Deliverable 5

Report

on

the design, the traceable characterisation (surface and dimension) and the use of several standard objects for characterisation/clinical phantoms. The report will contain qualification statements for the characterisation of those phantoms.

Project:

MetAMMI

Metrology for Additively Manufactured Medical Implants

Grant Agreement No. 15 HLT09

Partner involved:	FHOÖ, DTU, DFM, VTT, FAU, UNOTT, NSAI, SKBS, PAS
Lead Author	PTB
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1 INTRODUCTION

X-ray computed tomography (XCT) is an image technique used for more than 30 years as medical diagnoses and non-destructive technique [1]. More recently, in the beginning of the 2000's, XCT started to be used as a coordinate measurement system (CMS), the so-called CT-based CMS.
Although medical XCT and CT-based CMS use the same principle – i.e. X-ray attenuation at different angular orientation of the matter – they have some constructive differences. In the medical XCT, the X-ray source and the detector rotates around the patient, while in the CT-based CMS the X-ray source and the detector are fixed and the workpiece rotates around its axis, see Fig. 1.
In the medical field, although XCT uses ionizing radiation, it is one of the most trusted and used diagnostic imaging techniques, followed by restricted procedures of operation and justification of use. In the field of metrology, CT-based CMS is regarded as the third revolutionary development in coordinate metrology being the only technique able to measure inner and outer structures of workpieces as well as assemblies in their mounted state [2].
For metrology applications, extensive effort has been dedicated to created methods and traceable reference standards to test the metrological performance of CT-based CMSs. However, in the medical field, CT still partially lacks methods and traceable reference objects to test the performance of systems for specific tasks (e.g. distortion of the systems).
Therefore, this report presents a design of a traceable reference objects (or phantoms) suitable to test the metrological behaviour of medical XCT systems for length, resolution and size measurements. Additionally, some examples of the use of some already existing medical phantoms to test the metrological performance of medical XCT systems for length measurements and surface characterisation are shown. Following, a description on how a metrological reference standard can be used to test a medical system is given as well as a second design of a medical phantom to test medical systems developed in Finland. In the second part of the report, some existing metrological reference standards to test industrial and CT-based CMSs is presented with examples of CT-based CMS measurements.

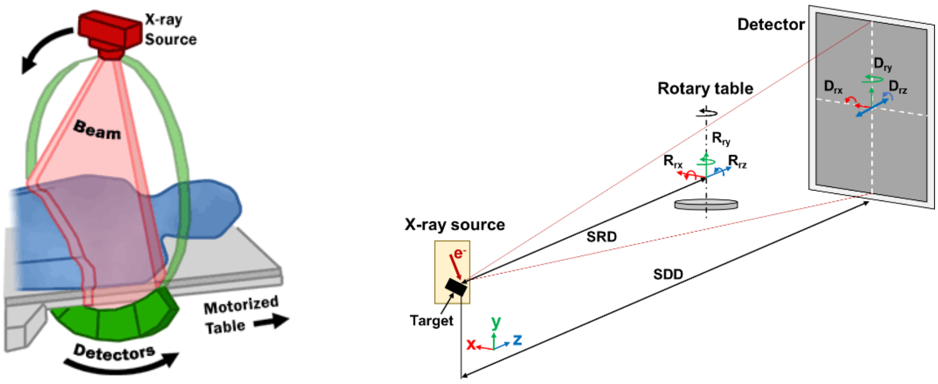


Fig. 1. X-ray Computed tomography constructions (left) medical XCT (source: [3]; and (right) CT-based CMS

2 CLINICAL PHANTOMS FOR SURFACE AND DIMENSION

2.1 DESIGN OF A MEDICAL PHANTOM SUITABLE FOR THE CHARACTERISATION OF DIMENSIONAL IN MEDICAL CT SYSTEMS

For characterisation of dimensional and surface in medical CT systems, the design presented in Fig. 2 was developed. The design consists of a massive PMMA cylinder (with nominal diameter of 150 mm) constructed by 9 slices (of different thickness) and approximately 3-7 high quality silicon nitride (Si_3N_4) spheres with different diameters per slice immersed in the PMMA.

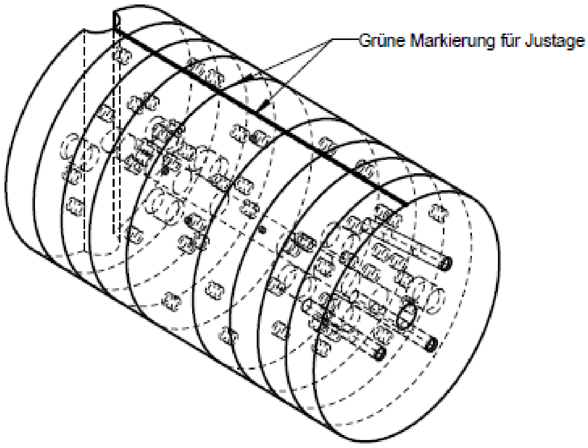


Fig. 2. Sketch of a medical phantom designed for the evaluation of the dimensional error and resolution of medical CT systems.

The spheres feature different diameters for different measurement tasks i.e. system resolution based on the modulation transfer function (MTF) and the dimensional characterisation of the system based on the measurement error of the distances between spheres.
PMMA was selected as basis material because it is widely used in the medical field due to its similarity to soft tissue in the human body. Si_3N_4 was selected as spheres material for the high availability and their high-quality regarding surface roughness, low form errors, appropriate X-ray attenuation coefficient and relatively low cost.
The phantom is constructed in a multi-step interactive process, where slices are stacked together step-wise enabling tactile reference measurements of all spheres with relation to the same coordinate system (using spheres of a most-lower slice in relation to slice 1).
The tactile reference measurements are to be carried out in several steps. A description of the procedure is presented following:

(1) Preparation of the first and second PMMA slice with the reference spheres. The first slice contains the reference spheres for the construction of the coordinate system. The second slice contains 4 spheres for regular measurements. As the spheres are to be glued in the PMMA, for the tactile measurement is important that at least half of the spheres are completely free (including free of glue);
(2) Tactile and CT-based CMS measurements of the spheres are to be carried out in the first and second slice.
(3) Implementation of the third slice: The phantom is to be sent to the manufacturing facility for the implementation of the third PMMA slice with spheres.
(4) Tactile and metrological CT measurements of the spheres are to be carried out in the first (as reference elements) and third slice.
(5) The process is repeated to the next slices until the phantom is completely characterised by tactile and CT-based CMS.

Important remark: As the PMMA slices with the spheres are added to the phantom, the tactile measurement becomes more and more difficult to the increasing distance between the measurement spheres and the reference spheres in the first slice. One should consider the complete length of the phantom and select an appropriate coordinate measurement machine (CMM) for the complete task.

<u>Realization of the clinical phantom</u>

The first steps were carried out towards the realization of this clinical phantom. A pre-study test was performed with a rectangular PMMA plate, see Fig. 3-left. Silicon nitride spheres were glued in the plate and CT scans as well as microscopic images were taken to evaluate if the free surface is glue free for the tactile measurement. The glue on the surface might severely impact the tactile measurements. The idea was, to pour liquid PMMA in the free surface above the sphere (liquid PMMA becomes firm in contact with air), after the tactile measurements to increase the stability of the sphere position over time. In the pre-study, two CT scans were performed, one before and one after pouring the liquid PMMA on the spheres. The scans were carried out to check if the sphere position has changed after pouring the liquid PMMA, and to verify if is there enough contact between the liquid PMMA and the sphere providing a more stable construction. The results showed that a slight change of the sphere distances (approx. 10 µm) was observed. Additionally, the glue (liquid PMMA) was not able to reach the surface of all spheres, see Fig. 3-right.

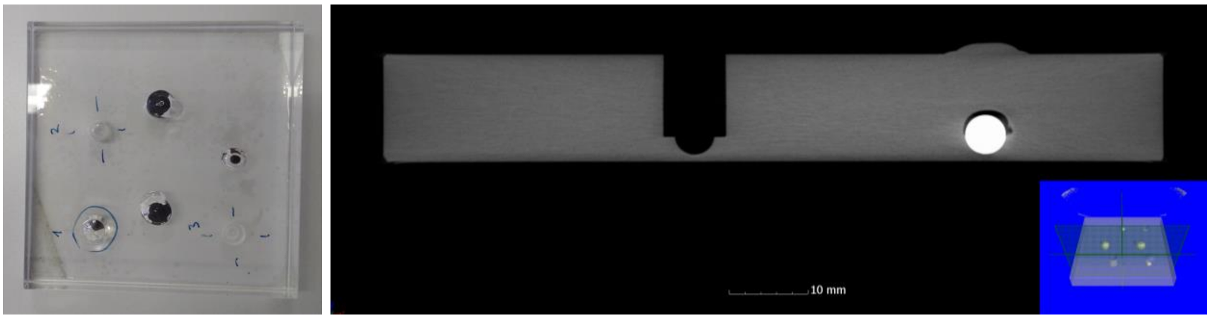


Fig. 3. Pre-test of the realization of the PMMA clinical phantom: (left) picture of the rectangular PMMA plate; (right) CT scan of a sphere, where the liquid PMMA did not reach the sphere surface.

The strategy of how to fix the sphere in the PMMA disk was changed as a consequence of the pre-test results. In the new strategy the liquid PMMA was poured in a hole pre-drilled in the PMMA slice, and the spheres were immersed to their half in the liquid PMMA. The first PMMA circular disk was constructed, see Fig. 4-left. It featured in total 7 silicon nitride spheres, 3 in the reference side (where the spheres would be free throughout the complete construction for the tactile measurements) and 4 in the opposite side for standard sphere measurements.

The first PMMA slice was scanned by industrial CT to check if the spheres are in suitable conditions for the tactile measurements, see Fig. 4.

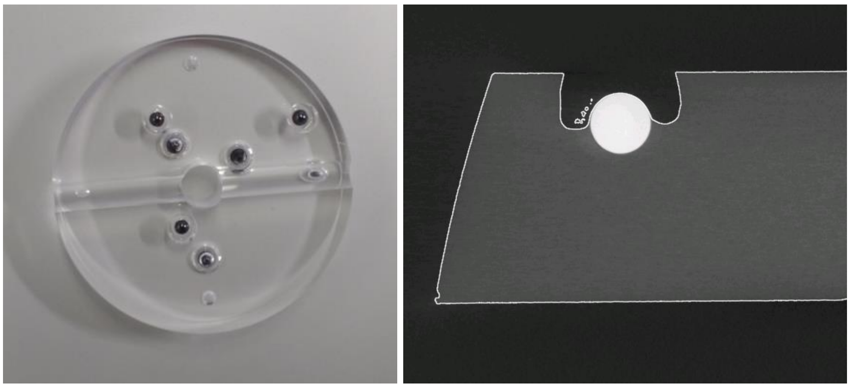
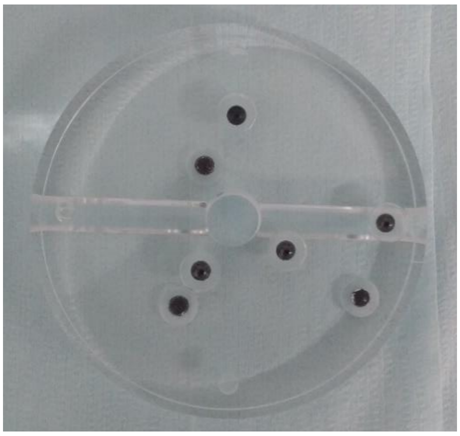


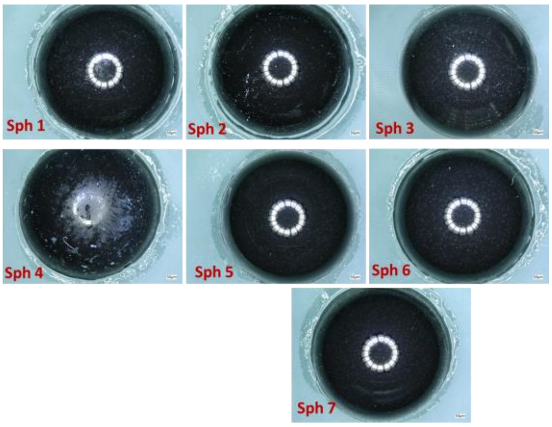
Fig. 4. First PMMA circular disk for the construction of the PMMA clinical phantom: (left) first PMMA circular slice of the PMMA CT clinical phantom; (right) industrial XCT image of a sphere. In detail, the sphere is more than half covered with PMMA.

Fig. 4-right shows the industrial XCT measurement of the PMMA slice 1 of the medical phantom. It is easy to observe from the XCT data that the glue is covering more than half of the sphere, i.e. only a small region in the pole of the sphere is free of glue. This hinders severely the tactile measurements, since the measurement uncertainty is significantly increased by the decrease of the measurement area on a sphere.

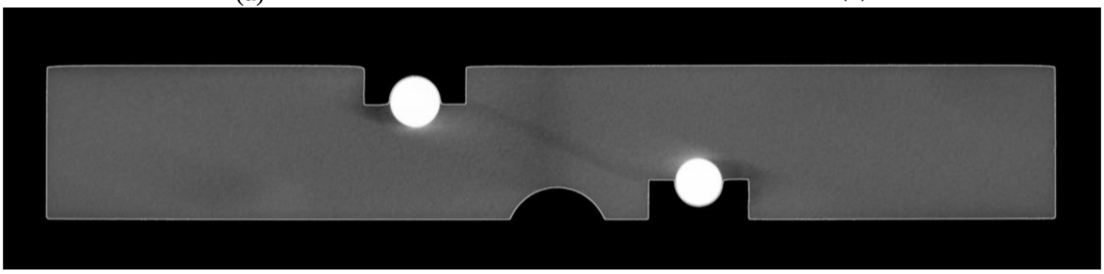
A new slice (#2) was constructed with a new fixation method of the spheres, using instant glue, see Fig. 5-a. Microscopic images of the spheres were taken of the spheres in slice #2, see Fig. 5-b. Also, an industrial CT scan of the slice #2 was made, see Fig. 5-c. Although the surface to be measured on the spheres are in the CT scan apparently free in comparison to slice #1, cf. Fig. 4-right and Fig. 5-c, from microscopic images it is possible to observe that the spheres are heavily contaminated by residual instant glue, although several attempts to remove/clean the spheres were made. From the results has been concluded that the slice #2 was only in adequate condition for low precision tactile measurements.
Considering the geometrical errors of medical CT systems (presumably higher than industrial CT), the slice #2 was measured by a tactile CMM to check if the glue influences significantly the measurements and the results were compared with the CT results, see Fig. 6.



(a)



(b)



(c)

Fig. 5. PMMA slice #2: (a) picture of the slice; (b) microscopic images of the free surface of the spheres in PMMA; and (c) CT scan image of the slice.

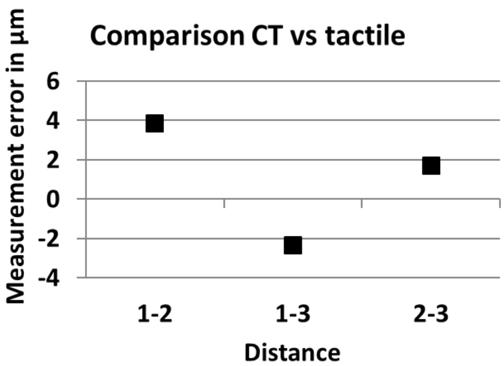


Fig. 6. Tactile measurement of the slice #2: (left) measurement set-up of slice #2 in a tactile measurement machine; (right) results of the comparison CT vs tactile.

After a few more interactions with the phantom manufacturer (one more slice was delivered – see Fig. 7), in which microscopic images were made of the slice #3. The PMMA slice #3 presented an improvement of the free surface of the spheres when compared to slice #2 (i.e. less residual glue on the sphere surface), however not yet in satisfactory conditions for high precision tactile CMM measurements. The manufacturer, presumably based on a strategic decision, stopped the interactions with the project partners, i.e. SKBS, PTB and FAU. After several attempts to reestablish contact with the manufacturer, the project partners decided to find alternative solutions to perform the characterisation of dimensional and surface in medical CT systems using medical or metrological objects.

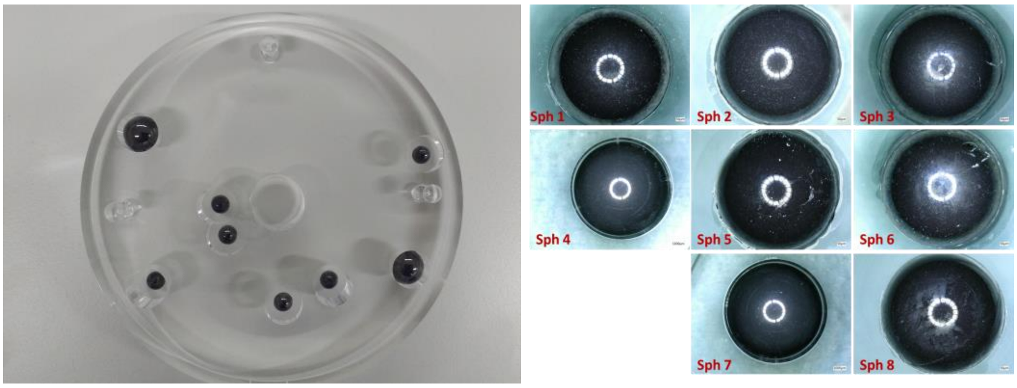


Fig. 7. PMMA slice #3: (left) picture of the slice #3; and (right) microscopic images of the free surface of the spheres.

2.2 ALTERNATIVE SOLUTION FOR CHARACTERISATION OF MEDICAL CT SYSTEMS

2.2.1 Medical objects

<u>CTDI-Phantom</u>

The CTDI-Phantom is a standardized test body made of PMMA which is used to measure CTDI (Computed Tomography Dose Index) in combination with a specially designed dose measurement chamber, see Fig. 8. Such measurements are e.g. required for regular quality control of medical CT systems.

As one of the main tasks in the project is the characterisation of dimensional error of medical CT systems, the planes and the holes of the CTDI-Phantom were used as geometrical fitting elements to perform dimensional measurements. Distances between the intersection points between each hole with the two planes were measured, see Fig. 9. All possible distances, created from all intersection points, were measured.

The distances were calibrated using a tactile CMM at PTB, see Fig. 8-right. Medical CT scans in different systems were carried out at SKBS, see § 3.1. The medical CT results and the tactile result were compared, see § 3.2.

Fig. 8. (Left) CTDI-Phantom used for the study; (right) CTDI-Phantom mounted in a tactile CMM for the reference measurement.

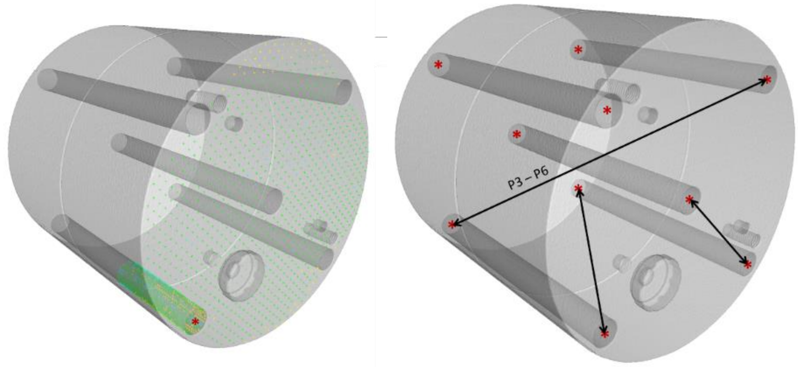


Fig. 9. Creation of the distances in the CTDI-phantom: (left) creation of the intersection points between the planes and the holes; (right) illustration of some example distances between the intersection points.

<u>PET QC Phantom</u>

This phantom consists of a cylindrical water tank made of PMMA. Rods of three different materials (Teflon, Air and water) are inserted to check image quality and alignment in clinical PET-CT systems. For clinical use, radioactive materials may be added to the water.

The whole PET QC phantom was scanned in its mounted state and filled with water. The water simulates soft tissue of the body, where the occurrence of scatter radiation is increased, and the Teflon simulated e.g. X-ray attenuation coefficient of bone. The rod was submersed in water, making the task of surface determination even more challenging.

For the tactile reference measurements performed at PTB, only the Teflon rod was measured. The measurement task was to measure diameter in different heights of the rod, using point-wise and scanning probing strategy – see Fig. 10-c an example graphical result of a circumferential profile measure in a tactile CMM ca be seen in Fig. 10-d.

The results, presented in § 3.2, are based on the comparison between the circle diameters obtained from medical CT data with the tactile reference results.

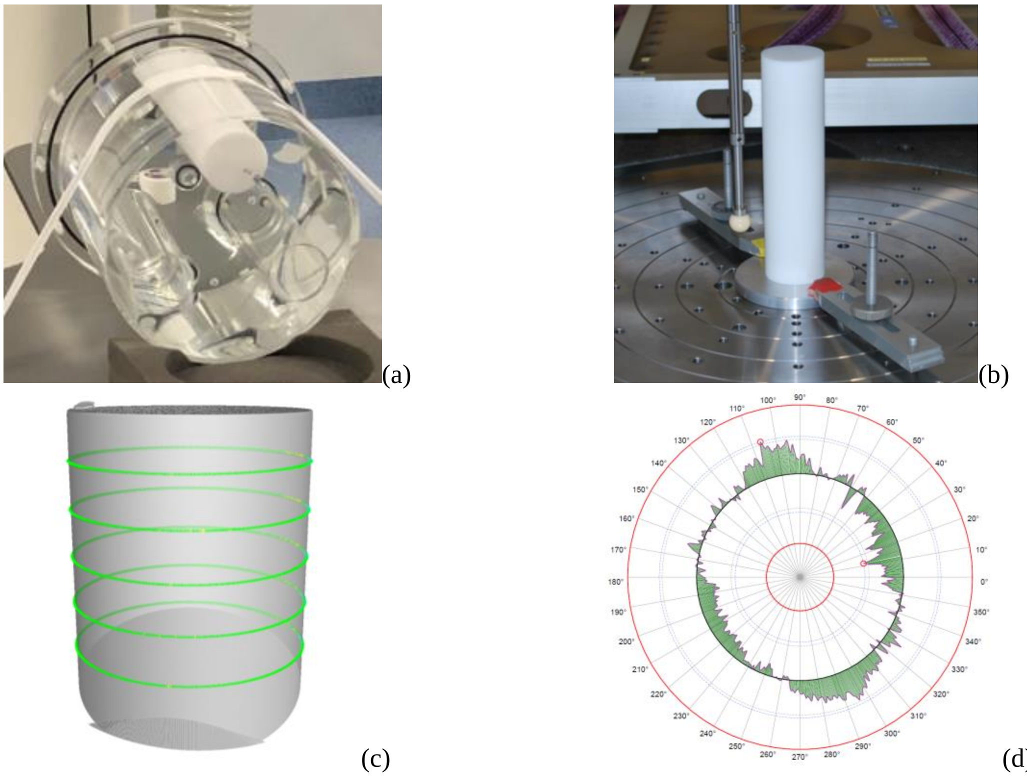


Fig. 10. CAT-CT phantom: (a) in its mounted state; (b) only Teflon rod mounted in the tactile CMM and (c) graphical representation of an example circle profile measured with a tactile CMM.

2.2.2 Alternative metrological reference standard

<u>Multi-sphere standard</u>

The multi-sphere standard is a commercial solution of a metrological reference standard to determine the voxel size of industrial CT measurements. There exist several versions of the multi-sphere standard in different sizes (e.g. outer diameter 56 mm and 120 mm), different number of spheres and they are manufactured and provided by different industrial CT devices manufactures. The determination of the voxel size is performed based on the distance between the spheres of the standard. Reference measurements are performed using a tactile CMM. The measurement task is to measure the sphere centre distances, i.e. measurement of the centre point of the sphere fitted.

Fig. 11. Multi-sphere standard (22 spheres) manufactured by Carl Zeiss, Oberkochen, Germany.

3 EXAMPLE USE OF THE CLINICAL PHANTOM/ REFERENCE STANDARDS TO TEST MEDICAL SYSTEMS

All the clinical phantoms and reference standards were scanned by different medical systems. In the following sections, a short description is given about the tested medical systems and the results.

3.1 TESTED MEDICAL CT SYSTEMS

In total 5 medical systems were tested during the study. All of them being in use for daily clinical purposes.
In Fig. 12, a picture of all systems is presented. Different modalities of clinical CTs were tested; Firstly, two Gantry-based medical CTs, a relatively new/modern system with larger detector (almost cone-beam system) and a relatively old system with fan-beam system, see Fig. 12-a and -b. Both Gantry-based systems feature helical and step and shoot scanning trajectories and are located at SKBS, Braunschweig, Germany. A second modality is a cone-beam CT-system, mounted in a C-arm-like construction, see Fig. 12-c. This kind of system is used e.g. for assisting surgeons during cardio surgeries. The C-arm system is also located at SKBS in Braunschweig. The third modality of systems tested is the digital volumetric tomography (DVT) largely used in the dental field and in the face reconstruction field, see Fig. 12-d and -e. The DVTs tested in the project feature cone-beam with circular scanning trajectory. The TeraView and Kavo systems are located at PAS dental clinic in Lüneburg, Germany and at SKBS in Braunschweig, Germany, respectively.

(a)

(b)

(c)

(d)

(e)

Fig. 12. Medical system tested during the MetAMMI project using the different medical phantoms and metrological reference standard: (a) 320 Slice modern CAT Scanner Aquillion One; (b) 16 Slice vintage CAT Scanner Somatom Sensation 16; (c) C-Arm with DVT function Artis Zee df; (d) Dental DVT VeraView EpocsR100; and (e) Dental DVT Kavo 3D Exam

3.2 RESULTS

The medical phantoms as well as the reference standards were scanned in different CT systems. By physical limitation not all the reference standards could be scanned in every CT scan, see Table 1. Also, to verify the influence of the scanning parameters on the results, for each CT system the scanning and reconstruction parameters were changed, see Table 2. For the dimensional error and surface characterisation analyses, absolute-based analyses, i.e. comparison of the CT scan value with the tactile reference value, were carried out.

Table 1. Medical systems where the clinical phantoms and reference standards were scanned.

Object	Medical systems				
	Somatom	Artis-Zee	Aquillon	DVT-PAS	DVT-SKBS
CTDI	X	X			
CAT-CT	X		X	X	
Multi-sphere	X	X		X	X

Table 2. CT scanning parameters changed.

	Somatom	Artis-Zee	Aquillon	DVT-PAS	DVT-SKBS
Scan mode	X		X		
Slice Thickness	X		X		
Voltage	X				
Exp. Time	X				
Eff. mAs	X				
Kernel/window	X	X			
Pitch	X		X		
Gantry tilt	X		X		
Table height	X		X		
Collimation	X		X		
Protocol		X			
Current			X		
Rec. Diameter			X		
Object position				X	X
FOV				X	X

<u>CTDI - Dimensional error</u>

The Siemens Somatom Sensation 16 and Siemens Artis Zee df measurements of the CTDI-Phantom are presented in Fig. 13 and Fig. 14, respectively.
In the plots, the red dot represents the average of all possible distances, black thick bar represents the standard deviation of all possible distances and the black thin bar represents the maximum and minimum measurement error obtained measured in the CTDI-phantom.
For all the scans of the Somatom 16 without slice thickness variation, a slice thickness of 0.75 mm was used. A total measurement error of +1000 µm -1500 µm was observed. Almost no significant influence of the scanning parameters in the dimensional error was observed in the measurements. A slight increase of the standard deviation and maximum/minimum values was observed when the slice thickness is increased and when the table position (where the patient lies) is changed, i.e. when the patient is moved away from the ISO-centre of the CT system.
For the Siemens Artis Zee df (cone-beam C-arm system) only Kernel/window and protocol were tested. The results are presented in Fig. 14. No significant influence of the Kernel/window was observed in the dimensional error of the system was observed. On the other hand, an influence of the reconstruction protocol on the results were observed.

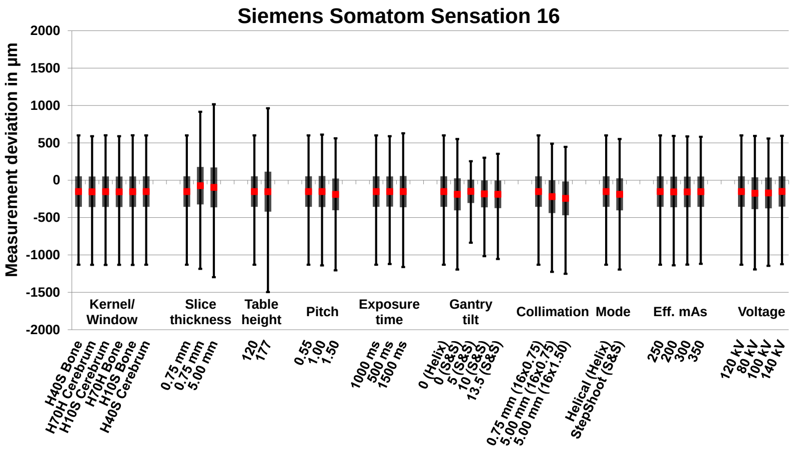


Fig. 13. Siemens Somatom Sensation 16 measurement of the CTDI-phantom for the evaluation of the system dimensional error.

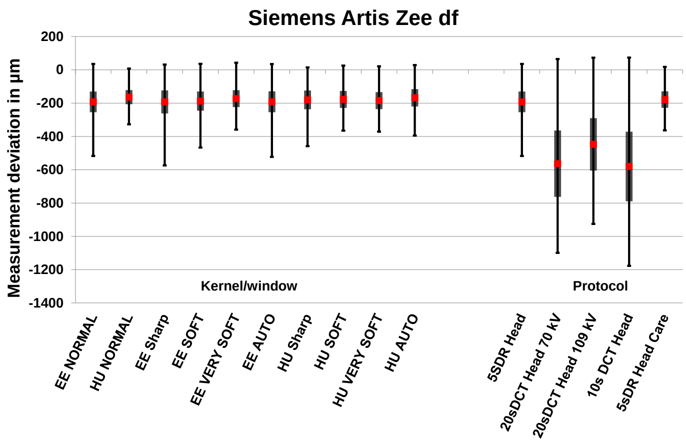


Fig. 14. Siemens Artis Zee df (C-arm) measurement of the CTDI-phantom for the evaluation of the system dimensional error.

Multi-sphere standard - Dimensional error

In addition to the CTDI-phantom, the multi-sphere standard was used for the dimensional error characterisation of the medical systems, as the distances of the CTDI-phantom strongly depend on two planes, i.e. 5 out of 10 points depend on the same plane to be constructed. Therefore, some of the distances in the CTDI-phantom are not independently created. The CTDI-phantom was used in the project due to its large use in the clinical field.

The multi-sphere standard-based results of the clinical systems (Somatom 16, Aquillion and Artis) are presented in Fig. 15, Fig. 16 and Fig. 17 respectively); and of the digital volumetric tomography (DVTs) – VeraView and Kavo - systems are presented in Fig. 18 and Fig. 19, respectively.

From the results obtained in the Somatom 16 system, a total measurement error of below 1000 µm was observed for most of the scanning parameters tested, see Fig. 15. Almost no significant influence of the scanning parameters was observed on the dimensional error of the Somatom system with the multi-sphere standard. A strong increase of the dimensional error was observed with an increase of the slice thickness.

Similar error behavior to the Somatom was observed in the Aquillion One system. However, for the Aquillion system, a smaller dimensional error was observed, see Fig. 16. The total measurement error of the multi-sphere standard measured by the Aquillion One system was below 500 µm for most of the scans. Only slice thickness impaired significantly the measurement results.

Only variation of the protocol was tested in the cone-beam medical Siemens Artis Zee df system, see Fig. 17. A total measurement error of approximately 250 µm was observed. No significant influence of the measurement protocol on the result was observed.

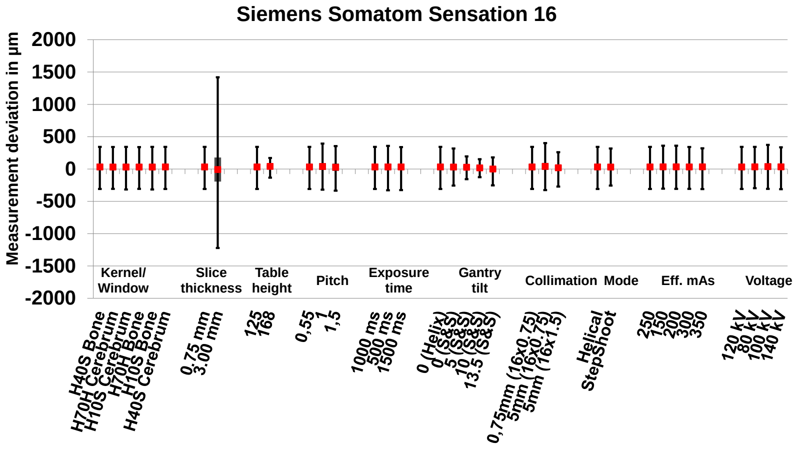


Fig. 15. Siemens Somatom Sensation 16 measurements of the multi-sphere standard.

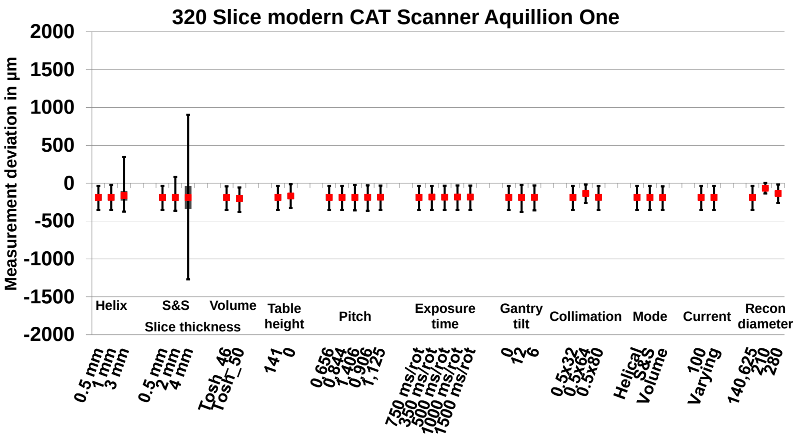


Fig. 16. Aquillion one measurements of the multi-sphere standard.

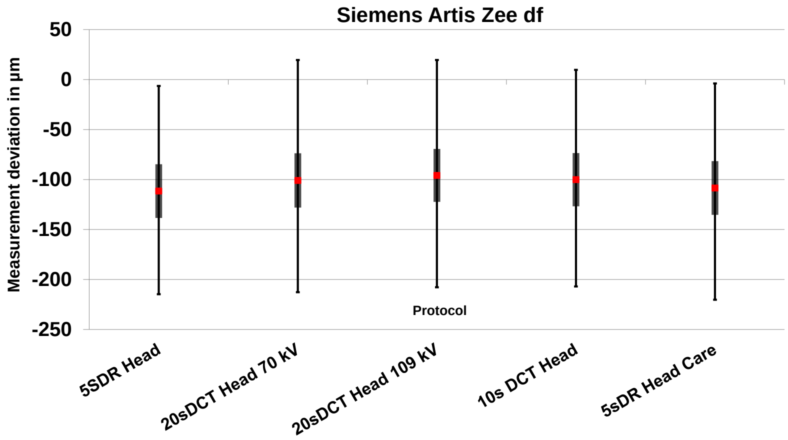


Fig. 17. Siemens Artis Zee df measurements of the multi-sphere standard.

The results of the dental DVT VeraView Epocs R100 of the multi-sphere standard are presented in Fig. 18. In this system, the position of the multi-sphere standard was varied. The field of view (FOV) was also changed (standard FOV used in all the other scans was set to be 80 × 80). A total measurement error of approximately 800 µm was observed. No significant influence was observed in the results when changing the field of view. A slight worsen measurement results could be observed

For the dental DVT Kavo 3D Exam, resolution and workpiece position were varied, see Fig. 19. A total measurement error of approximately 400 µm was observed. The results present a worsen result for the measurement with 0.2 mm Voxel size lasting 14.7 s. This effect is not yet fully understood, repetition of this measurement is necessary to verify if the effect is repeatable or it was an unexpected event (e.g. movement of the reference standard during the scan).

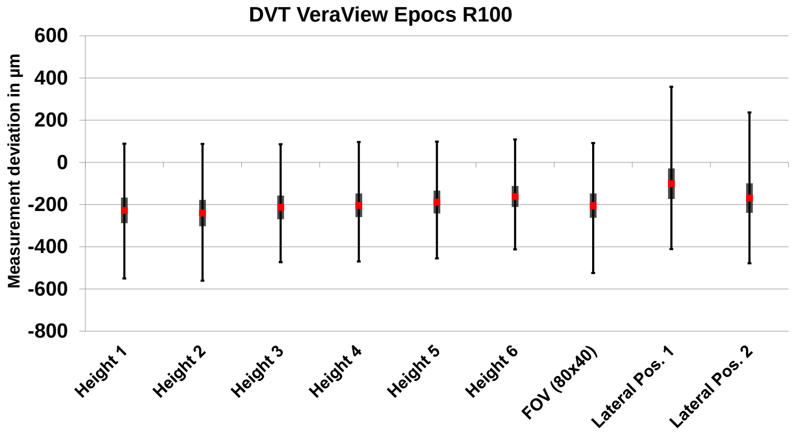


Fig. 18. DVT VeraView Epocs R100 measurements of the multi-sphere standard.

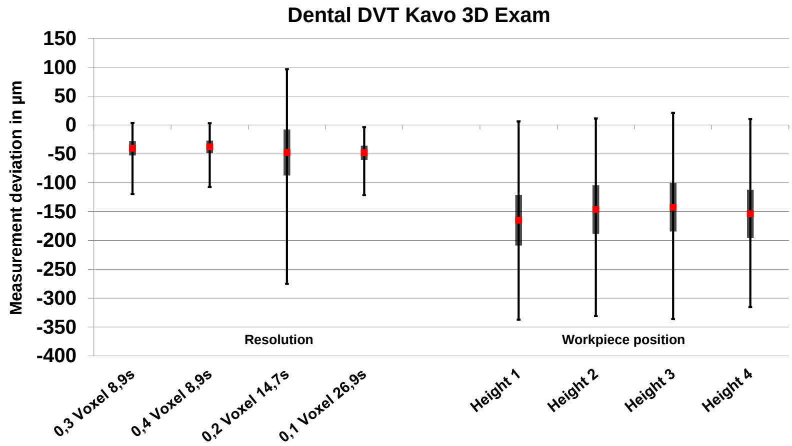


Fig. 19. Dental DVT Kavo 3D Exam measurements of the multi-sphere standard.

<u>PET QC Phantom (Teflon rod) – Surface characterisation</u>

The CT volumetric image of the PET QC phantom scan carried out in the Somatom 16 system is presented in Fig. 20. After segmentation of the volume and determination of the surface, only the Teflon rod volume (used for the evaluation) is presented in Fig. 20-right. In the image of the rod a relatively noisy surface can be observed.

Siemens Somatom Sensation 16

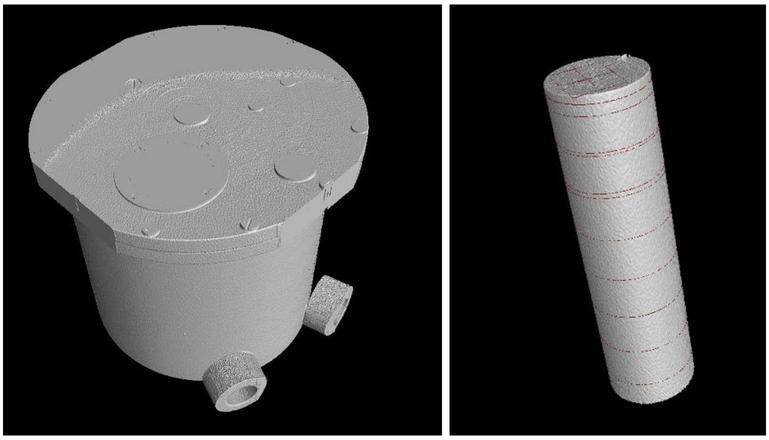


Fig. 20. CT volumetric image of the PET QC phantom obtained in the Somatom 16 system: (left) complete volume; and (right) only Teflon rod presented from the same scan.

The CT image obtained in the Dental DVT VeraView is presented in Fig. 21. Although the scan was performed with conditions similar to the conditions used when scanning with the Somatom 16 system (i.e. Teflon rod submersed in water), a noisier surface was observed in the measurement of the dental DVT system in comparison to the measurement with the Somatom 16 systems, cf. Fig. 21 and Fig. 20-right.

Dental DVT VeraView EpocsR100

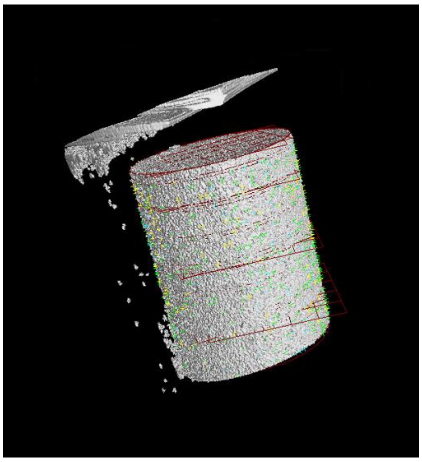


Fig. 21. Volumetric image of the Teflon rod obtained in the dental DVT VeraView Epocs R100.

The CT volume acquired with the Aquillion One system is presented in Fig. 22. After segmentation of the volume and surface determination only the Teflon rod is presented in Fig. 22-right. From a quick visual analysis of the Teflon rod image, a less noisy surface was observed with the Aquillion One system when compared to the Dental DVT VeraView and the Somatom 16 systems, cf. Fig. 22, Fig. 21 and Fig. 20.

Additionally, the diameter of the rod was measured in different heights for all the scans. The results are presented in Table 3. Despite the relatively noisy surface, the Somatom 16 system presented better results than DVT and the Aquillion One system. The measurement error of all diameters obtained with the Somatom 16 system was below 100 µm. On the other hand, the measurement error obtained with the Aquillion One and the DVT was below 350 µm. It is important to remark that the alignment procedure in such diameter measurements plays an important role in the results, considering the noisy surfaces obtained by the medical CT data and a slight conical shape of the Teflon rod (observed in the tactile reference measurement). Therefore, further tests considering the influence of the alignment procedure in the measurement result are necessary.

320 Slice modern CAT Scanner Aquillion One

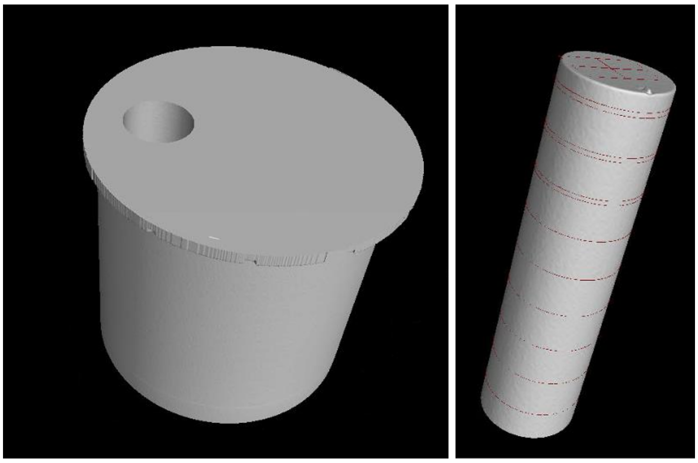


Fig. 22. CT volumetric image of the PET QC phantom obtained in the Aquillion One system: (left) complete volume; and (right) only Teflon rod presented from the same scan.

Table 3. Measurement error of the diameter measured in different medical CT systems.

	DVT VeraView	Som16	AQ1
-10	0.310 mm	-0.001 mm	0.334 mm
-30	0.267 mm	-0.091 mm	0.248 mm
-50	0.340 mm	-0.072 mm	0.263 mm

4 REFERENCE STANDARDS FOR CT-BASED COORDINATE MEASUREMENT SYSTEMS

Since CT was introduced as an alternative solution of coordinate measurement systems, several studies have been performed to verify and test CT's different metrological characteristics.
Some examples of reference standards were developed recently, a brief description on how to use the Example reference standards is presented in the following sections. Example CT measurement results are presented as well. All the CT measurements were carried out in the PTB's Nikon MCT225 with maximum voltage 225 kV, see Fig. 23.

Fig. 23. PTB Nikon MCT 225 system.

4.1 MULTI-SPHERE STANDARD

The multi-sphere standard is a proprietary standard for the evaluation of the voxel size of CT-based CMS measurement, evaluation of the overall scale error of the system as well as evaluation of the length measurement error of CT systems. A characteristic of this reference standard is that the material influence is included in the measurements to a very limited extend.
The reference standard is made of 22 spheres, each attached in a ceramic (Al_2O_3) holding shaft attached in an INVAR plate, see Fig. 11
Although sphere diameter is a possible measurement task in this standard, sphere centre-to-centre length measurements are the most common measurands performed in this reference standard. Centre-to-centre measurements allow stable and robust statements about the voxel size and system scale error, due to the massive averaging of the data points, by the least-square sphere fit. Subsequently the distances between two sphere centres are calculated. However, influences of the surface determination and image artefacts (e.g. beam hardening) are not included in this type of measurand.
Reference measurements are usually performed using traceable tactile systems, where well-distributed points (e.g. 25 points) are acquired all over the surface of each sphere, avoiding areas close to the holding shaft.

<u>Example use of the multi-sphere standard in a CT system</u>

The multi-sphere standard was scanned with a Nikon MCT225, using standard scanning parameters, and the distances between all the spheres were measured, and then compared with the tactile reference measurement. The result is presented in Fig. 24.

A total measurement error (i.e. CT result – tactile reference result) of approximately 6.5 µm which corresponds to approx. 20% of the voxel size was observed. An important remark is that no data correction (e.g. scale correction) was applied to show that the reference standard is able to detect and quantify scale error. The scale error was detected by the length-dependent measurement error. Applying linear interpolation of the points, a scale factor can be calculated and used to correct the voxel size of the measurement. Therefore, a relevant scale error was observed in the measurement.

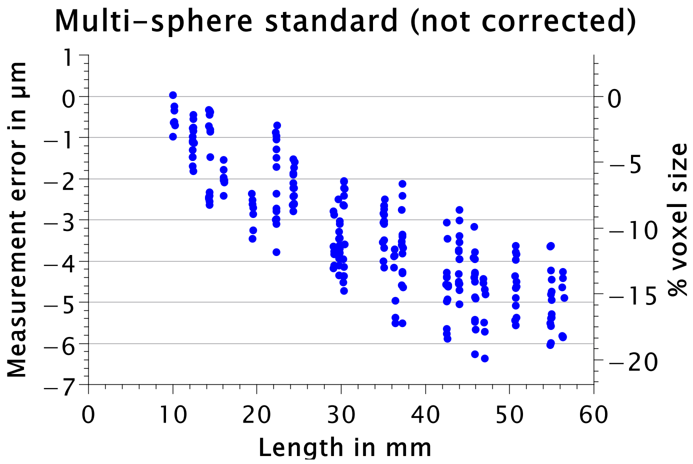


Fig. 24. CT measurement result of the centre-to-centre measurement of the multi-sphere standard.

4.2 MULTI-MATERIAL HOLE CUBE STANDARD

The multi-material hole cube standard is a reference standard developed at PTB – during the EU project INTERAQCT - to evaluate the performance of CT-based CMSs systems for the complex task of multi-material measurements [4]. The standard consists of 2 symmetric half cubes made of different materials (e.g. Al & Ti) and it features 17 holes, see Fig. 25-left. The standard also features a step-like cut enabling different material ratios over the standard height see Fig. 25-right.

Although cylinder diameter and form error are possible measurands to be evaluated in the multi-material hole cube, the most common measurement task in the hole cube standard are centre-to-centre distances between the hole centres at different heights and patch-based bidirectional distance measurements at different heights.

Absolute analyses are possible based on reference tactile measurements. Statements about different material ratios are also possible due to the cube's design.

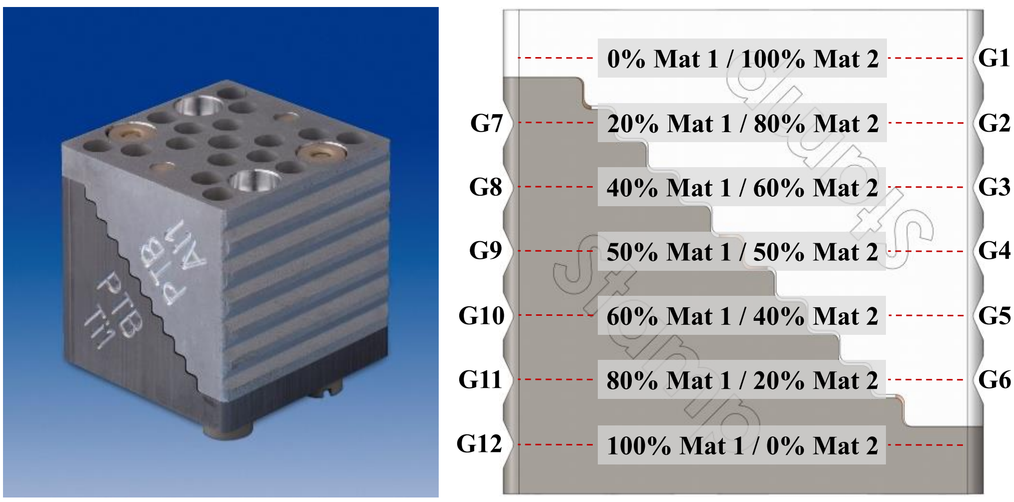


Fig. 25. (Left) PTB hole cube standard for evaluating performance of CT systems for multi-material tasks; and (right) description of the groove numbers and the material ratio.

Example use of the multi-material hole cube standard in a CT system

The multi-material hole cube standard was scanned in a Nikon MCT225 system with X-ray spectrum of 225 kV and 1 mm Ag beam filter. Cylinder-based centre-to-centre distances were carried out at different heights of the cube. All possible distances (between the 28 holes) were calculated and compared with the reference tactile values. The results of the centre-to-centre measurements are presented in Fig. 26. To provide a better overview of the multi-material influence on the CT performance, the results are presented height-wise, where the material ratio between Al & Ti is kept constant (i.e. G1 100% Al and 0% Ti; G4 50% Al and 50% Ti; G12 0% Al and 100% Ti, cf. groove # in Fig. 25). In Fig. 26, the red spots represent the average of all distance errors measured at each height or groove. The thick black bars represent the standard deviation of all distances measured at each groove and the thin black bars represent the maximum and minimum measurement error obtained at each groove of the cube.
The result show multi-material effects on length measurements. It is possible to observe that as the amount of Ti increases, the measurement result is degraded.

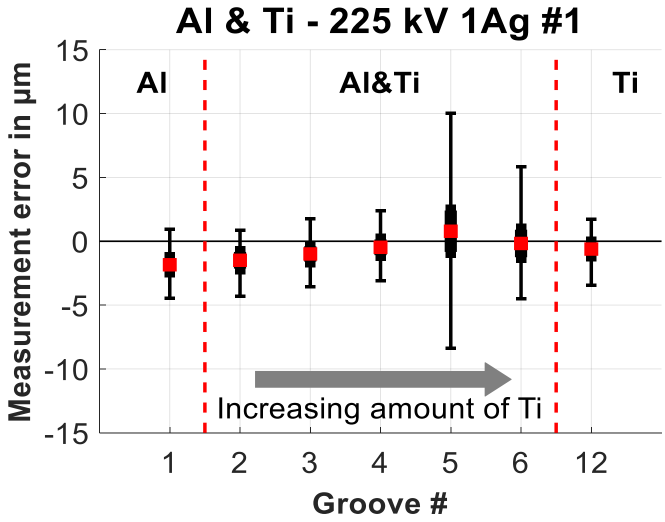


Fig. 26. CT centre-to-centre measurement result of the multi-material hole cube standard (Al & Ti)

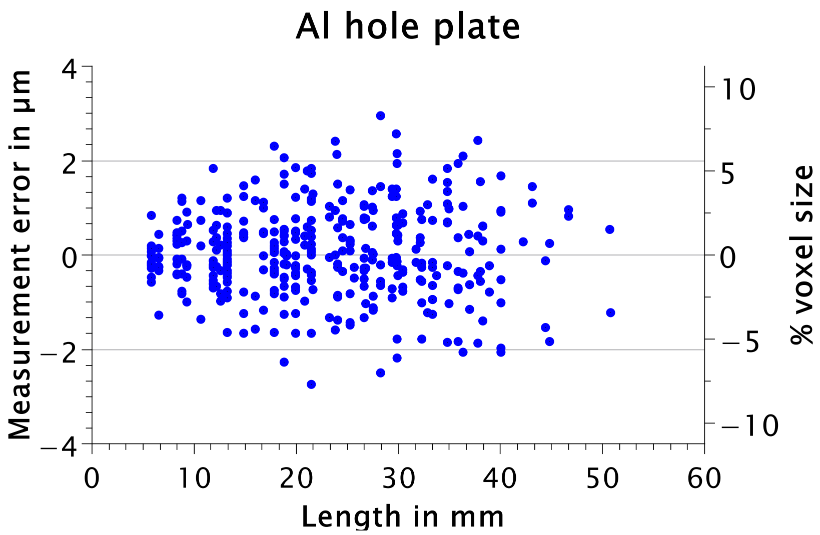
4.3 HOLE PLATE STANDARD

The hole plate standard was developed in collaboration between PTB, Germany and NMIJ, Japan to verify the performance of CT systems by a length measurement error test, considering the material influence and material thickness influence on the measurements [5].
The hole plate is made of Al, has a nominal size of (48 mm x 48 mm x 8 mm) and it features 28 holes arranged in such way that 5 independent lengths are obtained in 7 different spatial orientations, see Fig. 27. The design allows the evaluation of center-to-center, bidirectional as well as unidirectional lengths measurements. Also, diameter and form of the holes are possible measurands of the hole plate.

Fig. 27. PTB/NMIJ aluminium hole plate.

Example use of the multi-material hole plate standard in a CT system

Centre-to-centre length measurements were used to evaluate the performance of a CT-based CMS for length measurements. Scale correction was applied in the CT measurements using a projection-based scale correction method, more information in [6].The results show a total measurement error of approximately 6 µm which correspond to approximately 15% of the used voxel size.



4.4 CT MULTI-WAVE STANDARD

The metrological characteristic evaluated is the metrological structural resolution (MSR) of CT measuring systems [7,8].
The method consists in performing a frequency response analysis using calibrated multi-wave standards (MWS) as input signal [9]. Relative transmission values are calculated by the ratio between the measured and the calibrated amplitude values. Since MWS contains only discrete spatial frequencies, an amplitude transmission model is fitted to the relative transmission values. The MSR is defined as the wavelength (in mm) for a transmission model value of 50% [10].
The used implementation (CT-MWS) was designed for CT systems measuring in the voxel size range of 50-150 µm, see Fig. 28. Made of structural aluminium, it comprises five spatial frequencies (25, 50, 100, 200 & 400 UPR) with nominal half-amplitudes of 2.5 µm machined on a 40 mm diameter external cylinder [11].

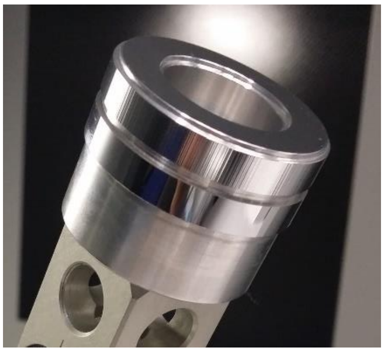


Fig. 28. Multi-wave standard made of Al designed by UFSC/CERTI (courtesy of UFSC/CERTI).

Example use of the multi-wave standard in a CT system

A CT-based CMS was evaluated with the MWS method. Different voxel sizes were used for the evaluation. The relative transmission values and associated transmission models for each voxel size are shown in Fig. 29-middle. The metrological structural resolution values for each voxel size are shown in Fig. 29-right. The results show the dependence of the structural resolution on the voxel size and demonstrate the potential of the method for evaluating the MSR.

Note to the results: the results presented here were created using the PTB's CT system during a collaboration between PTB and UFSC/CERTI.

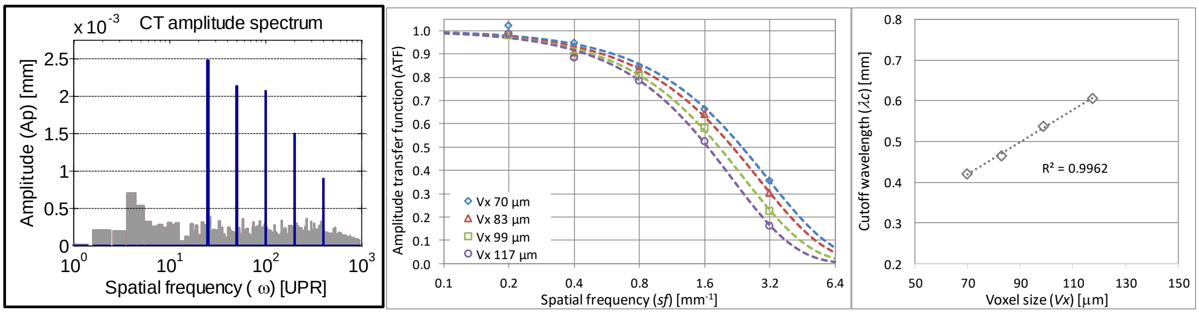


Fig. 29. Results of the multi-wave standard: (left) CT amplitude spectrum of the multi-wave profile; (middle) Amplitude transfer function measured; and (right) cut-off wavelength.

4.5 STRUCTURAL RESOLUTION STANDARD

The characteristic to be assessed with this standard is the metrological structural resolution of CMSs. It was developed by PTB, Germany. The method presented in [12] is based on the curvature transfer function measured at a cylinder that incorporates 3 grooves and 3 flanges, see Fig. 30. The prototype of the reference standard is a cylinder made of cooper plated with an amorphous nickel-phosphor layer in which the profile was manufactured by diamond turning. It features curvature radii between 1 µm and 5 µm, with 2 mm outer diameter of the cylinder.

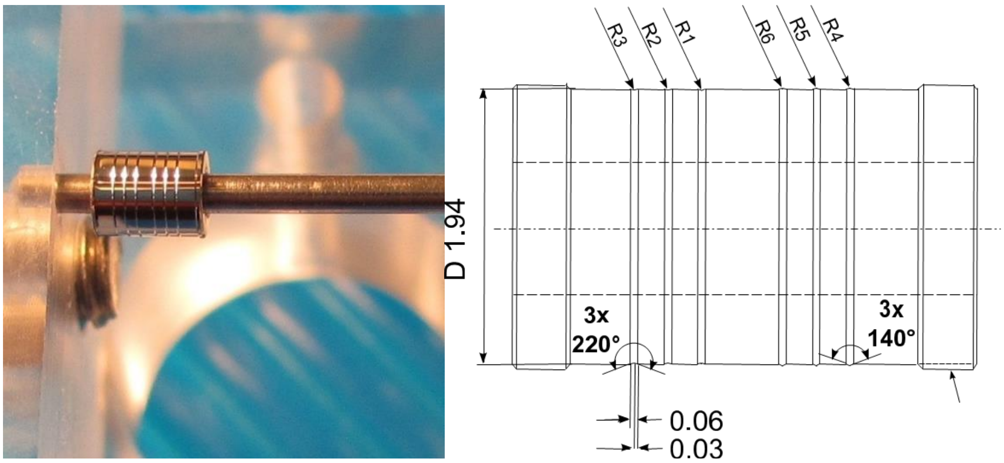


Fig. 30. Prototype of the structural resolution standard (left) picture of the standard; and (right) sketch of the grooves and flanges (source: [12]).

4.6 CALOTTE CUBE

The calotte cube is a reference standard developed at PTB, Germany, to evaluate also the performance of CT systems (for smaller magnifications than the hole plate standard cf. § 4.3) based on the procedure described in international series of reference standard for testing coordinate measurement system ISO 10360 [13].

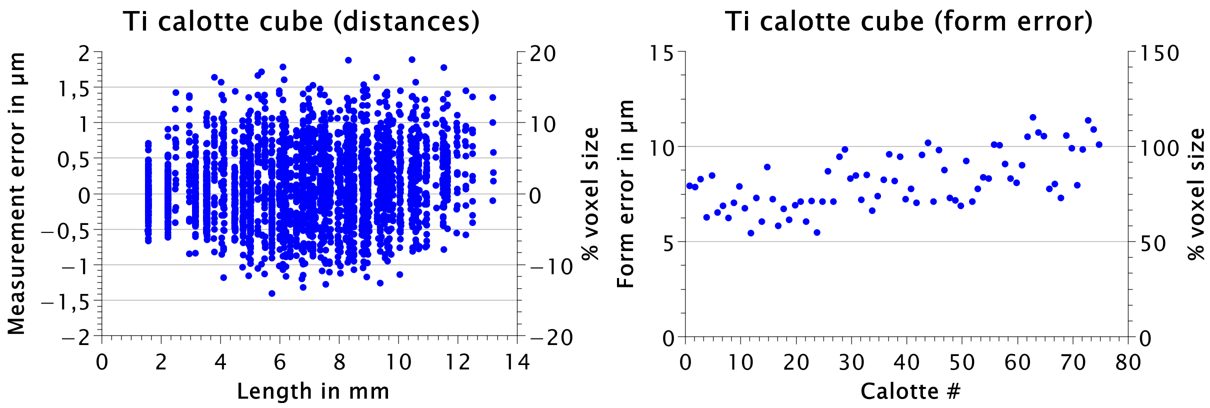
The calotte cube is made of titanium and has a side length of 10 mm x 10 mm x 10 mm and it features spherical structures on the surface, the so-called calottes, with a nominal diameter of 0.8 mm, Fig. 31.

The measures evaluated in the calotte cube are diameter, form error of the calottes and distances between calotte centres. The calotte cube was calibrated by a tactile CMM. The data analysis is based on the differences between CT measurements and tactile reference measurements.

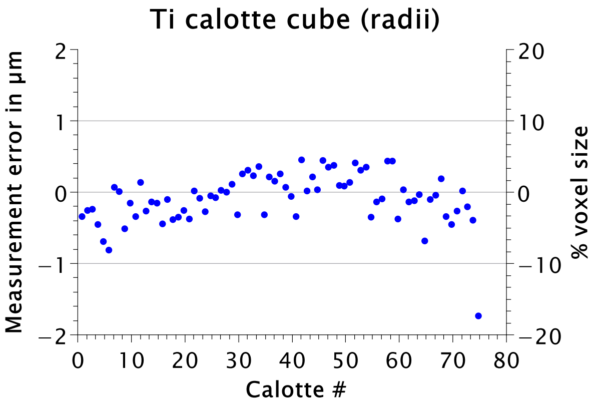
Fig. 31. PTB titanium calotte cube for testing industrial CT systems.

<u>Examplary use of the Ti calotte cube in a CT system</u>

The calotte cube was measured using the PTB's CT system using a voxel size of 10 µm. The results of the measurement are presented in Fig. 32. Centre-to-centre between all the calottes, calottes form error as well as calottes radii measurement error were measured, see Fig. 32-a, -b and -c, respectively. Scale error correction using a projection-based method was applied, see [6]. The measurement results, after the scale correction, presented a total measurement error of approx. 3.5 µm, which correspond to 35 % of the voxel size. In general, the form error was measured by CT larger than the calibrated value (calibrated value was smaller than 8 µm). The radii presented total measurement error of below 1.5 µm, corresponds with 15% of the voxel size.



(a) (b)



(c)

Fig. 32. Results of the CT measurements of the PTB Ti Calotte cube: (a) measurement error of the centre-to-centre distances between calottes; (b) form error measurements of the calottes; and (c) measurement error of the radii measured in each calotte.

4.7 CT GAP STANDARD

The gap standard is joint development between PTB, Germany and University of Padova, Italy to test the CT performance for measurements of small air gaps between parts made of equal and different materials [14].
The gap standard design consists in two prismatic parallelepipeds. The side lengths of the gap standard are 10 mm x 10 mm x 30 mm and it features step-like gaps with nominal gap sizes of 12.5 µm, 25 µm, 50 µm, 100 µm, 250 µm, 500 µm and 1000 µm. Additionally, the design features two tilted planes with a nominal angle of 1.43˚, characterising a continuous gap along the standard.
One gap standard is made of aluminium. A set of multi-material gap standards was also produced to test the CT performance for multi-material tasks. More details can be seen in [14]. However, only results achieved with an example CT gap reference standard made of Al are presented.
Reference measurements of the gap standard were carried out using a high precision tactile CMM at PTB. The step-like gaps as well as the continuous gaps were calibrated.

Fig. 33. PTB/University Padova (Al&Al) CT gap standards for testing industrial CT systems.

Example use of the CT gap standard in a CT system

The CT gap standard was also measured in PTB's CT system using a voxel size of approx.23 µm. The measurement task is to measure the distance between the planes of the small air gaps between the material. The results are presented in Fig. 34. Only step-wise gaps were measured. From the results it was observed that when the gaps are smaller than 50 µm, the measurement error was already in the order of the voxel size or larger. Gaps from 100 µm were measured with an error below 10% of the voxel size.

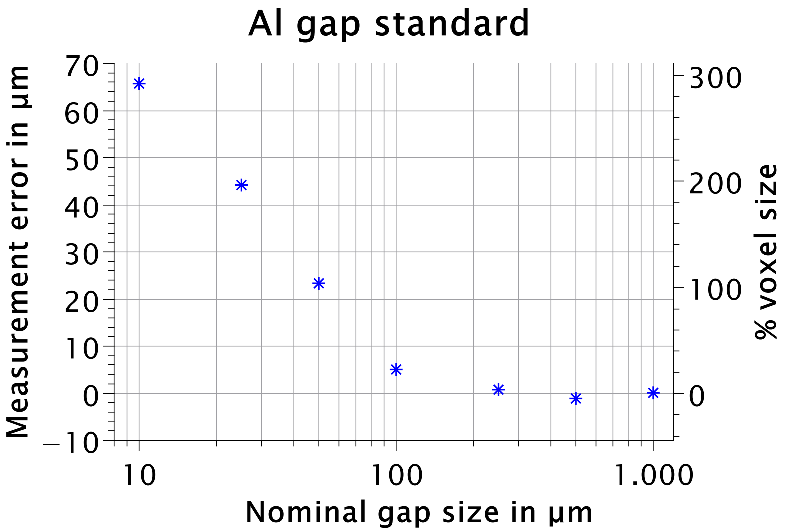


Fig. 34. Results of a CT measurement of the PTB/University of Padova Al&Al Gap standard.

4.8 STEP GAUGE

The step gauge standard was designed by DTU, Denmark to test CT-based CMSs to measure distances between planes. The step gauges in use have dimensions of 55 mm × 8 mm × 7 mm and feature 11 grooves at 2 mm steps (flatness of the grooves less than 5 µm), and they were designed, developed and manufactured by DTU and are described in more detail in [15]. The step gauge was manufactured in different materials (e.g. PPS and Al). In this study, the PPS step gauge was used.
The measurement task is to measure distance between planes of the step gauge. Unidirectional as well as bidirectional measurements are included in the data analysis. Reference measurements of the step gauge is performed in a tactile reference CMM.

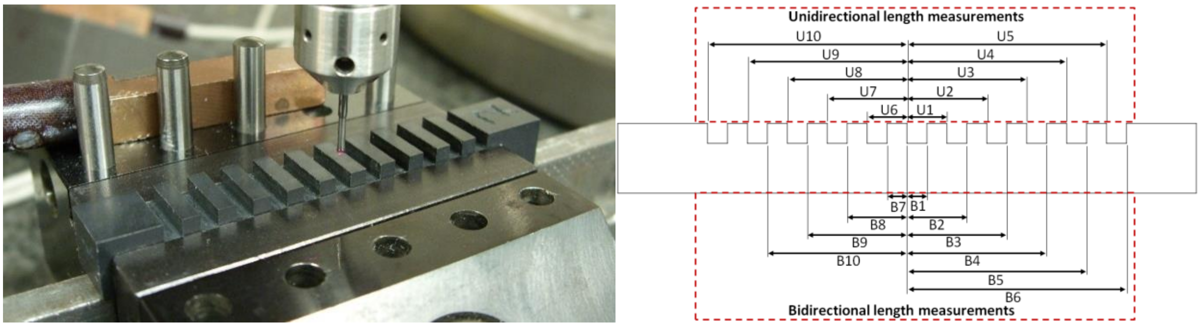


Fig. 35. DTU PPS step gauge for testing CT-based CMSs: (left) picture of the step gauge in a tactile CMM; and (b) description of the measurands.

<u>Example use of the PPS step gauge in a CT system</u>

The PPS step gauge was measured at PTB with a voxel size of approx. 24 µm. Distances between groove planes were measured. The results of the unidirectional and bidirectional measurements are presented in Fig. 36. A total measurement error of 10 µm was observed which correspond to 35% of the voxel size.

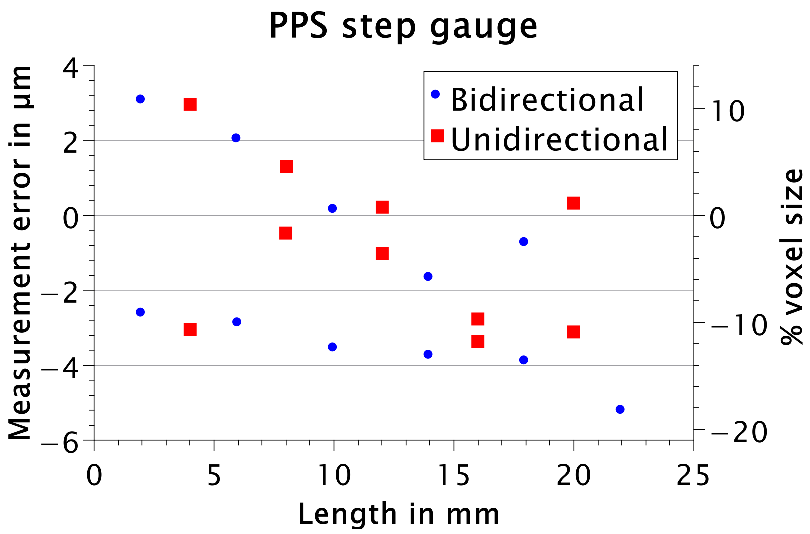


Fig. 36. CT measurement error of the measurement in the DTU PPS step gauge.

4.9 TRACEABLE PHANTOM FOR XCT DEVELOPED AT VTT

The material of the phantom is Polyoxymethylene (POM). This material has behaviour in XCT which is close to bone. A drawback with this material is sensitivity to humidity uptake. Immediately after the material is manufactured, it will expand slightly when absorbing humidity.
The phantom consists of two prismatic blocks and three rods. As seen in Fig. 37, the blocks have holes. In addition to hole positions, flatness of surfaces and angles, & distances between surfaces are measurands.

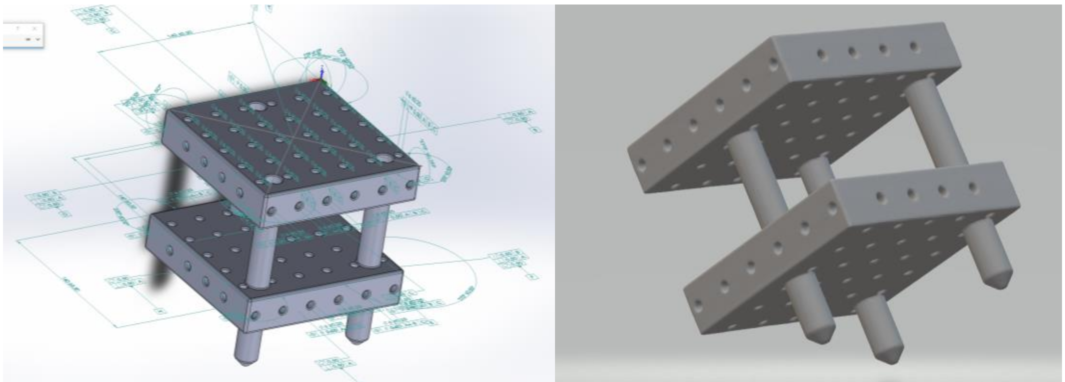


Fig. 37. Phantom developed at VTT

The reference measurements were made with the CMM at VTT, Mitutoyo Legex 9106 (Fig. 38). The CMM is periodically verified with the interferometrically calibrated gauge blocks ensuring a maximum permissible error, $E_{0,\,\mathrm{MPE}}$ value, of (0.35 + L/1000 µm), where L is length in mm. The CMM is in a laboratory with a temperature stability of 20°C ± 0.2°C. Using the CMM, 9 planes and 70 holes were measured (Fig. 38-right). These results serve as reference values.

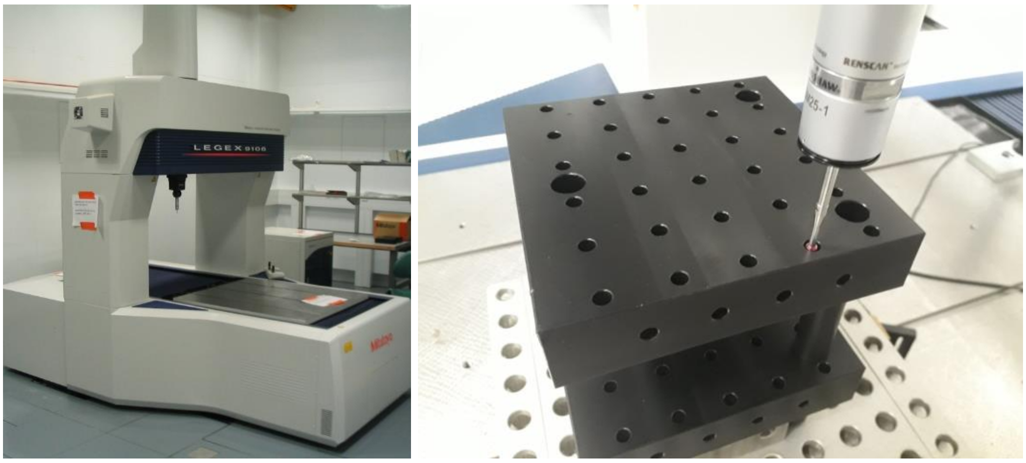


Fig. 38. (Left) The CMM at VTT, Mitutoyo Legex 9106; and (right) Reference measurements using tactile probe.

During the MetAMMI project, the phantom was scanned with two medical XCTs (Fig. 39).

Fig. 39. Scanning of Phantom at Hospital District of Helsinki and Uusimaa (HUS).

Using GOM Inspect software, hole distances and other measurands were extracted from the STL file generated from the thresholded (segmented) medical XCT scans (Fig. 40).

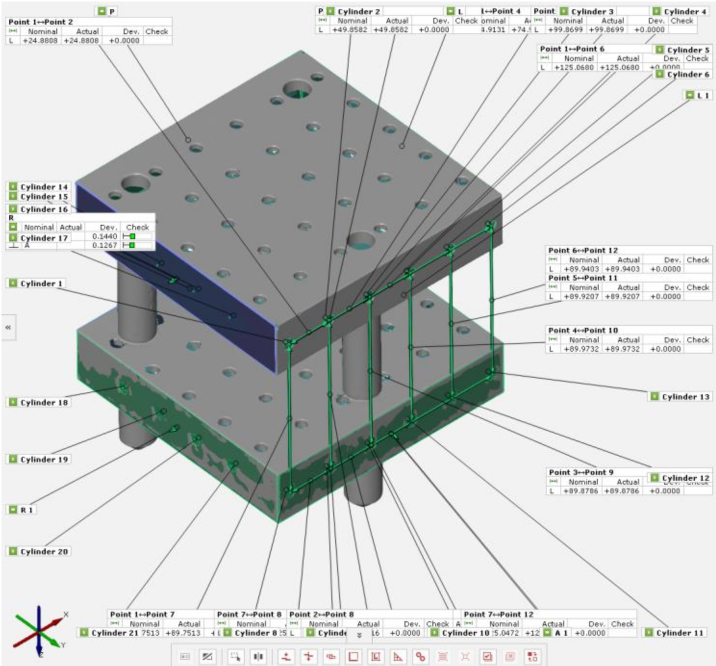


Fig. 40. Screenshot from GOM Inspect program.

4.10 FURTHER REFERENCE STANDARDS DEVELOPED TO TEST CT-BASED CMS

Bartscher et al. 2010 [16] applied a new dismountable traceable reference standard with internal geometries and sculptured surfaces for the analysis of the dimensional performance of CT. The conclusion is that dismountable workpiece-near reference objects (block size 120 mm x 90 mm x 60 mm) can be used as sensitive tools for verifying the entire measurement process of CT measurements of a given product, additional to the standard test.

Carmignato et al. 2009 [17] presented a test procedure to evaluate the length measurement error of CT using glass fibres-based reference standard featuring a regular array of inner and outer cylinders (so-called fibre gauge standard). The cylindrical shaft and the holes have diameter of 120 µm and 250 µm, respectively. The experimental results showed that the reference standard is suitable for determining the length measurement error as well as for compensating residual scale errors of the system.

Cantatore et al. 2011 [18] verified the CT performance based on the VDI/VDE 2617-6.2 guideline using a miniature step gauge (length of 42 mm), initially developed to test optical measurement systems. In the study, object orientation, magnification and surface extraction methods were evaluated. The experimental results showed that an optimal orientation of the workpiece on the rotary stage is important to enhance the reliability of the measurements.

Muller 2012 et al. [19] developed a new reference standard (the so-called CT ball plate standard) for evaluating the metrological performance of CT systems. The standard appears to be a valid solution for the length measurement error test.

Angel 2015 et al. [15] studied the length measurement performance of CT systems using statistical methodologies on step gauge standards made of different materials. Particularly, the material influence and object orientation were in focus. The main effect observed in the study is that the measurement errors are affected by X-ray scattering, therefore material-dependant.

Léonard et al. [20] presented a method of performance verification for CT systems based on tetrahedron made of 4 alumina spheres. The results showed that the reference offers a simple versatile solution for assessing CT systems.

Hermanek and Carmignato 2016 [21] developed a dismountable reference object for evaluating the accuracy of porosity measurement. The possibility of calibration of the internal structures using tactile or optical means is one of the main advantages of the standard.

The use integral feature-based analysis based on geometric product specifications (GPS) concepts was used by [22] to evaluate the quality of CT geometrical evaluations. The study used circumferential lines extracted from a multi-wave standard, a step cylinder standard and an electric toothbrush head (production workpiece).

Performance verification should include every step of the measurement chain, this also includes the evaluation of the measurement strategy. Therefore, the measurement procedure by CT was assessed by Krämer and Lanza [23]. The study is based on an object with 3 spheres attached in carbon fibre rod. The authors concluded from the study that with standardized procedures reliable and repeatable measurement results can be achieved.
For structural resolution, Carmignato2009 [17] proposed a reference standard and a test procedure for testing the structural resolution for dimensional CT measurements. The reference standard consists of two spheres with the same nominal diameter physically touching each other. The testing method is based on the diameters of the spheres and the height of the measured contact zone.

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