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COMPARISON OF IMAGE QUALITY BETWEEN A MEDICAL AND AN INDUSTRIAL CT SCANNER FOR USE IN NON-DESTRUCTIVE TESTING OF TREE-RING WIDTHS IN AN OAK (*QUERCUS ROBUR*) HISTORICAL SCULPTURE OF MADONNA

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ABSTRACT

The aim of this paper was to compare the tree-ring width measurement results obtained using standard medical CT scanner Light Speed VCT 64 with the results obtained from industrial CT scanner GE phoenix v|tome|x 240 during dendrochronological dating of a historical wooden sculpture. The examined object was a polychrome wooden sculpture of Madonna, which was of historical value – that is why equipment enabling non-destructive measurement of tree-ring width for dendrochronological dating had to be used. The sculpture was made of ring porous English oak wood (*Quercus robur*), which is very easy to measure. There are also standard chronologies available for this material for the area of the Czech Republic to be used for absolute dendrochronological dating. During the first stage of the research, an available CT scanner designed for medical examination of human tissue was used; then the object was measured again using an industrial CT scanner where better results could be expected thanks to higher image resolution. This paper compares the quality of images from both scanners and the results of tree-ring width measurement from the output of the two CT scanners. The re-sults successfully document the possibility of obtaining images of sufficient quality to measure the grow ring widths of oak wood using computed tomography, proving that wooden objects can be subject to dendrochronological dating even if strict non-destructivity is required.

KEYWORDS: CT computed tomography, non-destructive measurement, tree-ring width, dendrochronology, oak (*Quercus robur*).

INTRODUCTION

The standard dendrochronological measurement method requires that tree-ring widths are measured on whole cut-out or dendrochronological bored-out samples. Such samples usually need surface treatment to remove impurities and surface unevenness and increase the contrast between early and late wood (e.g. Sass and Eckstein 1994, Spiecker et al. 2000, Gartner and Nievergelt 2010). In addition to standard surface treatment methods, new methods are being developed, such as the use of microtomes where the cut through the cell is smooth and the lumens remain unfilled, as opposed to surface grinding. (Gartner and Nievergelt 2010). On the other hand, X-ray and CT scanning methods do not require demanding sampling and sample preparation processes; they do not damage the object being examined and their use satisfies all requirements for non-destructive testing of historical artefacts (e.g. polychrome sculptures).

This is why outputs from X-ray methods and computed tomography find their use in the dating of artistic, historical or archaeological objects along with common digital images such as photographs or surface scans. Measurement using X-ray radiography was dealt with by Okochi et al. (2006) who in their study compared microfocus X-ray CT measurement with soft X-ray measurement. Similar topics were covered by Bill et al. (2011), who compared measurement results between a medical CT scanner (Siemens Somatom Emotion single slice) and an industrial scanner (Nikon Metrology, model XT H 225 LC). The results of their measurement of archaeological oak wood proved the possibility of obtaining relevant images from a CT scanner designed for industrial applications. They were not able, though, to obtain images of sufficient quality from a medical CT scanner, mainly due to insufficient resolution of the device and little contrast of the examined object's tree rings. They also point out that they were limited by the size of the examined object.

Grabner et al. (2009) demonstrate that, considering the size of samples, the X-ray CT method is suitable for the dating of artistic/historical artefacts rather than for classical dendrochronological samples taken e.g. from roof structures. Wood dating by means of X-ray CT scanning was tested on blocks of archaeological wood excavated together with soil and on mineralized wood by Stelzner and Million (2015). According to the authors, the results were more dependent on the resolution and contrast of the samples than on the technical characteristics of the device. A different type of radiation as a dendrochronological tool was tested by Mannes et al. (2007), who compared images obtained using classical X-ray densitometry with neutron radiation. The authors' results agree that the method has its limits due to insufficient resolution of currently used devices and mainly due to individual wood properties such as the width and contrast of tree rings.

Another relevant reason for the use of non-destructive digital methods in dendrochronoloy is the limiting factor for long-term operation of a dendrochronological laboratory – the archiving and storage of dated samples and their databases for further use, as regards i.a. storage space, durability of the samples, organizing of the database etc. Creasman (2011) even says that it is necessary to think about data archiving and long-term storage of dendrochronological samples in order to protect dendrochronology as a science discipline. One of the possible so-lutions seems to be the digitization of measured samples and their archiving in the form of digital databases. This, however, means increased demands for the quality of capturing of all characteristics of the physical samples.

Another advantage of measuring digital images using specialized software is the automation of treering width measurement with subsequent speeding-up of the whole process. Half-automation of the treering width measurement process using digital images was dealt with by

He et al. (2008); the speeding up of obtaining dendrochronological data thanks to measurement automation was also tested by Fonti et al. (2008). Automatic reading of treering widths from the outputs of a CT scanner was the goal of Entacher et al. (2007).

This paper compares the currently available X-ray based methods and the quality of their outputs as regards non-destructive dendrochronological dating of historical wooden artefacts – in this case, a sculpture of Madonna made of oak wood (*Quercus robur*).

MATERIALS AND METHODS

The examined object was a valuable historical polychrome wooden sculpture of Madonna with dimensions of 220 × 650 mm. Almost the whole object is covered with polychromy, with the exception of its rear part (Fig. 1) where the wood species used could be determined ma-croscopically. The sculpture was made of ring porous English oak wood (*Quercus robur*), which is very easy to measure and for which there are standard chronologies available for central Europe – the area where this sculpture was probably made (the exact date and locality of origin are not known). The exact mass density could not be determined as it is an artistic historical object with a complicated shape; however, the fact that the wood showed no signs of attack by wood-destroying insects or fungi and the measured humidity was 8.23 % sug-gested standard mass density of oak wood as a medium hard wood, which is 680 kg·m^{-3} (Požgaj et al. 1997).

Fig. 1: Photographs of the examined object – the sculpture of Madonna with a line indicating the position of the cross-section.

Methods using electromagnetic ionizing radiation with wavelengths of 10^{-8} m to 10^{-12} m were used as non-destructive methods for the obtaining of digital images of cross-sections of the examined objects. As there are no such devices commonly available for scientific or in-dustrial applications in the field of diagnostics of wood or historical objects, devices designed for medical and veterinary purposes were used. In the first stage of our research we used a common mobile highfrequency X-ray device, EcoRay HF 1040 (Fig. 2) to verify the internal structure of the material, the absence of faults and defects and the absence of attack by wooddestroying insects or fungi and to verify the direction of tree rings and the position of the radial plane (direction) for the measurement of strictly perpendicular distances between individual tree rings.

After this verification stage, a CT scanner designed for medical examination of human tis-sue was used; as opposed to the X-ray device, targeted scans of the required planes of the object could be obtained. Then the measurement was repeated using an industrial CT scanner in order to obtain the best possible quality of the resulting image thanks to higher resolution of the scans.

The tree ring widths were measured on the CZ scans using the LignoVision^{TM} software with a measurement accuracy of 0.01 mm. The measured data were evaluated in the TSAP-WinTM software, which is designed for the measurement of tree-ring widths on a traversing table with a microscope with subsequent evaluation of the measured dendrochronological data, including tools for cross dating and statistical evaluation of matching treering curves for the creation of chronologies.

RESULTS AND DISCUSSION

X-ray scanning

In the first stage of examination we used a common mobile high-frequency X-ray device, EcoRay HF 1040 (Fig. 2), designed for veterinary purposes. The electrical exposure voltage of the device is 40–100 kV with an electrical charge of 0.32–100 mAs; the dimensions of the scanner's focal point are 1.2 × 1.2 mm and exposure times vary between 0.02–2.5 s. The mobile device with dimensions of 344 × 191 × 188 mm works with a DDR image receptor (X-ray panel, Fig. 2 on the left) to ensure direct digitization of samples into digital X-ray images. The Aero Dr wireless X-ray panel has a built-in battery that enables making about 120 scans if fully charged. Charging is performed by means of a charging dock which is a part of the transport case.

Fig. 2: Mobile device for X-ray diagnostics EcoRay HF 1040.

Previous measurements have shown that the best results for dried-out historical wood are achieved for exposures at 40 kV and 10 mAs. With these exposure parameters, the best im-ages with a resolution of 2424 × 2170 pixels could be obtained (Fig. 3).

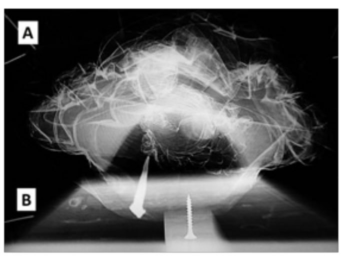

Fig. 3: Cross section of the sculpture of Madonna made using EcoRay HF 1040.

The obtained images confirmed that the sculpture consisted of two separate parts which were marked as part A and part B (Fig. 7). These two parts are connected with an unspecified bonding agent; X-ray scanning showed that no mechanical binding elements were used. At the same time, it was confirmed that the sculpture can be dated based on the tree ring widths as the tree ring boundaries are easily detectable in the images and there is a sufficient number of them in the wood mass. The existence of two separate parts of wood means the dating can be precised by creating summary tree ring curves for both parts. If a matching position of both summary curves is found, a chronology can be created based on their comparison by means of cross dating. However, when the whole object is exposed to radiation during X-ray scanning, the outlines of the examined object will overlap, wood growth and anomalies along the entire length will be captured and other conditions will hinder the detectability of tree-ring widths so that is is insufficient for dendrochronological dating. In medical practice, this problem is solved by using computer technology to display reconstructed specific cross sections of the object with a millimeter thickness.

Medical CT

The cross sections of the sculpture were scanned using multidetector CT scanner LightSpeed VCT 64 made by General Electric USA according to standard automatic exposure methods of the device (Fig. 4). A CT scanner of this type has 64 rows of ceramic detectors with 912 detectors in each row, works with 64 projections with 2.8° rotation of the X-ray tube and the opposition detectors and has a slicing thickness of 0.63, 1.25, 2.50, 3.75, 5.00, 7.50 or 10.00 mm and a minimum rotation speed of 0.4 s. This type of device is limited by the size of the patient (object): the maximum diameter of the examined object is 70 cm. The electrical exposure voltage of the device is 80–140 kV

Fig. 4: Medical CT scanner LightSpeed VCT 64.

Considering the mass density of oak wood, the operator selected an exposure voltage of 140 kV with a minimum slicing thickness of 0.63 mm, which corresponds to the conclusion given by Bill et al. (2011), who said 110 kV was the most suitable exposure voltage value. Our area of interest was the cross section in the hypothetical middle of the sculpture (Fig. 1). The resulting CT scan contains clearly visible boundaries of wider tree rings, but these boundaries become blurred in several areas where there is a greater number of thin tree rings (Fig. 5).

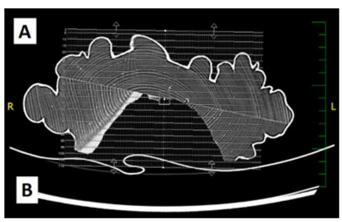

Fig. 5: The resulting image from the LightSpeed VCT 64 scanner.

Also, the resulting image has a rather small resolution (832 × 1008 pixels), which is not sufficient for the measuring of tree-ring widths with an accuracy of 0.01 mm. Due to this low resolution, neither adjustments of contrast nor testing of various filters in graphic software (Adobe Photoshop, GIMP) led to better results. Exact boundaries between individual tree rings could not be defined in areas where the tree rings were thinner than 1.2 mm. This means that in this case the medical CT scanner did not deliver suitable data for dendrochronological measurement.

Industrial CT

As the medical CT scanner did not deliver results of sufficient quality for dendrochronological dating of the sculpture, the next stage consisted in scanning the sculpture using a CT scanner designed for industrial applications. It was a General Electric USA device – GE phoenix v|tome|x L 240 (Fig. 6) from the Computed Tomography Laboratory of the Central European Institute of Technology in Brno CEITEC VUT (Technická 3058/10, 616 00 Brno, Czech Republic). The device has a flat digital detector GE"DXR 250" with unique high-contrast resolution and 1:10000 dynamics. The maximum voxel resolution is 2 μm, in some cases even 1 μm, depending on the size of sample. The scanning was performed with an expo-sure voltage of 240 kV at 320 W. However, the use of this device is very limited, even for historical artefacts. The limiting factor is the size of the examined object, which must not ex-ceed the dimensions of the 800 mm high and 500 mm diameter cylinder and must not be heavier than 50 kg. The sculpture of Madonna with its dimensions of 220 mm × 650 mm met these requirements.

Fig. 6: Industrial CT scanner GE phoenix v|tome|x 240.

As opposed to the medical CT scanner, the quality of outputs from the industrial CT scanner was so high (1500 × 1054 pixels) that it allowed for treering width measurement with an accuracy of 10 μm. The treering widths were measured in LignoVisionTM from the images obtained, whereas the images were calibrated to the actual size of the object (cross-section dimensions 220 × 140 mm). The technical parameters of the methods used are in Tab. 1

Tab. 1: Technical parameters of resulting images.

	Mobile X-ray scan-ner EcoRay HF 1040	**Medical CT scanner LightSpeed VCT 64**	**Industrial CT scanner GE phoenix v|tome|x L240**
Image type:	.jpg	.bmp	.tif
Measures [pixel]:	2424 × 2170	832 × 1008	1500 × 1054
Size [kB]:	1.72 MB	184 kB	1.15 MB

The measured data were evaluated in the TSAPWinTM software. Using the methods de-scribed above, we obtained a total of 6 tree-ring curves from part A of the sculpture and 8 tree-ring curves from part B of the sculpture (Fig. 7). Based on these curves 2 summary curves were created using cross dating, one summary curve for each part. Student's t-test and Baillie-Pilcher and Hollstein correlation methods were selected for the correlation of data (Baillie and Pilcher 1973, Cook and Kairiukstis 1990).

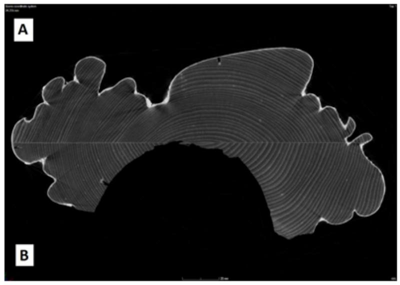

Fig. 7: The resulting image from the GE phoenix v|tome|x 240 scanner.

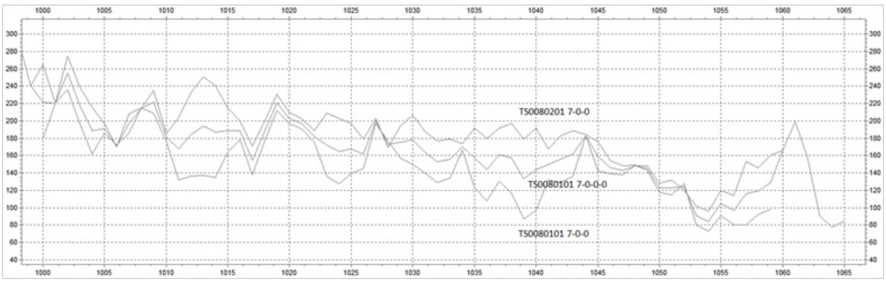

Fig. 8: Tree-ring curves for part A and part B and the resulting chronology of the sculpture.

Because both parts of the sculpture are supposed to be authentic, we attempted to perform relative dating of the summary curves and create one overall chronology for the whole sculpture based on both part A and part B. The attempt was successful; the summary curves were compared using cross dating methods and they appeared relatively synchronized in one chro-nology with 60 matching tree rings. The total length of the chronology obtained by matching the positions of the summary curves of both parts of the sculpture was 121.57 mm. The minimum measured treering width was 0.77 mm; the maximum measured tree-ring width was 3.31 mm and the average treering width was 1.712 mm.

To obtain the necessary digital images for the measuring of tree-ring widths and dendrocronological dating of a historical polychrome wooden sculpture of Madonna where complete non-destructivity was required, the sculpture was scanned using 3 X-ray devices: a mobile veterinary scanner EcoRay HF 1040 with an exposure voltage of 40 kV, a medical CT scanner LightSpeed VCT 64 with an exposure voltage of 140 kV and an industrial CT scanner GE phoenix v|tome|x 240 with an exposure voltage of 240 kV. The industrial CT scanner GE phoenix v|tome|x 240 was the only one to deliver images with sufficient resolution to enable dendrochronological measurement of tree-ring widths with an accuracy of 10 µm. This is mainly due to the technical parameters of the individual devices and to the low resolution of resulting digital images related to the primary application area of the devices.

Worse results are achieved by measuring X-ray or CT scans due to their low contrast and distortion of tree ring boundaries, as was also confirmed by other authors. Bill et al. (2011) compared the measurement results of a CT scanner developed for medical purposes and an industrial scanner; only the industrial scanner delivered satisfactory results. The next part of their experiment consisted in measuring dendrochronological data using CT from archaeological oak wood; however, they were not successful with this type of sample due to the low contrast of the images. Grabner et al. (2009) on the other hand, have proven the suitability of the X-ray CT method for the dating of artistic and historical artefacts; for larger artefacts, however, they consider the measurement problematic due to distortion of growth ring boundaries. Stelzner and Million (2015) state that the quality of the resulting data depends more on the contrast of the wood than on the technical characteristics of the scanning equipment.

The problem of low resolution and low quality of X-ray scans becomes evident mainly if thin or less accentuated tree rings (or generally not so clear areas of the sample) are to be measured. To emphasize the contrast of tree ring boundaries (other than by increasing the technological level of the devices used), the digital images can be processed in various soft-ware environments. Monochromatic processing is the method most frequently used. This leads to removal of parasitic noise when automatic reading of tree ring widths is applied. To emphasize the tree ring boundaries, Machado et al. (2013) tested a Geographic Information System (GIS) program for creating contour lines. Although satisfactory results were achieved, the authors state that a more detailed analysis using specific computer programs and specially trained operators would be necessary for their method.

According to the authors' results, the distortion of tree ring boundaries is directly proportional to the length of sample to be X-rayed when classical radiographic methods are used. It is, however, not possible to reduce the thickness of the sample without destroying the artefact. This limitation of 2D images in X-ray computed tomography was solved e.g. by Van den Bulcke et al. (2013), who programmed 3D images of samples in MATLAB, thus achieving angular and directional correction in tree ring width measurements. They also dealt with automatic analyses of growth ring widths, but the success of the analyses depended on the accentuation of the tree rings. The automatic measurement of growth ring widths in LignoVisionTM was also tested by the authors of this paper. However, due to the natural characteristics of the wood mass, automatic tree ring detection was not successful and it cannot be used even with subsequent manual adjustments as these adjustments are exceedingly time-consuming.

There is also an option of using another type of radiation. A different type of radiation as a dendrochronological tool was tested by Mannes et al. (2007), who compared images obtained using classical X-ray densitometry with neutron radiation. Both methods would lead to comparable data, but only samples of little thickness were irradiated. The authors recommend us-ing the neutron method only as supplementary to the standard X-ray method, regarding the varying sensitivity for different chemical elements.

CONCLUSIONS

The aim of the paper was to obtain digital scans for non-destructive dendrochronological dating of a historical polychrome wooden sculpture of Madonna. The sculpture was made of ring porous English oak wood (*Quercus robur*), which is very easy to measure. There are also standard chronologies available for this material for the area of the Czech Republic to be used for absolute dendrochronological dating.

To obtain the necessary digital images for the measuring of tree-ring widths and dendrochronological dating, the sculpture was scanned using 3 X-ray devices: a mobile veterinary scanner EcoRay HF 1040 with an exposure voltage of 40 kV, a medical CT scanner LightSpeed VCT 64 with an exposure voltage of 140 kV and an industrial CT scanner GE phoenix v|tome|x 240 with an exposure voltage of 240 kV.

Manual measurement of tree-ring widths from the digital images was performed using LignoVision^{TM}; automatic image analysis was also tested in this software. The measured data sets were compared with each other in the form of tree-ring curves and their correspondence was evaluated based on cross dating in the TSAPWin^{TM} software. Using the methods described in the paper, we obtained a total of 6 treering curves from part A of the sculpture and 8 treering curves from part B of the sculpture. Based on these curves 2 summary curves were created using cross dating, one summary curve for each part. Because both parts of the sculpture are supposed to be authentic, we attempted to perform relative dating of the summary curves and create one overall chronology for the whole sculpture based on both part A and part B. The attempt was successful; the summary curves were compared using cross dating methods and they appeared relatively synchronized in one resulting chronology for the sculpture.

The results and evaluation of the digital outputs showed that the industrial CT scanner GE phoenix v|tome|x 240 was the only one to deliver images with sufficient resolution to enable dendrochronological measurement of tree-ring widths with an accuracy of 10 μm. This is mainly due to the technical parameters of the individual devices and to the low resolution of resulting digital images; these factors affected the detectability of boundaries of thin and insufficiently accentuated tree rings.

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