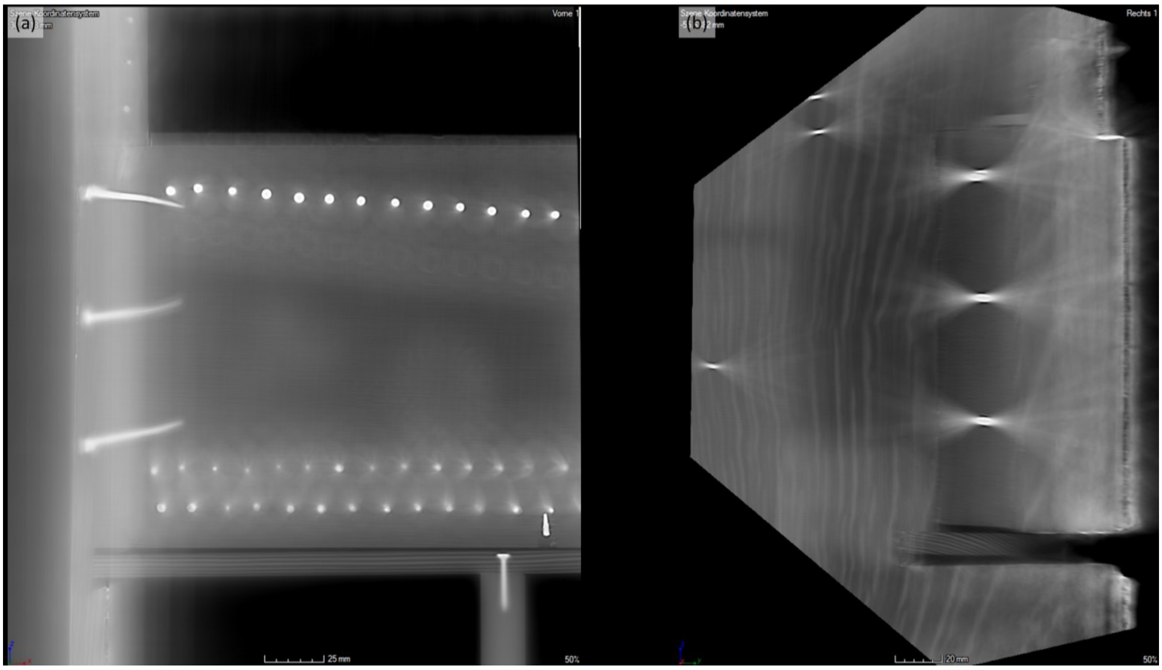

Figure 32: Combination of the scan trajectories used in Figure 31.

According to the examples given above, laminography should be considered if the organological question concerns structures oriented perpendicular to the detector plane, such as cracks in a pinblock. Otherwise a (limited angle) CT is expected to provide better results. In both cases the instrument has to be scanned in the orientation which results in the smallest diameter, i.e. upright in the case of grand pianos. If this is not possible for conservational reasons, there remains the possibility of a CT in a special facility like the XXL-CT mentioned above. Although at the moment comparable CT systems are rare, it is assumed that the conditions will change as the demand from industrial users increases.

14 Image Quality Improvement

To find the optimal parameters for a CT, several scans have to be compared. Therefore, some of the historical instruments have been scanned several times under different conditions. However, this was not done on a regular basis to avoid unnecessary exposure to radiation and to limit the time spent outside the well-tempered climate in the museum. Instead, either contemporary instruments were used for tests using different parameters or historical instruments with similar properties were compared.

14.1 Number of Projections Recorded per 360°

The number of recorded projections N per 360° is directly proportional to scan time and absorbed dose. Thus it was endeavoured to keep it as low as possible while still achieving the required image quality. A contemporary ukulele was scanned with $N = 2400, 3600$ and 4000. Equally spaced subsets of the projections were created. Finally, volumes were reconstructed with projection numbers ranging from $N = 360$ to $N = 4000$.

Choosing N too small leads to undersampling and thus to artefacts, typically in form of fine stripes seeming to originate from the edges of dense objects [21]. These artefacts can complicate analyses like surface identification and dimensional measurements. The improvement of image quality with increased N is visible in Figure 34.

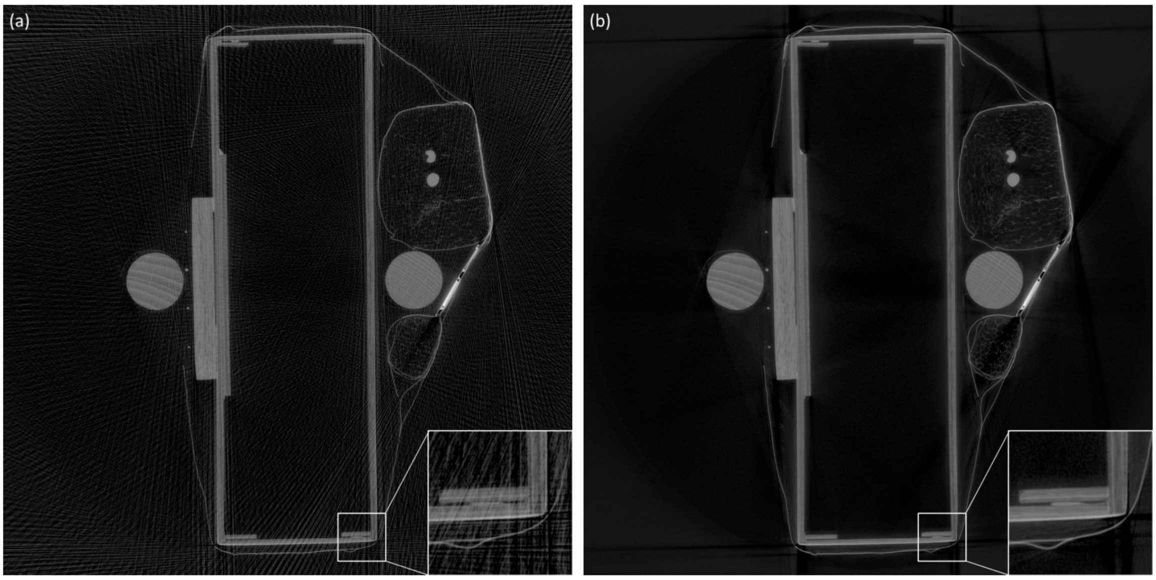

Figure 33: Cross section through a ukulele reconstructed from (a) 360 projections and (b) 4000 projections. The stripes caused by undersampling disappear when the projection number is increased.

For a quantitative analysis of the relation between N and the image quality the tailpiece was chosen. It consists of wood with an inserted plastic rod and was situated close to the centre plane of the reconstructed volume. Histograms of the attenuation coefficients of both materials were used to determine the mean attenuation coefficient and its standard deviation. As expected, mean attenuation and therefore the contrast were independent of N.

The noise measured by the standard deviation, decreases with increasing N. Consequently, the SNR increases with N, too. This dependence is plotted in Figure 35.

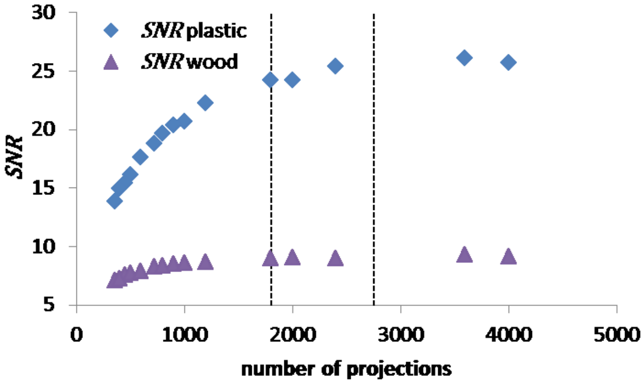

Figure 34: SNR ***of parts of the ukulele tailpiece depending on the number of projections recorded per 360°. The first and second vertical dashed lines indicate the number of projections typically used and the theoretically required number respectively.***

The contrast to noise ratio (CNR) also increases with N as shown in Figure 36. The CNR is given by the difference of the mean attenuation coefficient divided by the noise. When it becomes too low, two materials can no longer be distinguished.

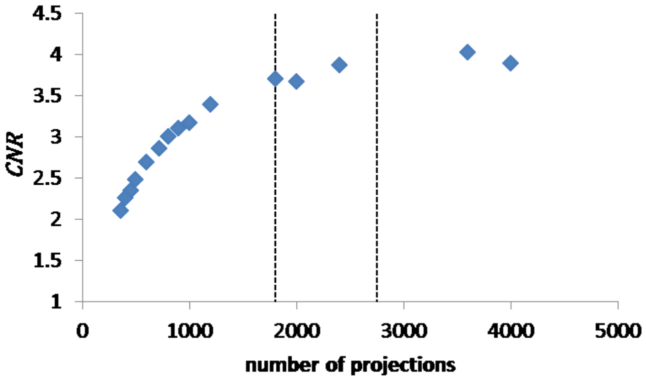

Figure 35:** CNR **between wooden and plastic parts of the ukulele tailpiece depending on the number of projections recorded per 360°. The first and second vertical dashed lines indicate the number of projections typically used and the theoretically required number, respectively.

As a rule of thumb, N should approximately equal the number of pixels the object covers on the detector in horizontal direction. In the case of the ukulele, this corresponds to $N \approx 2750$. Typically, $N = 1800$ was used in the project. Although the slope of the curves has not reached the plateau for this number, the expected gain in quality was deemed too small to justify the increase in scan time.

14.2 Reconstruction of Truncated Projections

Most of the CT scans recorded during the MUSICES project were reconstructed using state of the art filtered backprojection (FBP) algorithms. For scans with truncated projections Hilbert reconstruction was tested as well [22]. Suitable specimens were available in the form of stringed instruments. These were scanned with the aim of creating a high resolution reconstructed volume allowing a dendrochronological dating of the instrument's top plate. One of the test objects was the violin DNgnm_MI419. For comparison, two scans of a section of the corpus were carried out. The first one was a MFE comprising the whole diameter (Figure 37, a). With a resolution of 43 µm the tree ring structure is visible in detail (Figure 37, b).

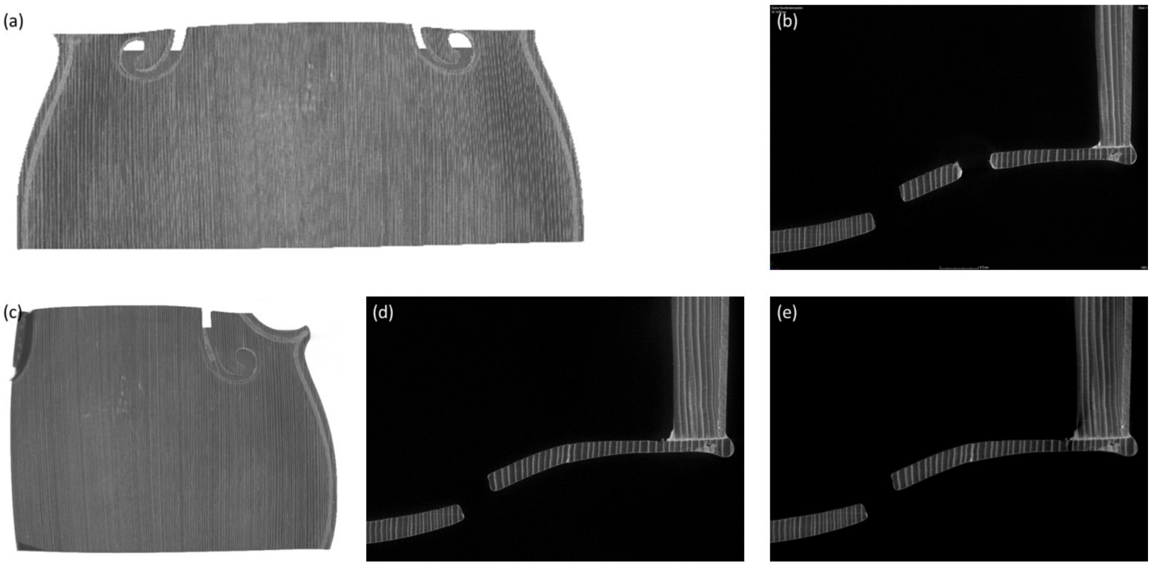

Figure 36: (a) A corpus section of violin DNgnm_MI419 was scanned using MFE. (b) The cross section through the top plate shows the tree ring structure. (b) A second CT comprised only a part of the right side of the corpus. (d) The cross section through the reconstruction of this second scan obtained using cosine padding shows a similar image quality. (e) Also a Hilbert reconstruction leads to similar results.

The second scan was a region of interest CT of the right side of the corpus section (Figure 37, c). Therefore, projections were truncated on both sides. The reconstruction was done either using FBP with cosine padding of the projections or by Hilbert reconstruction (Figure 37, d,e). Both data sets showed satisfactory image quality comparable to the MFE scan.

The Hilbert reconstruction is more complex and more time consuming than a standard FBP with cosine padding. Given that both algorithms give comparable results, FBP and cosine padding were chosen for other volume of interest scans.

14.3 Comparison of Different X-Ray Energies

The big bass pommer DBim_0289 was used to illustrate the influence of the X-ray spectrum on image quality. This woodwind instrument had been damaged and was repaired by fixing a metal patch to the corpus. The mended region was scanned with three different spectra (Figure 38).

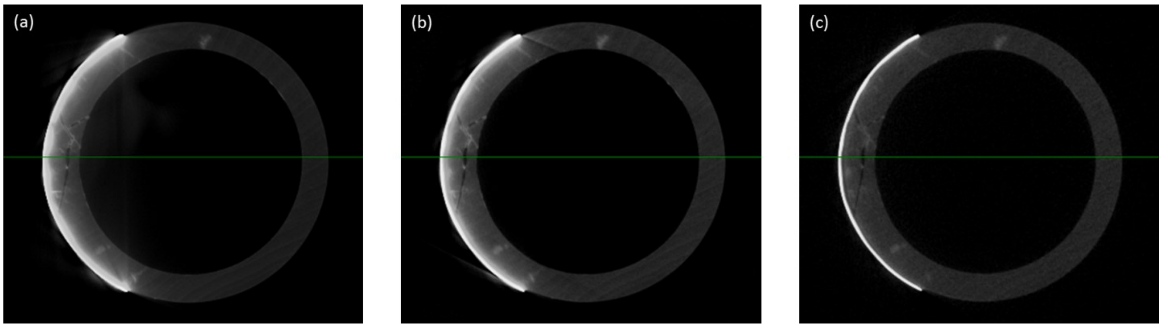

Figure 37: Cross section through the big bass pommer DBim_0289 for different X-ray tube voltages and prefilters: (a) **150 kV,** ***(b)*** **220 kV, 2.5 mm** ***Cu, (c)*** **600 kV, 6 mm** ***Cu,*** **1 mm** ***Zn. The artefacts caused by the metal patch are reduced when the spectrum becomes harder.***

To evaluate the changes due to the increased X-ray energy, line profiles through the object are considered in Figure 39. The measured attenuation of the wooden corpus changes from

0.1 cm^{-1} at 150 kV to 0.07 cm^{-1} when using a 600 kV spectrum prefiltered with 6 mm Cu and 1 mm Zn. At the same time the attenuation of the metal patch decreases by 60 %. This reduces the contrast by a factor of approximately two.

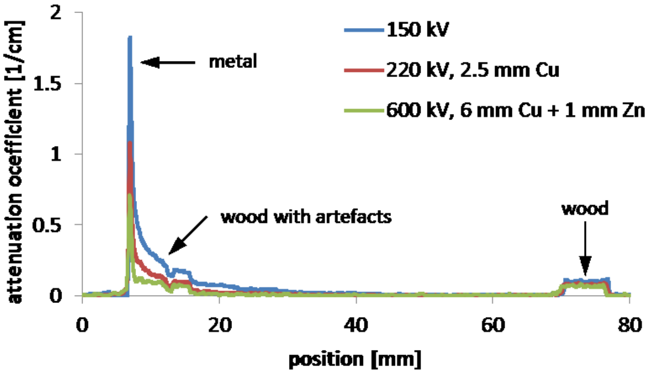

Figure 38: Line profiles along the green line in Figure 37. The reduction of artefacts and of the contrast between metal and wood with increasing X-ray energy is visible.

The line profiles also show that the value of the attenuation coefficient measured in the wood beneath the metal patch is close to the one measured on the other side of the instrument. This reduction of artefacts facilitates the determination of the interface between wood and metal, which increases the accuracy of measurements of the wall thickness.

14.4 Metal Artefact Reduction by Dual-Energy Methods

Musical instruments often consist of multiple materials with different X-ray attenuation coefficients. Wood and metal is a common combination, for instance in keyed woodwind instruments such as clarinets and oboes and in stringed instruments whose neck and corpus are connected by iron nails. When high spatial resolution is required, microfocus tubes have to be used. At the present time this limits the available tube voltage, which leads to metal artefacts.

An option to reduce the artefacts is the combination of two CT scans with different X-ray energies. There are several dual-energy approaches available [16, 23, 24, 25]. One of them is α-blending as used in medical CT [25]. This method is particularly easy to use as two volumes f_{HE} and f_{LE} reconstructed from a high energy and a low energy scan respectively, are weighted by a blending parameter α and combined linearly. As the aim is to reduce artefacts, α is not restricted to a particular range of values. The value of α depends on the X-ray spectra used and the scanned object. Finding the optimal α can be done either by visual evaluation or automatically using image quality measures as described, for instance, in references [14, 17].

A study using a contemporary clarinet showed that the two X-ray spectra should differ as much as possible while still transmitting the object [14].

As an example, Figure 40 shows cross sections through a part of the cor anglais DNgnm_MIR396. The maximum available tube voltage was 225 kV. As the low energy spectrum 220 kV with 0.89 mm Ti prefilter was used, which lead to strong artefacts in the form of extinction of the wooden structure. The high energy spectrum was chosen as 225 kV with 2.5 mm Cu prefilter, the amount of filtration being limited by the scan time. Although the artefacts are reduced in comparison to the low energy scan, parts of the wood are still not visible. The α-blending makes it possible to distinguish the wooden tube of the instrument. Also cupping artefacts in the metal parts are reduced. For more examples see [15].

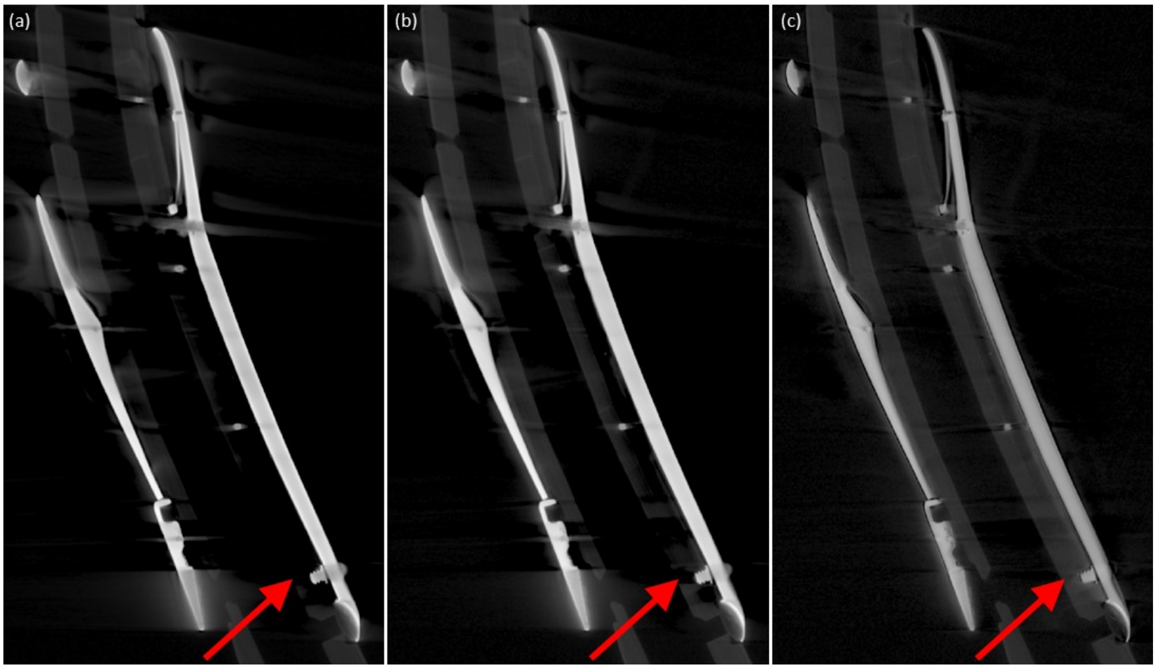

***Figure 39:** Cross section along the tube of cor anglais DNgnm_MIR396. (a) Scan with* **225 kV** *and* **0.89 mm** *Ti prefilter, (b)* **220 kV** *and* **2.5 mm** *Cu, (c) blending of both volumes with* α **= 1.6**. *Metal artefacts are reduced from left to right.*

Although α-blending could be used to approximate virtual monochromatic images, not every α actually corresponds to an X-ray energy [25]. Therefore, while α-blending successfully reduces artefacts, the resulting image does not necessarily correspond to physically meaningful values.

14.5 Iterative Beam Hardening Correction

Besides the dual-energy approach presented in section 14.4, a dedicated reconstruction algorithm was also tested to reduce artefacts caused by metallic structures. A method including an approximate model of beam hardening into a simultaneous algebraic reconstruction technique (SART) algorithm was used for this purpose [26, 27]. This method does not require knowledge of the X-ray spectrum or material parameters.

The method was tested using scans of a part of the glass transverse flute DNgnm_MI410. In an FBP reconstruction the inside of the glass tube shows an unrealistic increase of the attenuation coefficient of air beneath the metallic parts (Figure 41, a). The metal key itself shows cupping artefacts (Figure 41, b). When beam hardening is corrected with the SART

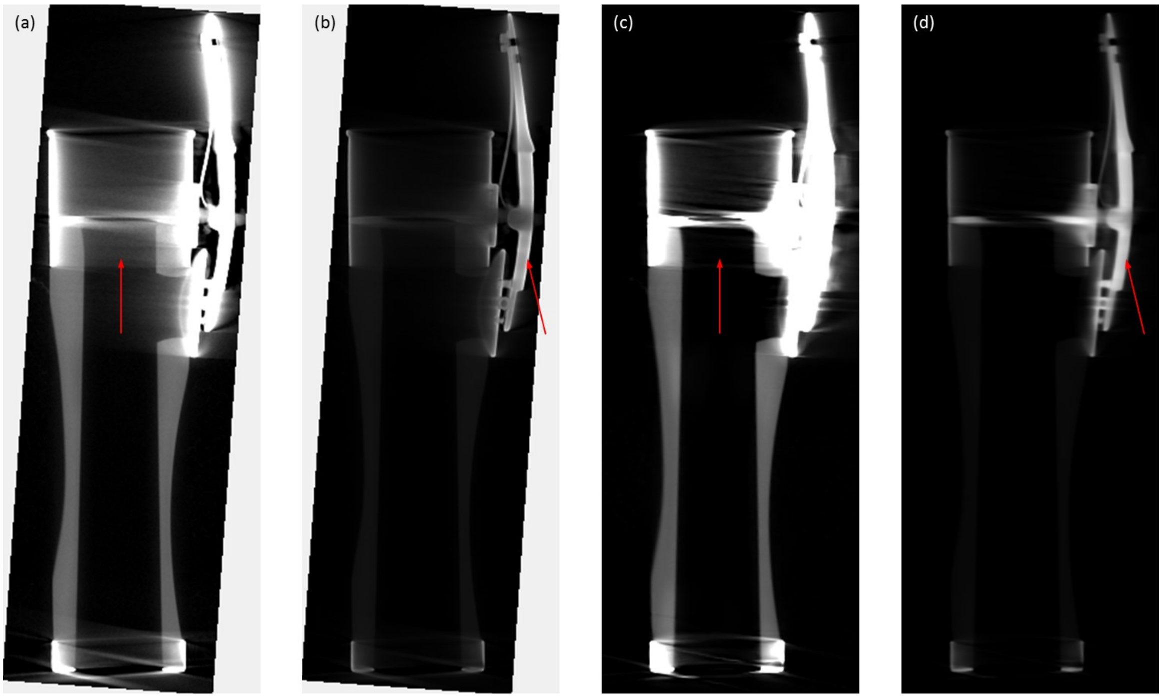

Figure 40: (a) A standard FBP reconstruction of a part of a transverse flute DNgnm_MI410 reveals artefacts inside the glass tube (metal parts appear white due to windowing) and (b) cupping artefacts in the metallic key. (c) Applying the SART algorithm brings the attenuation coefficient of air closer to zero inside the tube and (d) reduces the cupping artefact. Note that for the SART reconstruction twofold binning of the voxel size was applied.

algorithm these artefacts are successfully reduced (Figure 41, c,d). This method can be considered as an alternative to dual-energy methods to avoid two scans. However, as the algorithm is iterative and two parameters have to be optimized, the reconstruction time is increased as compared to standard FBP.

15 Material Characterization

15.1 Dual-Energy CT for Material Characterization

As the energy dependence of the attenuation coefficient depends on the material, dual-energy methods provide additional information that can help to distinguish different materials. There are various possible implementations that can be used to gain different material properties [16, 23, 24, 25, 28, 29, 19].

For instance, basis material decomposition can be used to attain the partial density of materials [19]. Other methods yield density and atomic number [29]. Typically, X-ray spectra and detector efficiency are required as input parameters. Also implementations using calibration measurements are possible.

The alpha-blending method described in section 14.4 can be used to obtain energy specific attenuation coefficients if choosing a corresponding value for α [25].

Most versions of dual-energy CT require two scans, which increases scan time, absorbed dose and cost. Due to conservational and economic reasons this is not always possible. As an alternative, specialized setups with either energy sensitive detectors or two sources and detectors can be used [16]. These setups allow the simultaneous recording of CT scans at two or more energies.

Dual-energy CT with the aim of characterizing materials was not tested thoroughly during the MUSICES project. The methods are mentioned here mainly for the sake of completeness.

15.2 Estimation of Wood Type and Density

Historical stringed musical instruments often contain various kinds of wood. For some objectives, like acoustical simulations or the creation of replicas, not only geometrical measurements are important, but also the density of the wood, as it influences the sound. For valuable historical objects this should be ascertained without disassembling the instruments to determine mass and volume of each part.

The used types of wood can also be of interest. However, in some cases parts of an instrument are not easily accessible for examination (corner blocks or linings in violins) and sometimes different types of wood appear similar (black stained pear and ebony). Furthermore, the identification of wood is usually done by investigating a small sample under a microscope, i.e. in a destructive manner. In some cases a measurement of the density might provide enough information to distinguish between certain kinds of wood.

Within the MUSICES project, it was investigated how much CT can contribute to the investigation of wood. To this end, a xylotheque from GNM, containing 120 blocks of different types of wood was used (Figure 42). Fifteen sets of eight blocks were scanned. The tube voltage was set to 200 kV, a value suitable for the CT of wooden musical instruments. Each block was segmented from the reconstructed volume to determine its volume and the mean attenuation coefficient. Furthermore, each block was weighted to calculate its density.

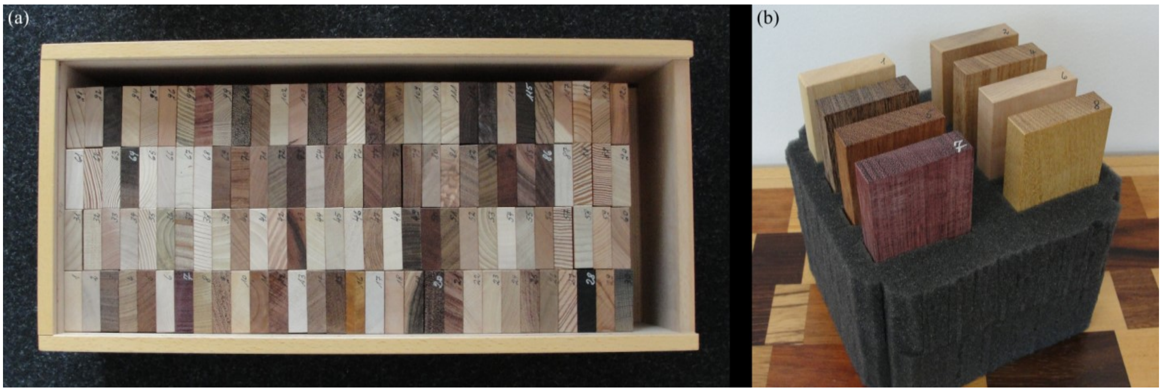

Figure 41: (a) Photograph of the whole xylotheque and (b) of one of the sets of eight wooden blocks assembled for a CT.

A plot of the mean attenuation coefficient over the density reveals a linear correlation (Figure 43). It indicates that different types of wood have a similar chemical composition and differ mainly in their density. This provides the possibility of gaining information on the woods present in a musical instrument. The instrument can be scanned together with several wooden reference samples. These samples should be placed at a position where no artefacts are expected, i.e. not close to high density parts. Their densities should preferably be distributed over a wide range. The density can be calculated from the mass and the volume. To attain the volume from the reconstruction by segmentation, it is important to separate the samples from each other and the instrument using low attenuation materials such as ethafoam. It is further recommended to use a helical scan trajectory to avoid affecting the measured attenuation coefficient by cone beam artefacts [20]. Using a plot as in Figure 43, the density corresponding to the attenuation coefficient of the types of wood in the instrument can be estimated. Furthermore, the CT scan reveals structural properties such as tree rings, rays or vessels and thus additional information on the type of wood.

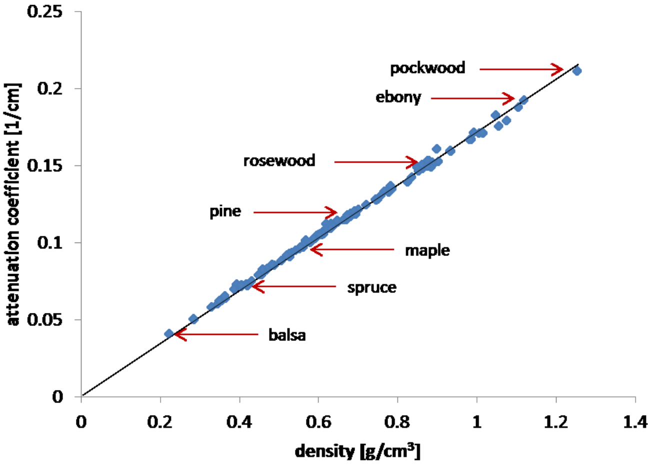

Figure 42: A linear relation is observed between the mean attenuation coefficient and the density of different types of wood. The position of some woods is indicated.

This is by no means a way of definitely identifying the exact type of wood. On the one hand, different woods such as fir and spruce can be similar in density and also in the appearance of the tree ring pattern. On the other hand, one kind of wood can have different properties depending on the origin of the tree or the location within the tree from which a piece of wood was taken. Thus, a higher resolution, comparable to that used for microscopy, is needed for a definite identification. Although this is possible, it requires a small sample and is therefore as destructive as the common microscopic method.

Nevertheless, the information provided by CT is useful. It allows an estimation of the density, which might be used for acoustic simulations. It can also narrow down the types of wood used in inaccessible places, such as softwood or hardwood, diffuse-porous or ring-porous wood etc. Furthermore, if it is suspected that a part of an instrument might be made of either one or the other of two kinds of wood, CT might help to clarify the question. In this case, it is suggested that the types of wood in question should be amongst the reference blocks.

When comparing the attenuation of an instrument with that of reference blocks, it is best to do so within one scan. The comparison of different scans is possible only when the same X-ray spectrum is used, as the slope of the curve in Figure 43 depends on the spectrum. In addition to this, it is important to compare the attenuation coefficient, not the grey values as the latter are normalized by a factor which is chosen arbitrarily in industrial CT.

While a xylotheque was used for the experiments, a similar method can be applied to some other materials as well. As in the case of wood, also for other organic materials, like ivory or mother of pearl, fluctuations of the X-ray attenuation were observed. Reference samples with different densities could thus be used to determine the density inside a musical instrument.

The identification of materials through comparison to references can also be attempted if the materials in question are known. However, the variation in density has to be taken into account when comparing parts of an instrument to reference samples. Attempting material identification purely on the foundation of density might not always be possible.

16 Geometrical Measurement Accuracy

To access the geometrical measurement accuracy of CT facilities, calibrated ball bars can be scanned with the instruments. After determination of the ball's surface, the distance of their centres d can be measured and compared to the calibrated value d_0. The deviation is given by $(d - d_0)/d_0$. It can be used to scale any geometrical measurements done in the reconstructed data.

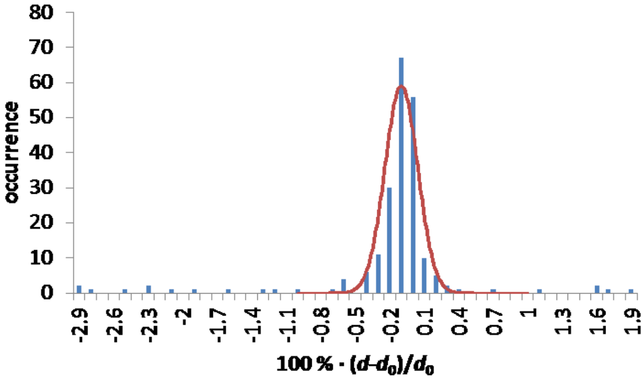

Figure 43: Histogram of the deviation of the measured ball bar size from the calibrated value. The red line shows a Gaussian curve fitted to the data.

A histogram showing the deviations found during the MUSICES project is provided in Figure 44. A Gaussian fitted to the data is centred at -0.1 % with an FWHM of 0.4 %. This accuracy is deemed sufficient for a utilisation of the reconstructed volume data.

17 Conventions for the Nomenclature of Files

17.1 Identifiers and Work Flow Numbers

The persistent and unambiguous storage of data sets requires their traceable naming. When dealing with large CT data sets, it is highly recommended to record the most important specifications in their filename to minimise the risk of “orphaned” data sets in the data management. This also facilitates merging distributed data pools, for instance to establish research infrastructures. Encoding the identifiers permits an unambiguous assignment of the objects to the respective measurements and reconstructions in all steps of the workflow. Therefore, the proposed naming conventions document information concerning the object as well as the measurement. The filenames of projections and reconstructions are assembled from identifiers assigned during the workflow. In every working step the object-ID is retained and expanded by appropriate supplements to obtain the IDs of measurement and reconstruction.

17.1.1 Identifiers in the Working Area “Object Description”

In a first step, each object is given an identifier (object-ID), composed of the owner (for collections of musical instruments, the ICOM-CIMCIM-Sigel[24] of the preserving institution [25] is used) and the inventory number of the object. The form of the object-ID is:

Owner_InventoryNumber

For example:
DNgnm_MI419

17.1.2 Identifiers in the Working Area “Measurement”

In the working area “measurement” the ID is expanded by information regarding date, measurement site and operating institution of the CT facility. This results in the following basic structure:

Owner_InventoryNumber*_Date_SiteOfMeasurement_OwnerOfCTfacility*

example:
DNgnm_MI419*_20150917_FUERTH_FHGEZRT*

There are three possible supplements for naming the projection data. They are, if applicable, appended to the basic structure in the following order:

_M*xx*	Supplement for object measurements with identical scan procedure (helical, MFE…) and identical parameters such as tube voltage, prefilter, *FDD* and *FOD*. Several measurements are assigned to the same object measurement if the individual data sets can be combined to a larger one.
_VOI*x*	Volume of Interest. Supplement, if the object measurement comprises only a part of the instrument.
_V*x*of*y*	Supplement for the measurement of an individual volume within one object measurement. Several of these volumes can be assembled to a larger one.
x resp. *xx*	numbering of object measurements, volumes and VOIs
y	total number of measurements within one object measurement

17.1.3 Identifier in the Working Area “Reconstruction“

The name of the reconstruction is created from the name of the measurement and two possible supplements:

_TV	Partial volume (from German: Teilvolumen). Supplement, if an instrument is cut from the measurement of a cluster.
_R*xx*	Supplement for reconstructions.
xx	numbering of reconstructions

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[24] Cf. http://network.icom.museum/cimcim/resources/sigla-for-musical-instrument-collections/, (last access 19.2.2018) or: The Grove Dictionary of Musical Instruments. Second edition. Edited by Laurence Libin. Vol. 1, New York 2014, S. lix–lxxxiii. – The dots in the sigel are erased for the data name.

[25] Usually the preserving institution orders a CT-scan and not a private owner in case of a permanent loan of an object.

When combining several reconstructions, the respective present supplements are continued in a way preserving the meaning.

17.2 Examples

17.2.1 Object Measurement

Three CT scans of a violin were carried out. The first of them was a helical scan of the whole instrument. Subsequently, two scans of partitions were done, applying MFE in one case and a simple circular CT in the other. The file names are accordingly:

DNgnm_MI419_20150917_FUERTH_FHGEZRT_*M01*

DNgnm_MI419_20150917_FUERTH_FHGEZRT_*M02*_VOI1

DNgnm_MI419_20150917_FUERTH_FHGEZRT_*M03*_VOI2

17.2.2 Measurement of Part of an Instrument

Each of the object measurements M02 and M03 of the violin comprised only a part of the instrument with high spatial resolution. Using an MFE and a circular CT with truncated projections, different parts of the corpus were captured. Thus, the filenames receive the supplements VOIx:

DNgnm_MI419_20150918_FUERTH_FHGEZRT_M02_*VOI1*

DNgnm_MI419_20150918_FUERTH_FHGEZRT_M03_*VOI2*

17.2.3 Measurement of Several Volumes to Be Concatenated

17.2.3.1 Example 1: Viola da Gamba DNgnm_MIR791

The viola da gamba DNgnm_MIR791 was scanned in seven sections. The projections are named:

DNgnm_MIR791_20150414_FUERTH_FHGEZRT_M01_*V1of7*
…
DNgnm_MIR791_20150414_FUERTH_FHGEZRT_M01_*V7of7*

When combining some of the reconstructions of these volumes, e.g. for the neck, the resulting name is:

DNgnm_MIR791_20150414_FUERTH_FHGEZRT_M01_*V5to7*_R01

The supplement *V5to7* reveals that this data set contains only a part of the object scanned in object measurement M01.

When all volumes are assembled to a reconstructed data set of the whole instrument, it is called:

DNgnm_MIR791_20150414_FUERTH_FHGEZRT_M01_R01

As all volumes of object measurement M01 are included, a supplement *V1to7* is not required.

17.2.3.2 Example 2: Viola da Gamba DNgnm_MI5

The case of viola da gamba DNgnm_MI5 is more complex. Its corpus was scanned using seven threefold MFE scans, while four twofold MFEs were needed for the neck. Hence, there are two object measurements, each of which only concerns a part of the instrument. The files corresponding to the corpus are entitled:

DNgnm_MI5_20151020_FUERTH_FHGEZRT_M01_VOI1_*V1of7*
…
DNgnm_MI5_20151020_FUERTH_FHGEZRT_M01_VOI1_*V7of7*

When these volumes are combined to a reconstructed data set of the whole corpus, this results in:

DNgnm_MI5_20151020_FUERTH_FHGEZRT_M01_VOI1_R01

The corresponding names for the neck are:

DNgnm_MI5_20151020_FUERTH_FHGEZRT_M02_VOI2_*V1of4*
…
DNgnm_MI5_20151020_FUERTH_FHGEZRT_M02_VOI2_*V4of4*

If the reconstructions of corpus and neck are combined, the result is:

DNgnm_MI5_20151020_FUERTH_FHGEZRT_*M01_R01_M02_R01*

As the supplements for the reconstruction numbers of both object measurements could be different, they have to be retained. The supplements VOI1 and VOI2 are not mentioned any more since the reconstruction contains the whole instrument.

17.2.4 Processing of Several Measurements of the Same Region

The basset horn DNgnm_MIR465 contains several metal parts. To reduce artefacts caused by the metal, dual-energy methods were to be used. To this end, sections of the instrument were scanned repeatedly, using different prefilters each time.

The scan of the whole tube of the instrument is denoted:

DNgnm_MIR465_20170309_FUERTH_FHGEZRT_*M01_VOI1*

A further scan with different prefilter encompassed only the lower part of the tube. It consequently concerns a different VOI, which is a part of VOI1. The measurement is thus called:

DNgnm_MIR465_20170309_FUERTH_FHGEZRT_*M02_VOI2*

The further processing of the measurements using dual-energy methods can only make use of the smaller region *VOI2*. Only this smaller volume is thus shown in the resulting volume data set. Consequently, the region *VOI2* is indicated in the file name, although one of the measurements comprised a larger volume originally. Hence, this yields:

DNgnm_MIR465_20170309_FUERTH_FHGEZRT_*M01_VOI***2**_R01_*M02_VOI2*_R01

17.2.5 Instrument Cut from a Cluster of Instruments

Four recorders were scanned together as a cluster to reduce scan time. If, later one of these instruments is cut out in a processing program, the inventory numbers of the other instruments are eliminated from the filename. To make sure that it can still be recognised that the instrument was scanned in a cluster, *_TV* is appended to the file name. As an instrument can only be at one place at a given time, the corresponding cluster can be found in the data base by means of the time stamp.

The whole cluster is denoted:

DNgnm_*MI140_MI139_MI138_MI211*_20150303_FUERTH_FHGEZRT_M01_R01

A reconstructed volume data set of a single instrument thereof is named:

DNgnm_*MI140*_20150303_FUERTH_FHGEZRT_M01_*TV*_R01

17.2.6 Reconstruction

As there are different options to create a reconstruction from a projection data set, these reconstructions are numbered. The FBP with cosine padding and a Hilbert-reconstruction procedure were used for the truncated projections of the violin mentioned in 17.2.2. This results in the names:

DNgnm_MI419_20150918_FUERTH_FHGEZRT_M03_VOI1_*R01*

DNgnm_MI419_20150918_FUERTH_FHGEZRT_M03_VOI1_*R02*

18 Cross Sections

18.1 Definition Basis

The recommended definition of cross sections is based on intense research concerning de-facto documentation standards in catalogues and other publications on musical instruments. They were defined for the representative selection of musical instruments for the MUSICES-project and are also transferable to further types of musical instruments.

Due to the fact that cross sections always depend on the geometry of objects which are, in the case of musical instruments, not congruent to their organological classification (e.g. in case of straight and curved cornettos) sometimes individual solutions have to be found which might differ from organological criteria.

18.2 Description

The vocabulary for the description of the cross section is based on the anatomical terms for locations and directions in medicine. The orientation of an object is described in an x-y-z-coordinate system. The plane which is defined by x- and z- axis is named frontal plan, the one defined by y- and z-axis is named sagittal plane and the one defined by x- and y-axis is named transversal plane (Figure 45). The orientation in which an instrument is scanned in the CT-facility matches only by chance the one which is suitable for viewing and evaluation. This is why the reconstruction has to be turned by a rotation vector according to the conventions. If the scan of a recorder is aligned along the z-axis, the tone holes can point in the direction of the y-axis (“in frontal direction”). A cross section through the centre of the bore which shows also the tone holes is made in the sagittal plane.

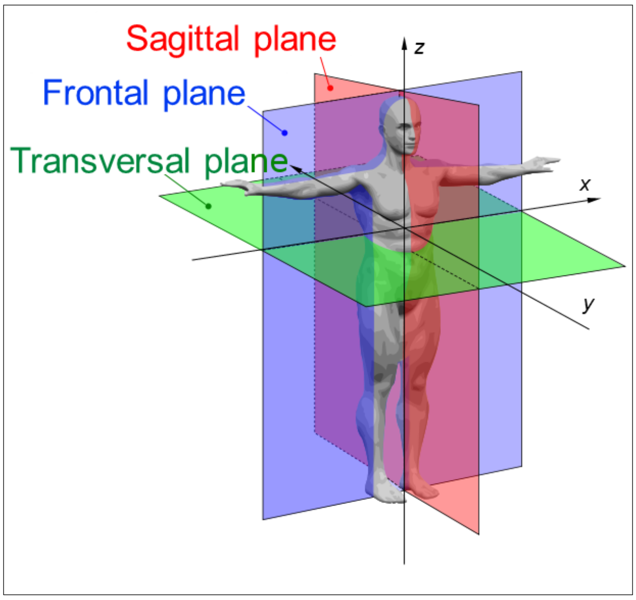


Figure 44: Illustration of cross sections at a human body.

In order to document the exact position of the cross section, two description systems are used. The approximate position can be indicated by a short description which is based on the constructional elements of the instruments and which defines the location at the object (“longitudinal cross section through the centre of the instrument in the position of the tone holes”).

A different form of description uses the reconstructed data set as orientation in which every position in the 3-dimensional space can be described using coordinates. In case the origin of the coordinate system is placed in the centre of the volume, every position can be defined relatively to this zero point. This guarantees an unambiguous description of the position of a cross section through a data set. The required data are:

1. The rotation vector
2. The angle of rotation around the rotation vector in degrees

3. The actual position in the orthogonal display which describes the distance to the zero point in millimetres

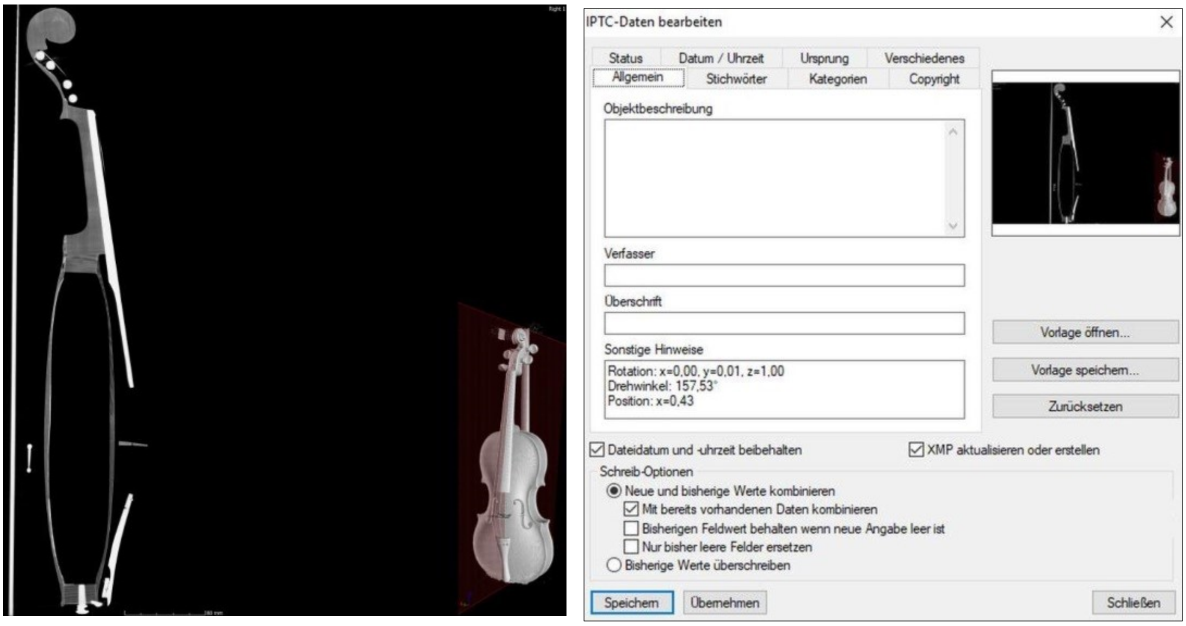
For a better orientation in every cross section image a 3D-miniature is implemented which shows the actual plane (Figure 45).

The image should be saved in the best possible resolution. The format Tiff, 24 bit RGB is recommended.[26] The named metadata should be entered in the IPTC data in the following format using the field “other notes”:

Rotation vector: x=0.00, y=0.01, z=1.00

Angle of rotation: 157.53°

Position: x=0.43 mm



Objektbeschreibung

Verfasser

Überschrift

Sonstige Hinweise

Rotation: x=0,00, y=0,01, z=1,00
Drehwinkel: 157,53°
Position: x=0,43

☑ Dateidatum und -uhrzeit beibehalten
☑ XMP aktualisieren oder erstellen

Schreib-Optionen
● Neue und bisherige Werte kombinieren
  ☑ Mit bereits vorhandenen Daten kombinieren
  ☐ Bisherigen Feldwert behalten wenn neue Angabe leer ist
  ☐ Nur bisher leere Felder ersetzen
○ Bisherige Werte überschreiben

Figure 45 left: cross section, made with „myVGL“; right: input field for IPTC data in „XnView“

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[26] X-ray images only contain differences in light intensity and a grey scale image would be sufficient. The RGB-format provides the possibility to display coloured cross sections or false colour renderings of different materials

The following tables provide an overview of the cross sections recommended for different types of instrument. The table on the right explains the colour coding:

Orientation Abbr.	Description	Instruments
A1	Lengthwise to y-axis, finger-hole diameter parallel to frontal plane	Reeds, transverse flute, recorder, crumhorn, cornet, rackett
A2	Baseboard and underboard respectively parallel to transversal plane, key-fronts parallel to frontal plane	Keyboard instruments
A3	Neck and pegbox respectively parallel to y-axis, top parallel to frontal plane	Bowed and plucked stringed instruments
A4	Actioin parallel to frontal plane, cf. MIMO, cross section: bell	Brass instruments
A5	Baseboard parallel to transversal plane, strings parallel to frontal plane (playing position)	Dulcimer and zither
D	Individual description	

Type of Instrument	**Cross Section 1**	**Cross Section 2**	**Cross Section 3**	**Cross Section 4**	**Cross Section 5**	**Orientation**	**Description**
Woodwinds							
Recorder	Sagittal plane	Frontal plane	Transversal plane			A1	
Crumhorn	Sagittal plane	Transversal plane				A1	
Rackett	Sagittal plane	Frontal plane	Transversal plane			A1	
Shawm	Sagittal plane	Frontal plane	Transversal plane			A1	
Cornetto	Sagittal plane	Transversal plane				A1	
Clarinet	Sagittal plane	Frontal plane	Detail mouthpiece			A1	

Type of Instrument	Cross Section 1	Cross Section 2	Cross Section 3	Cross Section 4	Cross Section 5	Orientation	Description
Transverse Flute	Sagittal plane	Frontal plane	Transversal plane			A1	
Harmonica	Sagittal plane	Transversal plane				A1	Orientation of key axis to median axis; Transversal through reed
Saxophone	Sagittal plane					D	Lengthways to y-axis, bell frontal, cross section to sagittal plane
Shawm	Sagittal plane	Frontal plane	Transversal plane			A1	Transversal through reed
Oboe	Sagittal plane	Transversal plane				A1	
Bassoon, Dulcian	Frontal plane	Sagittal plane	Sagittal plane			A1	Frontal plane (both joints), 2x sagittal plane (1x wing joint/ bocal, 1x bass joint/ incl. bell)
Cor Anglais	Sagittal plane	Transversal plane				A1	
Blow Pipe	Sagittal plane	Frontal plane				A1	
Drone Pipe	Sagittal plane	Frontal plane				A1	
Bell	Sagittal plane					D	Opening of bell to y-axis, opening of tube to z-axis
Wooden Trumpet	Frontal plane					A1	
Serpent	Frontal plane					A1	

Type of Instrument	Cross Section 1	Cross Section 2	Cross Section 3	Cross Section 4	Cross Section 5	Orientation	Description
Brass Instruments							
Box Trumpet	Sagittal plane	Transversal plane				D	bell shows down in direction to y-axis, mouthpiece in direction to z-axis, Sagittal = median (transversal through mouthpiece)
Double Horn	Frontal plane	Detail valves				A4	2 orientations: 1. bell stay on transversal plane, Corpus parallel to x-axis: Frontal section (middle of bell). 2. orientation valves vertical to y-axis, parallel to x-axis
Cornet	Frontal plane	Valves				A4	Valves parallel to frontal plane, cf. MIMO, cross section: bell
Bass Tuba	Frontal plane	Valves Sagittal plane				A4	Valves parallel to frontal plane, cf. MIMO, cross section: bell
Mouthpiece	Sagittal plane					D	Shank along the y-axis

Type of Instrument	Cross Section 1	Cross Section 2	Cross Section 3	Cross Section 4	Cross Section 5	Orientation	Description
Keyboard Instruments							
Harpsichord, Pianoforte	Sagittal plane	Transversal plane	Frontal plane			A2	1: Cross section: middle of instrument (through a key/hammer-shank/jacks). 2: Cross section 1 through the ribs, cross section 2 through rim and braces. 3: Cross section 1 through pinblock, cross section 2 through rim/braces/soundboard.
(Octave) Spinet	Sagittal plane	Transversal plane	Frontal plane			A2	1: Cross section: middle of instrument (through key/hammer-shank/jacks). 2: Cross section 1 through the ribs. 3: Cross section1 through the pinblock, cross section 2 through the back third.

Type of Instrument	Cross Section 1	Cross Section 2	Cross Section 3	Cross Section 4	Cross Section 5	Orientation	Description
Square Piano	Sagittal plane	Transversal plane	Frontal plane			A2	1: Cross section 1 through the action (through a key/hammer-shank), cross section 2 through soundboard. 2: Cross section 1 through the ribs and pinblock, cross section 2 key-frame. 3: Cross section 1: anterior third, cross section 2: back third.
Bowed and Plucked Stringed Instruments							
Violin, Viola, Violoncello	Frontal plane	Sagittal plane	Transversal plane	Transversal plane	Transversal plane	A3	3a: Cross section widest distance of lower bout, 3b: shortest distance of waist, 3c: widest distance of upper bout
Kit (Pochette)	Frontal plane	Sagittal plane	Transversal plane			A3	
Viol (Viola da gamba)	Frontal plane	Sagittal plane	Transversal plane	Transversal plane	Transversal plane	A3	3a: Cross section widest distance of lower bout, 3b: shortest distance of waist, 3c: widest distance of upper bout

Type of Instrument	Cross Section 1	Cross Section 2	Cross Section 3	Cross Section 4	Cross Section 5	Orientation	Description
Hurdy-gurdy	Frontal plane	Sagittal plane	Transversal plane	Transversal plane	Transversal plane	A3	3a: Cross section widest distance of lower bout, 3b: shortest distance of waist, 3c: widest distance of upper bout
Guitar	Frontal plane	Sagittal plane	Transversal plane	Transversal plane	Transversal plane	A3	3a: Cross section widest distance of lower bout, 3b: shortest distance of waist, 3c: widest distance of upper bout
Lute, Mandolin	Frontal plane	Sagittal plane	Transversal plane			A3	
Harp	Sagittal plane					D	Orientation: frontal, strings parallel to sagittal plane, upright to y-axis
Cittern	Frontal plane	Sagittal plane	Transversal plane			A3	
Dulcimer and Zither							
Dulcimer	Transversal plane	Frontal plane				A5	Transversal below the soundboard, frontal plane definition strings
Zither	Transversal plane	Frontal plane				A5	Transversal below the soundboard, frontal plane definition strings
Automatic Musical Instruments							
Metronome	Sagittal plane	Transversal plane	Frontal plane			D	Transversal through the mechanic
Automatic Virginal	Sagittal plane	Transversal plane	Frontal plane			A2	

Type of Instrument	Cross Section 1	Cross Section 2	Cross Section 3	Cross Section 4	Cross Section 5	Orientation	Description
Ribbon Metronome	Sagittal plane	Transversal plane				D	
Manopan	Sagittal plane	Transversal plane	Frontal plane			D	Underbody parallel to transversal plane, mechanic for score at front
Non-European Musical Instruments							
Sheng	Sagittal plane	Transversal plane				D	Mouthpiece to sagittal plane; Cross section through the mouthpiece; Transversal through the pipes
Arched Harp	Sagittal plane					D	Level of strings sagittal
Lutes	Frontal plane	Sagittal plane				A3	
Gamelan-Gong	Sagittal plane					D	Upright like a bell
Conch-shell Trumpet	Transversal plane	Frontal plane				D	Lying on the x-axis, mouthpiece in direction to z-axis. Cross section: frontal widest diameter, transversal
Panpipe	Frontal plane	Transversal plane				D	Playing position
Vessel Flute in Bird Shape	Sagittal plane					D	Lengthways to sagittal plane
Membranophones							
Damaru/Drum	Sagittal plane					D	Drumhead parallel to transversal plane
Tube Mirliton	Sagittal plane	Transversal plane				A1	Bell staying on transversal plane, corpus parallel to x-axis

Type of Instrument	Cross Section 1	Cross Section 2	Cross Section 3	Cross Section 4	Cross Section 5	Orientation	Description
Mirliton	Sagittal plane	Transversal plane				A1	Bell staying on transversal plane, corpus parallel to x-axis
Drum	Frontal plane	Transversal plane				D	Staying on transversal plane
Kettledrum	Frontal plane	Transversal plane				D	
Other Types							
Whistle	Sagittal plane					A1	
Ocarina in Bird Shape	Sagittal plane					D	Lengthways to sagittal plane
Accordion	Sagittal plane	Frontal plane	Transversal plane	3D-Volume (parts of metal)		D	Playing position 1. Sagittal: reeds right hand; 2. Sagittal left hand; 3. Transversal through the bar
Ocarina	Sagittal plane	Transversal plane	Frontal plane			D	Orientation: laying, labium parallel to x-axis 1. Cross section sagittal through the labium 2. Transversal through the widest diameter
Physharmonica	Sagittal plane	Transversal plane	Frontal plane			A2	

19 X-ray Relevant Object Information (Example)

1. Identification

Object: Oboe in C, 3 keys
Maker: Cosins, N.
Date of manufacture: 2nd half of 18th century
Place of manufacture: France (?)
Owner: GNM
Inventory number: **MIR 375**

Abb.1 MIR375 Oboe in C

2. Date and Executor

Date of scan: 11.04.2017
Performance of scans:
Transport of the objects:

3. X-Ray-Relevant Features

Description:
Straight-Top-Model. 3-part body: upper joint, lower joint, bell. 3 keys: c1, d#1 (2x). d#1-keys and c1 key lever mounted in ring, c1 key cover mounted block. Double tone holes III and IV, two resonance holes in the bell.

Object size:
Max. height: 545 mm
Max. width: 58 mm

Further dimensions see below

Overall size including mounting (exhibition size):
Max. Height (y): 785 mm
Max. Width (x): 105 mm

Material

Wood; ferrules and keys: brass

4. Conservational Requirements

Object must be handled by conservator; climate: max. 50 % RH at 18–20 °C.

5. Scientific Issue

Examination of construction, modifications and repairs

Keys may be removed. The springs under the keys cannot be removed and probably consist of spring steel (Position: see arrows).

Dimension springs: length approx. 12 mm, width approx. 1.5 mm, thickness approx. 0.1 mm.


16,5 mm
185
21,5
545
180
71
100
8
21
125
58

20 Check Lists

The following check lists have served very well during the MUSICES project. They are a valuable aid in supporting the somewhat complex workflows and last but not least they are a good means of protecting the delicate objects and obtaining the best possible results.

These check lists can be used freely and modified to suit any user´s requirements. The single fields are not focused on musical instruments, so the lists can be used for other types of cultural heritage objects.

Check List for the CT Examination of Historic Musical Instruments and Other Cultural Assets

– Museums and Other Institutions of Cultural Heritage –

Object / Inv.-No.
ID (Owner_InventoryNumber_Date_SiteOfMeasurement_OwnerOfCTfacility)

1. Preparation Museum

Make appointment for measuring campaign	Date of measuring campaign:	☐
Insure Object		☐
Organise Transport		☐
Take object from reserve / showcase		☐
Check and document conservational condition; perform fixing measures if necessary		☐
Clean if necessary		☐
Object documentation: 1. Object description 2. X-ray-relevant features 3. Conservational requirements 4. Scientific issue		☐
Plan fixing and positioning of the object for the examination, test and take photos.		☐
Pack object for transport (taking external climate and climate in CT-facility into consideration)		☐
Prepare camera, hygrometer, climate-data-logger, packing and supporting materials		☐
Transport to CT-facility	Date of transport:	☐

2. Measurement

Mounting and positioning of the object		☐
Photo documentation		☐
Transport back to museum	Date of transport:	☐

3. Follow up

Register return of the object	☐
Unpack the object and put it back in place	☐

4. Data storage

Record data in database	☐

5. Reconstruction files

Reconstruction files received	Date, name:	☐
Reconstruction files stored	Date, name:	☐

Check List for the CT Examination of Historic Musical Instruments and Other Cultural Assets

– X-Ray Institutes –

Object	**Inv.-No.**
Owner	

1. Long-Term Measurement Planning

Description of object, X-ray relevant properties, conservational requirements, scientific question available	Date	☐
Choosing CT facility and method (circular-CT, helical-CT, MFE…)		☐
Calculation focus-object- and focus-detector-distance		☐
Checking planned positions using dummy if necessary		☐
Choosing spectrum, tube current and integration time		☐
Definition projection number according to width of object		☐
Drawing up schedule and transmitting it to customer		☐
Entering planned parameters into checklist		☐

2. Short-Term Measurement Planning

Turning on air conditioning and / or humidifier if necessary	☐
Checking of CT facility (adjustment, filament…)	☐

3. CT Scan

Mounting of image quality identifiers and reference materials to object	☐
Positioning of object and verification of planned CT parameters	☐
Recording of offset image	☐
Recording of gain image using measurement conditions	☐
Performing calibrations (e.g. identification of rotation centre…)	☐
Photographic documentation of setup	☐
Checking available memory on data storage medium	☐
Recording projection at starting position for later check for object movement	☐

4. CT Scan Parameters

Object	**Inv.-No.**
Date	
ID (Owner_InventoryNumber_Date_SiteOfScan_OwnerOfCTfacility_MeasurementNo)	

	planned parameters	**comments**	**used parameters**	**comments**
Facility				
Detector				
Detector binning				
X-ray tube				
Tube voltage				
Prefilter				
Tube current				
Tube position				
Object position				
Detector position				
Focus-object-distance				
Focus-detector-distance				
Voxel size				
CT-method				
FlyBy / Stop&Go				
Projection no./360°				
Integration time				
Averaging / skip				
Image quality identifier				

5. After the Scan

Recording projection at starting position for check for object movement	☐
Twofold securing of recorded data	☐
Measurement of absorbed dose (air kerma K_a)	☐

21 Key Data of Objects / CT-Parameters

The following tables contain the most important physical properties, namely material and size, as well as the applied scanning parameters for a representative selection of instruments. This compilation should help to assess whether a CT scan of a particular object can be performed with the technical equipment of a certain X-ray institute.

Information on X-ray voltage and the prefilters used can be especially useful when scanning objects which are made of high-absorbing materials such as brass instruments. Instruments which cannot be entirely scanned by a circular-CT were measured either using helical-CT (column “trajectory”) or by assembling several scans (column “number of assembled scans”). The number of projections per 360° is determined by the diameter of the object and allows the operator of the CT-facility to estimate the scan time when combining them with the distance of X-ray source and detector. The achieved voxel size can be estimated by combining focus-object-distance (FOD) and focus-detector-distance (FDD) in correlation to the pixel size of the detector.

A detailed documentation of all parameters concerning objects and technical setting can be retrieved from the MUSICES database.

Other Wind Instruments

Object (ID)	Common Name	Material	Dimension	Dimensions in mm	Number of Assembled Scans	X-ray Voltage in kV	Trajectory	Focus-Object-Distance in mm	Focus-Detector-Distance in mm	Angles per 360° Rotation	Prefilter - Element	Prefilter - Thickness in mm	Pixel size N_X in mm	Pixel size N_Y in mm
DNgnm_W2586	3 whistles	Metal, bone, wax	Height	84.2/81/77.4	-	220	Helix	116.183	658	1200			0.2	0.2
DNgnm_MIR240	Vessel flute	Red clay with lead glaze			-	150	Circular	133.156	704.086	1200			0.148	0.148
DNgnm_MIR1041	Harmonica in form of a flageolet	Metal	Height Width Material thickness bell, Material thickness keys	346 55 0.4 1 – 3.5	2	600	Circular	2198.83	2500	2400	Cu + Zn	4.5 + 1	0.2	0.2
DNgnm_MIR1041	Harmonica in form of a flageolet with mouthpiece	Metal	Height Width Material thickness bell, Material thickness keys	346 55 0.4 1 – 3.5	-	220	Helix	162.25	593.305	1600	Cu	2.5	0.2	0.2
DNgnm_MIR243	Ocarina	Clay			-	150	Helix	332.261	704.086	1200			0.148	0.148
DBem_VA598	Vessel flute	Clay	Height Width Depth	151 224 103	-	150	Helix	447.7	703.399	1800			0.148	0.148

Other Wind Instruments														
Object (ID)	Common Name	Material	Dimension	Dimensions in mm	Number of Assembled Scans	X-ray Voltage in kV	Trajectory	Focus-Object-Distance in mm	Focus-Detector-Distance in mm	Angles per 360° Rotation	Prefilter - Element	Prefilter - Thickness in mm	Pixel size N_X in mm	Pixel size N_Y in mm
DNgnm_MIR103	Tube mirliton	Wood, iron	Height Width	215 80	-	150	Circular	579.493	833	1440			0.148	0.148
DBem_VA13068	Conch-shell trumpet	Conch	Height Width Depth	102 182 143	-	220	Helix	273.5	593.25	1600	Cu	2.5	0.2	0.2
DBem_VA18511	Conch-shell trumpet	Clay	Height Width Depth	95 169 124	-	220	Helix	324	643.246	1600	Cu	2.5	0.2	0.2
DBem_IC7743	Conch-shell trumpet (barataka)	Conch	Width Depth Length	111 80 72	-	220	Helix	201	593.249	1600	Cu	2.5	0.2	0.2
DNgnm_MIR1378	Sheng	Wood	Height Width	420 105	-	220	Helix	273.684	613.247	1600	Cu	0.5	0.2	0.2
DNgnm_MI977	Whistle	Wood, horns, brass	Height Depth	93 26.2	-	220	Helix	116.183	658	1200	Cu	1	0.2	0.2
DNgnm_MI978	Whistle	Wood, horns, brass	Height Width	73 23	-	220	Helix	116.183	658	1200	Cu	1	0.2	0.2
DNgnm_W2587	Whistle (cuckoo)	Ivory, maple	Height	121.2	-	160	Helix	116.183	658	1200			0.2	0.2

Brass Instruments														
Object (ID)	Common name	Material	Dimension	Dimensions in mm	Number of Assembled Scans	X-ray Voltage in kV	Trajectory	Focus-Object-Distance in mm	Focus-Detector-Distance in mm	Angles per 360° Rotation	Prefilter - Element	Prefilter - Thickness in mm	Pixel size N_X in mm	Pixel size N_Y in mm
DNgnm_MI685	Bass tuba in B	Metal	Width Depth Length	900 460 322	4	600	Circular	2106.041	2492.108	1600	Cu + Zn	7.5 + 1.5	0.2	0.2
DLEu_1867	Box trumpet	Brass	Height Diameter top Diameter bottom	2098 116 163	-	600	Circular	1495.004	2000	1600	Cu + Zn	7.5 + 1	0.2	0.2
DNgnm_MI205	Box trumpet	Metal	Height Width Width bell Length mouthpiece	162 175 115 77.8	-	600	Circular	1875.271	2500	2400	Cu + Zn	7.5 + 1	0.2	0.2
DNgnm_MIR100	Wooden trumpet („Wurzhorn“)	Spruce, birch, bast	Height Width	1670 160	2	150	Helix	531.75	783.397	1800			0.148	0.148
DNgnm_MI826	Cornet in B	Metal	Tube: diameter Wall thickness tube Wall thickness draw tube	12.5 0.5 1	-	600	Circular	1549.14	1802.444	1600	Cu + Zn	7.5 + 1	0.2	0.2
DNgnm_MIR40	Curved cornett	Metal, wood	Height Width	640 39	-	150	Helix	579.494	833	1440			0.148	0.148
DNgnm_MI119	Curved cornett	wood, leather, textile	Width Length Wall thickness	695 20 – 45 4.4 – 5.6 (leather thickness: ca. 0.5 – 1 mm)	-	150	Helix	328.255	704.084	1600			0.148	0.148
DNgnm_MIR41	Curved cornett	wood, leather, thread	Height Width Wall thickness	610 36 – 18 5.7 – 4.1	-	150	Helix	328.255	704.084	1600			0.148	0.148

Brass Instruments														
Object (ID)	**Common name**	**Material**	**Dimension**	**Dimensions in mm**	**Number of Assembled Scans**	**X-ray Voltage in kV**	**Trajectory**	**Focus-Object-Distance in mm**	**Focus-Detector-Distance in mm**	**Angles per 360° Rotation**	**Prefilter - Element**	**Prefilter - Thickness in mm**	**Pixel size N_X in mm**	**Pixel size N_Y in mm**
DNgnm_MIR67_A	Mouthpiece for baritone horn	Metal	Height Diameter Material thickness	85 38 max. 4	-	220	Helix	156.5	683.901	1600	Cu	2.5	0.2	0.2
DNgnm_MI148	Serpent in C upper bend	Wood, leather	Height Width Depth Wall thickness	825 410 105 3 – 6	-	150	Circular	653.502	904.998	1600			0.148	0.148
DNgnm_MI148	Serpent in C without upper bend	Wood, leather	Height Width Depth Wall thickness	825 410 105 3 – 6	4	150	Circular	653.502	904.997	3200			0.148	0.148
DNgnm_MI530	Double horn	Metal	Height Width Depth Wall thickness bell	610 430 310.5 0.35	2	500	Circular	2106.783	2492.108	1600	Cu + Zn	7.5 + 1	0.2	0.2

Woodwind Instruments														
Object (ID)	**Common name**	**Material**	**Dimension**	**Dimensions in mm**	**Number of Assembled Scans**	**X-ray Voltage in kV**	**Trajectory**	**Focus-Object-Distance in mm**	**Focus-Detector-Distance in mm**	**Angles per 360° Rotation**	**Prefilter - Element**	**Prefilter - Thickness in mm**	**Pixel size N_X in mm**	**Pixel size N_Y in mm**
DNgnm_MIR486	Alto saxophone	Metal	Height Width Depth Material thickness bell, Material thickness key lever	640 375 140 0.4 < 5	3	600	Circular	2140.988	2500	2000	Cu	7.5	0.2	0.2
DNgnm_MI528	Baroque Rackett	Metal, wood	Height Width	182 92	2	220	Circular	266.416	658	1600	Cu	2.5	0.2	0.2
DNgnm_MIR465	Basset horn in F, 8 (7+1) keys, book	Metal, wood, leather, horns	Height	580	-	220	Circular	538.65	851.698	1200	Cu	2.5	0.2	0.2
DNgnm_MIR465	Basset horn in F, 8 (7+1) keys, tube	Metal, wood, leather, horns	Height	580	-	220	Helix	538.65	851.707	1600	Ti	0.89	0.2	0.2
DBim_0642	Bass pommer , tube, without fontanelle	Brass, iron, maple, nickel silver	Height Width	1853 156	2	150	Helix	462.75	728.596	1800	Cu	0.5	0.148	0.148
DNgnm_MI211	Recorder in f1	Ivory, wood	Height	494	-	150	Helix	332.77	703.708	1600			0.148	0.148
DNgnm_MI140	Recorder in f1	Ivory, wood	Height	499.5	-	150	Helix	332.77	703.708	1600			0.148	0.148
DNgnm_MI139	Recorder in f1	Wood	Height	496.5	-	150	Helix	332.77	703.708	1600			0.148	0.148
DNgnm_MI138	Recorder in f1	Wood	Height	504	-	150	Helix	332.77	703.708	1600			0.148	0.148
DNgnm_MIR364	German shawm (treble)	Metal, wood, bone	Height Width	645 71	-	220	Helix	242.1	699.989	1600	Ti	0.89	0.2	0.2
DNgnm_MI125	Dulcian, *gedackt*, without bocal	Metal, wood	Height Width	960 74	-	200	Helix	352.5	695.663	1200	Ti	0.89	0.2	0.2
DNgnm_MIR396	Cor anglais	Metal, wood, leather	Height Width max. Diameter	770 200 70	-	220	Helix	512.5	839.991	1600	Cu	2.5	0.2	0.2

Woodwind Instruments

Object (ID)	Common name	Material	Dimension	Dimensions in mm	Number of Assembled Scans	X-ray Voltage in kV	Trajectory	Focus-Object-Distance in mm	Focus-Detector-Distance in mm	Angles per 360° Rotation	Prefilter - Element	Prefilter - Thickness in mm	Pixel size N_X in mm	Pixel size N_Y in mm
DNgnm_MI127	Bassoon	Metal, wood	Height Width	1280 81	3	220	Helix	350.65	663.162	1200	Cu	2.5	0.2	0.2
DBim_0289	Great bass pommer, without fontanelle	Brass, maple, felt	Height Width	2710 190	2	150	Helix	462.75	728.595	1800	Cu	0.5	0.148	0.148
DNgnm_MIR460	Clarinet in B, 13 keys	Metal, wood	Height Width Material thickness plate	666 78 0,6	3	600	Circular	1833.439	2492.108	2000	Cu + Zn	7.5 + 1	0.2	0.2
DNgnm_MI149	Clarinet in D, 2 keys	Metal, wood	Height Width	542 63	-	150	Helix	271.6	553.396	1800	Cu	0.1	0.148	0.148
DNgnm_MI109	Crumhorn	Brass, maple, robinia	Height Width Length	630 270 45	-	150	Helix	447	703.399	1800			0.148	0.148
DNgnm_MIR423	Crumhorn (bass) in, bend with keys	Metal, wood	Height Width Depth	970 380 50	-	220	Circular	464.106	813.249	3200	Ti	0.89	0.2	0.2
DNgnm_MIR423	Crumhorn (bass), tube above the bend	Metal, wood	Height Width Depth	970 380 50	-	220	Helix	464.105	813.248	1600	Ti	0.89	0.2	0.2
DNgnm_MIR482	Metal bass clarinet in B, 21 keys (Bimbonclarino)	Metal, rubber	Height Width Depth	860 330 144	3	600	Circular	2220.255	2492.108	2000	Cu + Zn + Messing	7.5 + 1 + 0.5	0.2	0.2
DNgnm_MIR653	Mirliton	Wood	Height Width	540 102	-	150	Helix	579.494	833	1600			0.148	0.148
DBim_0581	Oboe da Caccia	Leather, brass, maple	Height Width	777 110	2	220	Helix	298.829	618.242	1600	Cu	1	0.2	0.2

Woodwind Instruments

Object (ID)	Common name	Material	Dimension	Dimensions in mm	Number of Assembled Scans	X-ray Voltage in kV	Trajectory	Focus-Object-Distance in mm	Focus-Detector-Distance in mm	Angles per 360° Rotation	Prefilter - Element	Prefilter - Thickness in mm	Pixel size N_X in mm	Pixel size N_Y in mm
DBem_Panflöte	Panpipe	Textile, bamboo	Height Width Depth	288 113 50	-	220	Helix	324	643.248	1600			0.2	0.2
DNgnm_MIR281	Transverse flute in F	Wood, horns	Height Width	476 38	-	180	Helix	362.5	839.99	1600			0.2	0.2
DNgnm_MI955	Transverse flute, Boehm system	Silver	Height Width Wall thickness	673 45.6 0.3	3	600	Circular	2220.255	2492.108	2000	Cu + Zn + Messing	7.5 + 1 + 0.5	0.2	0.2

Automatic Musical Instruments

Object (ID)	Common name	Material	Dimension	Dimensions in mm	Number of Assembled Scans	X-ray Voltage in kV	Trajectory	Focus-Object-Distance in mm	Focus-Detector-Distance in mm	Angles per 360° Rotation	Prefilter - Element	Prefilter - Thickness in mm	Pixel size N_X in mm	Pixel size N_Y in mm
DNgnm_MIR1223	Automatic virginal	Ivory, metal, wood, leather, glass, felt, pigments, binder	Height Width Depth	488 255 305	-	600	Circular	1750.001	2170	3200	Cu + Zn	7.5 + 1	0.2	0.2
DNgnm_MI1016	Organetta Manopan	Metal, wood	Height Width Depth	740 480 335	4	600	Circular	1630.001	2020	2400	Cu + Zn	7.5 + 1	0.2	0.2

Percussion Instruments

Object (ID)	**Common name**	**Material**	**Dimension**	**Dimensions in mm**	**Number of Assembled Scans**	**X-ray Voltage in kV**	**Trajectory**	**Focus-Object-Distance in mm**	**Focus-Detector-Distance in mm**	**Angles per 360° Rotation**	**Prefilter - Element**	**Prefilter - Thickness in mm**	**Pixel size N_X in mm**	**Pixel size N_Y in mm**
DLEu_2310	Damaru	Bone, parchment, textile, putty	Height Width Depth	188 180 160	-	150	Helix	336.75	584.999	1800			0.148	0.148
DBem_VIIc168a	Gong bonang panerus	Bronze	Diameter Height Wall thickness	180 120 4	-	600	Circular	1638.744	2000	1600	Cu	6	0.2	0.2
DBem_VIIc727g	Gong bonang panerus	Bronze	Diameter Height Wall thickness	170 105 3	-	600	Circular	1638.744	2000	1600	Cu	6	0.2	0.2
DNgnm_MIR635	Drum	Metal, wood	Height Width	465 25	-	150	Helix	579.496	833	1800			0.148	0.148
DNgnm_MIR627	Kettledrum	Metal, hide	Height Width	280 800	2	600	Circular	1658.667	2050	2400	Cu + Zn	7.5 + 1	0.2	0.2

Bowed Stringed Instruments

Object (ID)	Common name	Material	Dimension	Dimensions in mm	Number of Assembled Scans	X-ray Voltage in kV	Trajectory	Focus-Object-Distance in mm	Focus-Detector-Distance in mm	Angles per 360° Rotation	Prefilter - Element	Prefilter - Thickness in mm	Pixel size N_X in mm	Pixel size N_Y in mm
DNgnm_MI641	Viola	Wood, varnish	Height Width Depth	770 260 140	-	150	Helix	702	1003.391	1800			0.148	0.148
DLEu_3505	Hurdy-gurdy	Wood, brass, iron	Height Width Depth	773 255 246	4	600	Circular	1491.04	2000	2400	Cu	4	0.2	0.2
DNgnm_MIR762	Kit (pochette)	Ivory, wood, Nacre, gut	Height Width Depth	500 40 60	-	180	Helix	362.5	839.99	1600			0.2	0.2
DNgnm_MI582	Viola (treble), without strings, tailpiece, tuning peg	Ivory, wood, tortoiseshell	Height Width Depth	590 196 54	-	150	Helix	292.5	550	1800			0.148	0.148
DNgnm_MI5	Viola da Gamba (Big Bass), neck	Wood	Height Width Depth Height rib Max. distance area upper block Thickness belly Thickness ribs	1725 558 163 322 190 6 – 6.5 3.5	4	220	Circular	852.881	1281.987	1600			0.2	0.2

Bowed Stringed Instruments

Object (ID)	Common name	Material	Dimension	Dimensions in mm	Number of Assembled Scans	X-ray Voltage in kV	Trajectory	Focus-Object-Distance in mm	Focus-Detector-Distance in mm	Angles per 360° Rotation	Prefilter - Element	Prefilter - Thickness in mm	Pixel size N_X in mm	Pixel size N_Y in mm
DNgnm_MI5	Viol (Viola da Gamba, big bass), corpus	Wood	Height Width Depth Height rib Max. distance area upper block Thickness belly Thickness ribs	1725 558 163 322 190 6 – 6.5 3.5	7	220	Circular	852.885	1281.993	2400			0.2	0.2
DNgnm_MIR786	Viol (Viola da Gamba, small alto), corpus	Wood	Height Width Depth	435 250 100	-	150	Helix	579.5	832.999	1800			0.148	0.148
DNgnm_MIR791	Viol (Viola da gamba, tenor)	Wood	Height Width Depth (with strings)	1170 370 245	7	200	Circular	701.829	1039.998	1600	Cu	0.5	0.2	0.2
DNgnm_MIR836	Viola pomposa	Wood	Height Width Depth (corpus) Depth (back-bridge)	302 760 54 – 55 160	-	150	Helix	951	1205	1600			0.148	0.148
DNgnm_MI419	Violin	Wood	Height Width Depth Height ribs Material thickness Corpus	600 153/93/193 28 – 29 91 2 – 3.5	-	150	Helix	448.75	742	1800			0.148	0.148

Bowed Stringed Instruments														
Object (ID)	**Common name**	**Material**	**Dimension**	**Dimensions in mm**	**Number of Assembled Scans**	**X-ray Voltage in kV**	**Trajectory**	**Focus-Object-Distance in mm**	**Focus-Detector-Distance in mm**	**Angles per 360° Rotation**	**Prefilter - Element**	**Prefilter - Thickness in mm**	**Pixel size N_X in mm**	**Pixel size N_Y in mm**
DNgnm_MIR809	Violin	Wood	Height Width Depth Height ribs Material thickness corpus	601 163/107/202 30 – 32 100 2 – 3.5	-	150	Helix	448,75	742	1800			0.148	0.148
DNgnm_MIR2033	Violin of aluminium sheet, corpus	Metal, wood, plastic	Height Width Depth Height ribs	585 198 93 37	3	220	Circular	604.999	917	1800	Ti	0.25	0.1	0.1

Keyboard Instruments

Object (ID)	Common name	Material	Dimension	Dimensions in mm	Number of Assembled Scans	X-ray Voltage in kV	Trajectory	Focus-Object-Distance in mm	Focus-Detector-Distance in mm	Angles per 360° Rotation	Prefilter - Element	Prefilter - Thickness in mm	Pixel size N_X in mm	Pixel size N_Y in mm
DNgnm_MIR1126	Fortepiano	Ivory, metal, wood, leather, felt	Height Width Length	2080 1275 400	-		Stacked Fan-Beam	9913	11858	2880			0.4	0.6
DNgnm_MIR1119	Fortepiano	Ivory, metal, wood	Height Width Depth	365 1231 2450	-		Stacked Fan-Beam	9913	11858	2880			0.4	0.6
DLEu_4199	Accordion	Metal, wood, textile, celluloid, paper	Height Width Depth	240 225 125	2	600	Circular	1491.04	2000	2000	Cu + Zn	7.5 + 1	0.2	0.2
DNgnm_MIR1028	Physharmonica	Metal, wood	Height Depth Length (with lever)	490 143 140	2	600	Circular	1430.004	1820	1600	Cu + Zn	7.5 + 1	0.2	0.2
DNgnm_MINe94	(Octave) Spinet	Metal, wood	Height Width Depth (bass) Depth(descant)	145 662 155 375	6	220	Circular	470.65	781.707	3200	Cu	2.5	0.2	0.2
DNgnm_MIR1145	Square piano	Ivory, metal, wood, leather, felt, whalebone			-		Stacked Fan-Beam	9913	11858	1800			0.4	0.6
DNgnm_MI954	Square piano, hitch-pin block	Ivory, metal, wood, leather	Height Width Depth	185 1270 460	-	220	Helix	734	1206.5	1600			0.2	0.2
DNgnm_MINe85	Two-manual harpsichord, wrest-plank	Metal, wood	Height Width Length	2005 820 245	4	150	Laminography, 277 projections, cone opening angle 27.86°, offset 220 mm	541.891	700				0.2	0.2

Keyboard Instruments														
Object (ID)	Common name	Material	Dimension	Dimensions in mm	Number of Assembled Scans	X-ray Voltage in kV	Trajectory	Focus-Object-Distance in mm	Focus-Detector-Distance in mm	Angles per 360° Rotation	Prefilter - Element	Prefilter - Thickness in mm	Pixel size N_X in mm	Pixel size N_Y in mm
DNgnm_MINe85	Two-manual harpsichord, wrest-plank descant	Metal, wood	Height Width Length	2005 820 245	5	225	Circular	752	1526.5	2400			0.2	0.2

Accessories														
Object (ID)	Common name	Material	Dimension	Dimensions in mm	Number of Assembled Scans	X-ray Voltage in kV	Trajectory	Focus-Object-Distance in mm	Focus-Detector-Distance in mm	Angles per 360° Rotation	Prefilter - Element	Prefilter - Thickness in mm	Pixel size N_X in mm	Pixel size N_Y in mm
DNgnm_MIR1220	Metronome	Metal, wood	Height Width Depth	355 123 123	2	600	Circular	1313.106	1820	1200	Cu + Zn	7.5 + 1	0.2	0.2
DNgnm_MI934	Ribbon metronome	Metal, wood, textile	Height Width Length	72 38 25	-	220	Circular	84.65	593.165	1600	Cu	2.5	0.2	0.2

Plucked Stringed Instruments

Object (ID)	Common name	Material	Dimension	Dimensions in mm	Number of Assembled Scans	X-ray Voltage in kV	Trajectory	Focus-Object-Distance in mm	Focus-Detector-Distance in mm	Angles per 360° Rotation	Prefilter - Element	Prefilter - Thickness in mm	Pixel size N_X in mm	Pixel size N_Y in mm
DNgnm_MIR859	Bass guitar, neck	Ivory, metal, wood, tortoiseshell	Height Width Depth	801 303 115	-	150	Circular	579.499	833	1800			0.148	0.148
DNgnm_MIR859	Bass guitar, corpus	Ivory, metal, wood, tortoiseshell	Height Width Depth	801 303 115	3	150	Circular	579.5	833	2400			0.148	0.148
DBem_VIIC620b	Bow of Sarangi		Height Width Depth	685 210 175	-	150	Helix	447.25	703.4	1800			0.148	0.148
DBem_IIIE10465	Arched harp (ennanga)	Wood, leather, textile	Height Width Depth	660 500 245	-	150	Helix	647	903.398	1800			0.148	0.148
DNgnm_MI59	Diatonic harp	Metal, wood, gut	Height Width Depth	930 410 160	6	150	Circular	602.5	903.391	3200			0.148	0.148
DNgnm_MI497	Descant zither	Metal, wood	Height Width Depth	560 290 65	3	600	Circular	1518.706	1820	2000	Cu + Zn	7.5 + 1	0.2	0.2
DNgnm_MIR691	Triple zither	Metal, wood	Height Width Length	640 420 85	3	600	Circular	1350.003	1820	2400	Cu + Zn	7.5 + 1	0.2	0.2
DNgnm_MI57	Guitar	Ivory, wood	Height Width Depth	860 235 105	-	150	Helix	576.4	833.4	1800			0.148	0.148
DNgnm_MI58	Guitar	Ivory, metal, wood, tortoiseshell	Height Width Depth	920 250 90	-	150	Helix	687	953.397	1800	Cu	0.6	0.148	0.148

Plucked Stringed Instruments

Object (ID)	Common name	Material	Dimension	Dimensions in mm	Number of Assembled Scans	X-ray Voltage in kV	Trajectory	Focus-Object-Distance in mm	Focus-Detector-Distance in mm	Angles per 360° Rotation	Prefilter - Element	Prefilter - Thickness in mm	Pixel size N_X in mm	Pixel size N_Y in mm
DNgnm_MIR721	Dulcimer	Metal, wood	Height Depth Width (in front) Width (back) Length of diagonal frame	90 605 345 300 270	3	600	Circular	1430.002	1820	2000	Cu + Zn	7.5 + 1	0.2	0.2
DNgnm_MI67	*Hamburger cithrinchen* (cittern)	Ivory, wood	Height Width Depth	640 240 70	-	150	Helix	471.6	728.397	1800			0.148	0.148
DNgnm_MIR902	Lute (German theorbo), corpus	Ivory, wood, ebony	Height Width Depth	1138 305 180	3	150	Circular	547.5	799.999	2400			0.148	0.148
DNgnm_MIR898	Lute, 11-course	Wood, gut	Height Width Depth Depth corpus	815 300 273 170	-	150	Helix	1294.5	1553.4	1800			0.148	0.148
DNgnm_MIR885	Neapolitan mandoline	Ivory, nacre, bone, conifer wood, wood putty, cypress, ebony, rosewood, tortoiseshell	Height Width Depth	564 164 118.9	-	150	Helix	423.5	803.4	1800			0.148	0.148
DBem_VIIB231	Rabab	Metal, wood, nacre, gut, hide, bone	Height Width Depth	730 160 180	-	150	Helix	447.25	703.4	1800			0.148	0.148

Plucked Stringed Instruments

Object (ID)	Common name	Material	Dimension	Dimensions in mm	Number of Assembled Scans	X-ray Voltage in kV	Trajectory	Focus-Object-Distance in mm	Focus-Detector-Distance in mm	Angles per 360° Rotation	Prefilter - Element	Prefilter - Thickness in mm	Pixel size N_X in mm	Pixel size N_Y in mm
DBem_VIIC620a	Sarangi	Metal, wood, leather, textile, plastic	Height Width Depth	685 210 175	-	220	Helix	684.75	1003.249	1600	Cu	2.5	0.2	0.2
DLEu_0463	Zither	Wood, brass, iron, copper, gut	Length Width Depth	519 278 64	-	220	Helix	414	733.247	3200	Cu	2.5	0.2	0.2
DLEu_0628	Key cittern, neck	Wood, leather, brass, textile	Length Width Depth	324 70 73	2	600	Circular	1491.04	2000	1600	Cu	4	0.2	0.2
DLEu_0628	Key cittern, corpus	Wood, leather, brass, textile	Length Width Height corpus	419 308 130	3	600	Circular	1491.04	2000	2000	Cu	4	0.2	0.2
DNgnm_MIR862	Chitarra battente, neck	Ivory, metal, wood, nacre, putty	Height Width Depth	1000 290 180	-	220	Helix	383	700.662	1600	Cu	1.69	0.2	0.2
DNgnm_MIR862	Chitarra battente, corpus	Ivory, metal, wood, nacre, putty	Height Width Depth	1000 290 180	5	220	Circular	383	700.659	3200	Cu	1.69	0.2	0.2
DNgnm_MIR862	Chitarra battente, pegbox	Ivory, metal, wood, nacre, putty	Height Width Depth	1000 290 180	-	220	Circular	383	700.664	1600	Cu	1.69	0.2	0.2

22 Abbreviations

3D	*three-dimensional*
CNR	*contrast to noise ratio*
CT	*computed tomography*
etc.	*et cetera - and so on*
FBP	*filtered backprojection*
FDD	*focus detector distance*
FOD	*focus object distance*
i.e.	*that is (from Latin: id est)*
MFE	*measurement field extension*
SART	*simultaneous algebraic reconstruction technique*
SNR	*signal to noise ratio*

23 Glossary

Artefact	structure appearing in the reconstructed volume that does not exist in the real object
Back	Backside of a corpus of stringed instruments.
Ball bar	An image quality indicator consisting of two or more balls connected by a rod. The distances between the balls are known from a calibration. When a ball bar is present in a reconstructed volume, it can be used as a scale.
Belly	Top plate of a stringed instrument which is stimulated by the strings via the bridge.
Binning	Binning combines the signal of adjacent pixels within the X-ray detector. The intensity detected by the virtual pixel created this way is increased. For a given integration time, the SNR is enhanced. For given SNR, the required measurement time is reduced. In turn the spatial resolution decreases. Binning is also possible as a later processing step before reconstruction.
Bit depth	Number of bits used when an analogue signal is quantized into a digital representation. It determines the dynamic range of the signal. Typical X-ray detectors use 16 bit and can represent 65536 different grey values.
Bore	Hollow tube inside wind instruments (internal diameter)
Circular CT	The object is rotated between X-ray source and detector without movement in vertical direction.
Cluster-scan	Several objects are scanned together and the volumes are separated afterwards.
Computed tomography	X-ray projections of an object are recorded from different directions. A digital three-dimensional representation of the object is computed from them.
Conservational requirements	Requirements concerning climatic conditions (relative humidity and temperature) as well as the handling of objects in order to avoid damage through transport or storage.
Corpus	Resonating body of a stringed instrument. Consists of top plate (belly), back and ribs (sides).

DICOM	Data format DICOM (Digital Imaging and Communications in Medicine) is an open standard for storage and exchange of imaging data in the medical sector. For viewing DICOM data a large amount of freeware exists. This is why it is recommended for the imaging of cultural heritage objects. Alternatively the format DICONDE (Digital Imaging and Communication in Nondestructive Evaluation) can be used, which is based on DICOM.
Duplex wire	Duplex wires can be used to determine the spatial resolution of X-Ray systems. Pairs of wires with a given diameter d are placed at a distance d to each other onto a support, which is scanned with the object. The spatial resolution is given by the pair that cannot be recognized as such.
Dual-energy methods	Two sets of X-ray projections are recorded using different X-ray energies. The additional spectral information can be used to reduce artefacts or to determine material properties.
Electron volt, eV	Unit of energy often used to describe X-rays. One electron volt is the energy of an electron accelerated by a voltage of 1 V. It is equal to $1.6 \cdot 10^{-19}$ J.
Flat panel detector	A digital detector for X-rays. The sensitive area is subdivided into a two dimensional pixel matrix (in contrast to a line detector).
FlyBy	Computed tomography employing a constant rotation of the object during the acquisition of X-ray projections (in contrast to Stop&Go).
Frame	Shape formed by the external walls (ribs or sides) of a grand piano
Header	Part of a file used to store metadata. For instance, the header of a file containing an X-ray projection can contain information on the X-ray parameters used.
Helical CT	The object is rotated between X-ray source and detector. Simultaneously, either the object or source and detector are moved in a vertical direction.
Homogeneity	Independence of a property from the position in space. In a reconstruction, a homogeneous material should ideally be represented by an equally homogeneous grey value.
Image quality indicators	Device to quantify the quality of a reconstruction. It typically consists of elements of graded size or thickness such as wires or steps and holes. Each type has a specific purpose, like the evaluation of spatial resolution or contrast.
Isotropy	Independence of any property from the direction.
Laminography	Method to obtain cross sectional images of objects that are not suitable for a rotation by 360°. Especially suitable for wide, but flat objects. X-ray source and detector move in planes parallel to the object, which is not rotated.

Line detector	A digital detector for X-rays. The sensitive area is subdivided into a single row of pixels (in contrast to a flat panel detector).
Measurement field extension	Method to virtually increase the detector width for objects too wide to fit on the detector. A CT scan can be performed for several, slightly overlapping, horizontal detector positions. The projections can be stitched together afterwards. There are also methods, in which the object is shifted horizontally instead of the detector.
Metadata	Data describing other data, e.g. the file format of a data set, date of creation, file size, resolution of an image file etc. Metadata is classified as descriptive, structural or administrative.
Metadata standard	A document describing the formal and contentual characteristics of metadata for a given purpose.
Neck	Longitudinal part of stringed instruments at which the pegbox for the strings and the fingerboard is fastened.
Neck graft	Joint of two wooden parts. In case an old pegbox is reused on a new neck, it is joined by a neck graft.
Neck joint	Joint between corpus and neck of stringed instruments. Sometimes reinforced with a nail.
Object measurement	Scans of an instrument or a part of it with identical CT parameters that can be combined to a larger volume.
Optical path	The geometrical path an X-ray takes between X-ray source and detector.
Peg box	Part of a stringed instrument at the end of the neck. This is where the strings are fastened and tuned using pegs.
Persistent	Long term existence of a thing. Ability to save data structures in non-fugitive storage media like data systems or data bases.
(X-ray) projection	Image recorded when an object is transmitted by X-rays from one direction. Each image point shows a superposition of all structures along a line from the X-ray source to this point.
Ravalement	Structural alteration of a harpsichord in order to enlarge the tonal spectrum.
Reconstruction	A digital three-dimensional representation of an object obtained from X-ray projections using a reconstruction algorithm. It consists of a matrix of voxels. Each voxel is associated with a value that measures the ability to attenuate X-rays of the corresponding volume element of the object. Employing suitable software, arbitrary cross sections through the object can be visualized.
Reconstruction algorithm	An algorithm that creates a reconstruction from X-ray projections.
Ribs	Sides of a stringed instrument or keyboard instrument. Connects top plate and back. Also called sides.

Rotary table	The item of a CT facility on which the object is mounted during a CT scan. It allows rotation of the object between X-ray source and detector around a vertical axis.
Sides	Sides of a stringed instrument or keyboard instrument. Connects top plate and back. Also called ribs.
Sound post	Small wooden stick that connects top plate and back in bowed stringed instruments.
Spatial resolution	Spatial resolution is a quantification of a system's ability to image separately two structures that are in close proximity. For the examination of musical instruments a voxel size of 100 µm or better should be obtained.
Stop&Go	Computed tomography where the object stands still during the acquisition of X-ray projections (in contrast to FlyBy).
Tomosynthesis	Reconstruction method for projections acquired using laminography.
Top plate	Also called belly. Top plate of a stringed instrument which is stimulated by the strings via the bridge.
Virtual research environment (VRE)	A tool for managing research data, e.g. WissKI (http://wiss-ki.eu/).
Volume of interest	In case only a part of an object is scanned, this area is called volume of interest. This is abbreviated in data names and identifiers as VOI.
Voxel	Volume element of a reconstruction. The equivalent in two dimensions is a pixel.
Voxel size	Distance between adjacent voxels in the three spatial directions.
WissKI	Abbreviation for the German expression „Wissenschaftliche Kommunikationsinfrastruktur“ (scientific communication infrastructure). Name of an online research environment developed by the Germanisches Nationalmuseum, Zoologisches Forschungsmuseum Alexander Koenig Bonn and the chair for Informatics 8 for Artificial Intelligence at the Friedrich-Alexander-University of Nuremberg-Erlangen Uses the ISO certified standard CIDOC-CRM for internal data handling.
Wrestplank	Constructional element of a keyboard instrument. A piece of wood in which the pegs are fastened.

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Fig. 44: Human_anatomy_planes-HR.svg: *Human_anatomy_planes.svg: YassineMrabet. Diese Vektorgrafik wurde mit Inkscape erstellt. - Human_anatomy_planes-HR.svg, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=14709215 (This image has been digitally altered from its original version. Modifications: *Coordinate axis were added by Meike Wolters*).

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