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Quality control test of cone beam computed tomography – constancy tests

J. Redutko [a,*], K. Wrona [b], A. Szarek [a], Ł. Bańczyk [b]

[a] Department of Technology and Automation, Faculty of Mechanical Engineering and Computer Science, Czestochowa University of Technology, Al. Armii Krajowej 21, 42-201 Częstochowa, Poland

[b] Alfamedica Czestochowa Medical Center, ul. Kilińskiego 166, 42-201 Częstochowa, Poland

* Corresponding e-mail address: jredutko@iop.pcz.pl

ORCID identifier: https://orcid.org/0000-0001-7488-5874 (J.R.); https://orcid.org/0000-0002-5910-0554 (A.S.)

ABSTRACT

Purpose: The paper describes tests of CBCT cone beam scanners carried out to ensure projection quality.

Design/methodology/approach: During the studies, phantoms were scanned with a leading brand volumetric CT scanner according to the device manufacturer's recommendations. The water phantom and phantom made of PMMA with materials of different radiological densities were used in the performed tests. The image area during the tests was determined as a cylinder with diameter of 80 mm and height of 90 mm. In turn, exposure parameters were selected on the basis of clinically applied protocols of cranial imaging. Within carried out research, tests of noise level were performed, image homogeneity was analysed and Hounsfield units constancy was determined. To this end, 18 quality control tests were analysed, which were performed at intervals of about 30 days. Images obtained during phantom scans were analysed by determining the Hounsfield value of selected areas and their changes over time.

Findings: The analysis of all carried out projection quality control tests showed that they met the criteria set by the manufacturer, falling within the predefined value ranges. One of the performed tests presented results approaching the limit of acceptable values. After notifying this case, it was shown that the CT scanner was serviced during that period. The obtained results of the quality control tests of water phantom as well as of the material phantom imaging were maintained at similar levels after the service activities. No changes were observed in the obtained mean values of Hounsfield units, which would indicate a decrease in diagnostic quality of CBCT projections.

Research limitations/implications: The results presented in this publication require further analysis. These should be complemented by incl. analyses of spatial resolution and image geometry.

Practical implications: Carried out research has shown that cyclical quality control testing by a qualified operator is an essential activity to ensure high diagnostic quality of the device. In addition, this analysis showed that procedures of in-service tests should not be omitted and delayed.

Originality/value: Originality in these tests is the possibility to improve the procedures for performing basic quality control tests.

Keywords: CBCT, Cone Beam Computed Tomography, Phantom, Quality control

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BIOMEDICAL AND DENTAL ENGINEERING AND MATERIALS

1. Introduction

Cone beam computed tomography (CBCT), otherwise known as volumetric tomography is a modern imaging method, consisting of taking multiple X-rays in two dimensions at different angles, on the basis of which a 3D volumetric image is created. A volumetric tomograph differs from classical CT scans in the shape of the X-ray beam used. In this case, the beam has the shape of a cone or pyramid, hence the device is also called a conical tomograph [1].

CBCT is a relatively young method of imaging – its origins have dated back to the 1990s, when the first CBCT scanner for maxillofacial examination was produced [1]. Currently, cone beam tomography is used mainly in dentistry, maxillofacial surgery, implantology, laryngology and angiography. This quite wide range of application is the result of many advantages of the device, such as low radiation dose, which, depending on the CT scanner, may vary between 20-50 μSv, and short time of the examination, ranging from a few to several seconds [2]. An additional convenience of this type of CT scanners is the position which the patient takes during the examination – he can both sit and stand, there is no need to place the patient in a lying position, as is the case of conventional CT scanners [3].

The image obtained by CBCT imaging very clearly reflects the patient's bone tissue, but soft tissues are not well recognized in this case. This is result of the low dose of X-rays applied during the examinations [4-6].

The use of CBCT during dental treatment is much more effective than intraoral X-ray or pantomography, due to the possibility of imaging the anatomical region of the facial part of the skull from many sides simultaneously. To that end, MPR (Multi-planar Reconstruction), i.e. 3D reconstructions in typical imaging planes (axial, coronal, sagittal) are used [1, 6-8].

Essential for safe diagnosis is periodic verification of the quality of radiological images. All methods in radiology have protocols and tools for image quality control assurance. Currently both scientists in different publications and technical specialists propose phantoms quality control models for CT scanners, whereby variety of these technological concepts of phantom models requires the development of all possibilities, including angle of rotation, different sizes of field of view (FOV) and FOV combinations [9-11].

The projections were obtained by scanning two types of phantoms: homogeneous and nonhomogeneous, made especially for quality assurance purposes. The aim of the presented study is the assessment of the repeatability of projections performed with a cone beam tomograph used in clinical practice [3].

2. Methodology

Quality control of volumetric tomography equipment was performed using dedicated phantom sets, according to the procedures provided by the device manufacturer. Such tests should be performed cyclically, as recommended, to exclude the possibility of image quality regression and to maintain a high diagnostic value of the obtained images.

Companies producing CBCT devices and specialist instrumentation recommend performing quality control of the projection, during which the following parameters are measured:

- noise,
- homogeneity [3, 11-14].

The tests were carried out with using certified cone beam tomography. Measurements of the value of Hounsfield units were made using RadiAnt DICOM Viewer.

The phantoms used in the studies were specialised accessories, adapted to the volumetric tomography used in the tests. These phantoms are used only for the purposes of the tests presented.

The performed analyses were based on a comparison of the changes in the value of Hounsfield units of particular regions of interest over time. The HU scale is determined by the linear attenuation coefficient (μ) of each tissue and takes into account the linear water attenuation coefficient. The radiological density of distilled water in this case is defined as 0 HU and of air as -1000 HU (at standard pressure and temperature). For a particular material the HU value is determined by the following formula:

$$HU = (\mu x - \mu_{H2O})/(\mu_{H2O} - \mu_{air}) \times 1000 \quad (1)$$

where μ_{H2O} and μ_{air} are the linear attenuation coefficients of water and air respectively [15].

2.1. Homogeneous phantom

In performed test the water phantom was used. It was made from a thin-walled, cylindrical plastic container 120 mm in diameter, 205 mm high and less than 1 mm thick, filled in 75% of its volume with water distilled at room temperature.

Analysis of the water phantom projection allows to determine the homogeneity, constancy of Hounsfield units (which is the value used to describe the average X-ray attenuation associated with the basic image surface) and noise level for a specific CBCT camera (standard deviation of the HU level of the marked test image field) [4,16].

Hounsfield's (HU) units were measured for five different areas of water volume, in the transverse plane. The selected circular ROI areas had diameters not exceeding 10% of the phantom diameter and were defined so that they did not overlap [13].

Homogeneous phantom is mainly used to control noise level of particular ROI over time.

Noise is a local statistical change in HU of individual picture elements of a homogenous ROI. Level of noise in CBCT is strictly related to the number of detected photons, pixel size, slice thickness, scattered radiation and the size of the object.

2.2. Non-homogeneous phantom

The phantom has a cylindrical shape with a diameter of 150 mm and a height of 26 mm. It was made of polymethyl-methacrylate (the material of the core of the phantom), while three cylindrical elements, which were fitted to it (with 12 mm diameter and 26 mm height) were made of other polymers such as low density polyethylene (LDPE), acrylic (PMMA), teflon (PTFE) and an air gap of the same dimensions as the material elements (Fig. 1). The materials have been selected so that the resulting HU values cover the desired range of values recorded in clinical images (soft tissue, bone, fat, etc.). In the centre of the phantom there are 7 groups of notches for measuring spatial resolution [7,12,17,18].

This phantom is used in the cone beam CT lab to specifically control the presence of artifacts, HU value and spatial resolution [12,19,20].

For this phantom, the stability of Hounsfield units was measured for both each phantom material and air. The analysed areas (ROI) were defined as circles, which are the central part of each material of the phantom structure and the air gap in it.

The phantom was placed in the imaging area so that the air hole and material elements (PMMA, low density polyethylene, PTFE) were perfectly visible in this area and the phantom symmetry axis was parallel to the lamp rotation axis [12].

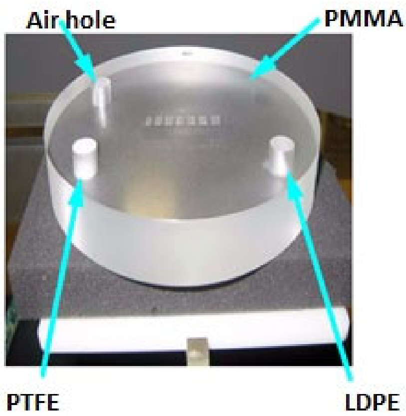


Fig. 1. Phantom scheme containing materials of different values HU

The imaging parameters during each exposure were determined on the basis of clinically applied exposure parameters:

- Intensity: 3-7 mA,
- Lamp peak voltage: 120 kVp,
- Radiation dose: 3.77 dGy*cm^2,
- Voxel size: 0.2 mm x 0.2 mm x 0.2 mm,
- Imaging field in the cylindrical shape with 80 mm diameter and 90 mm high.

After the exposition, the visibility of artifacts on all clinically applied windows and the stability of HU values (for homogeneous water phantom and for phantom from materials of different densities) were determined, while this stability was characterized by comparing average HU values. The homogeneity of the image was also determined using the existing differences in average HU values measured in the central and coastal area of the water phantom.

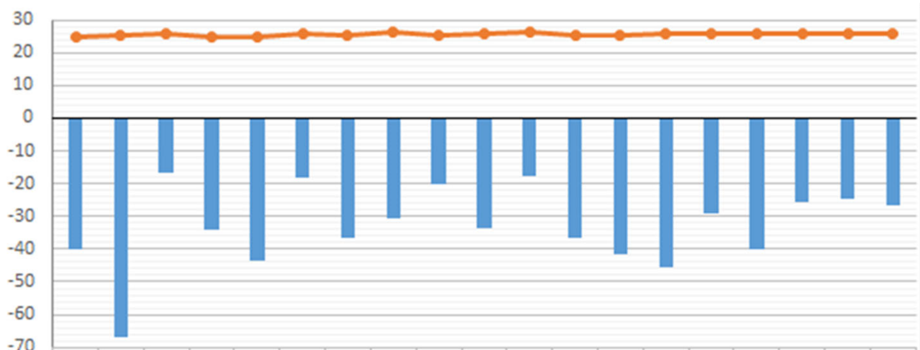
It should be added that after the second quality control test performed, a note appeared on the instrument display suggesting service and calibration to maintain a high level of diagnostics. Such actions were immediately carried out by a cone beam tomograph service authorised by the manufacturer. The service check of the volumetric tomograph should be performed each time the operator observes significant differences between the results obtained in the operational tests.

3. Results

In this study the results of operational tests of a volumetric tomograph, which is part of the diagnostic imaging laboratory of one of the medical centres in Częstochowa were dissected. The analysis included 18 quality control tests, performed cyclically, once a month. Each test included imaging of water and material phantoms. As the first ones, the images of the homogeneous phantom were analysed, in which the ROI was defined in the form of circles, each with a field of about 1760 mm^2 in the central part of the examined element. The parameters of the area of interest have been determined according to the procedure of testing the projection noise level. The main compared value was the average value of Hounsfield units in the marked field. The results are presented in the diagram in Figure 2.

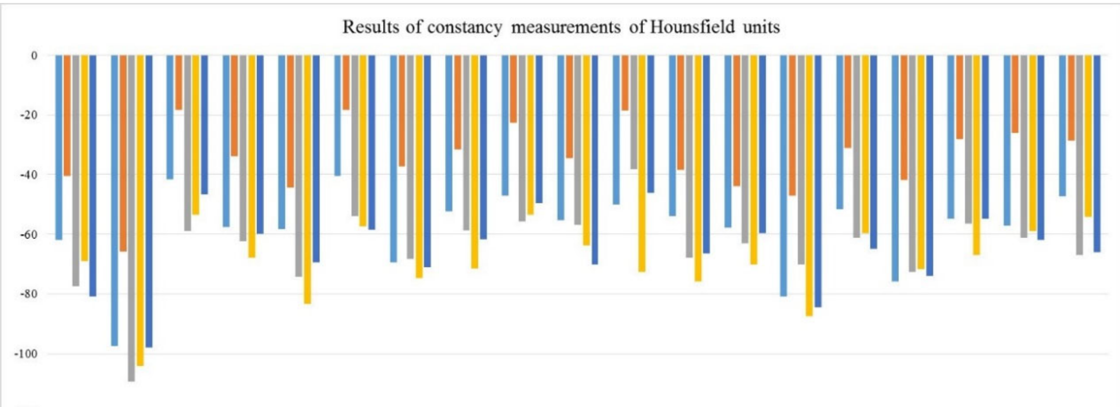
According to the literature and recommendations in the presented test procedure, the expected value for water is 0 HU (with a tolerance from -70 HU to 70 HU) [3,7]. In the analysed test, the average HU values corresponded to the adopted tolerance range, ranging from -16.5 HU to -66.8 HU. The value from 02.2018 is clearly marked, assuming an average value of 30 HU lower than the other tests. The standard deviation of subsequent measurements has also been recorded and should also be checked according to the specified test procedure.

The next step in the study was to compare the values obtained in the same test windows as the noise test, but this time 5 areas of ROI were identified in key positions for the assessment of projection (Fig. 3) [21]. For each ROI, the programme shows the average values of HU, its minimum, maximum, standard deviation as well as the field of the analysed area. For this test, the single area of interest not be less than 400 mm^2. The results of average HU values of each analysed point are presented in Figure 4.



	01.2018	02.2018	03.2018	04.2018	05.2018	06.2018	07.2018	08.2018	09.2018	10.2018	11.2018	12.2018	01.2019	02.2019	03.2019	04.2019	05.2019	06.2019	07.2019
Mean	-39,85	-66,83	-16,51	-34,3	-43,51	-18,37	-36,71	-30,43	-20,34	-33,69	-17,91	-36,54	-41,48	-45,44	-29,01	-40,3	-25,58	-24,75	-26,57
Standard deviation	24,58	25,45	25,62	24,85	24,95	25,7	25,2	26,16	25,53	25,73	26,16	25,26	25,19	25,69	25,81	25,63	25,56	25,62	25,97

Fig. 2. Results of measurements of the noise level of the homogeneous phantom image



	01.2018	02.2018	03.2018	04.2018	05.2018	06.2018	07.2018	08.2018	09.2018	10.2018	11.2018	12.2018	01.2019	02.2019	03.2019	04.2019	05.2019	06.2019	07.2019
1	-62,01	-97,57	-41,55	-57,66	-58,17	-40,46	-69,46	-52,39	-47,08	-55,26	-50,07	-53,98	-57,7	-80,94	-51,58	-75,77	-54,86	-57,24	-47,35
2	-40,47	-65,8	-18,42	-33,94	-44,29	-18,39	-37,36	-31,56	-22,6	-34,46	-18,63	-38,45	-43,88	-47,07	-31,1	-41,96	-28,1	-26,13	-28,66
3	-77,45	-109,37	-58,84	-62,32	-74,26	-54,04	-68,35	-58,82	-55,79	-56,91	-38,2	-67,74	-62,99	-70,07	-61,17	-72,57	-56,5	-61,12	-67,02
4	-69,07	-104,08	-53,54	-67,84	-83,4	-57,29	-74,58	-71,48	-53,44	-63,74	-72,58	-75,82	-70,04	-87,54	-59,59	-71,73	-66,92	-59,05	-54,19
5	-80,91	-97,88	-46,56	-59,94	-69,38	-58,49	-70,94	-61,77	-49,67	-70,09	-46,11	-66,51	-59,59	-84,38	-64,85	-73,94	-54,87	-61,87	-66,11

Fig. 3. Results of constancy measurements of Hounsfield units

Measurements of homogeneity of water projection show that the highest HU values were recorded in the central part of the phantom and did not exceed 65 HU in any study. The lowest values are recorded, in most tests for point 4 on the right-hand side of the test window. In this test, it can be seen that in the part of the analysed ROI outside the central ones, water takes values exceeding -70 HU. In order to assess the correctness of the projection in places not within the tolerance adopted during the noise level tests, each mean value had to be subtracted from the mean value of the middle area of interest, and then assessed if the obtained values did not exceed 90 HU. This procedure is recommended by the CBCT scanner manufacturer. In the homogeneity tests analysed, the differences between the average HU of individual ROI and the average HU of the central part did not exceed the set limit. The results are presented in Table 1.

The next stage of the exploitation tests is to perform the projection of the heterogeneous phantom and assess the stability of Hounsfield units of air and materials of different densities.

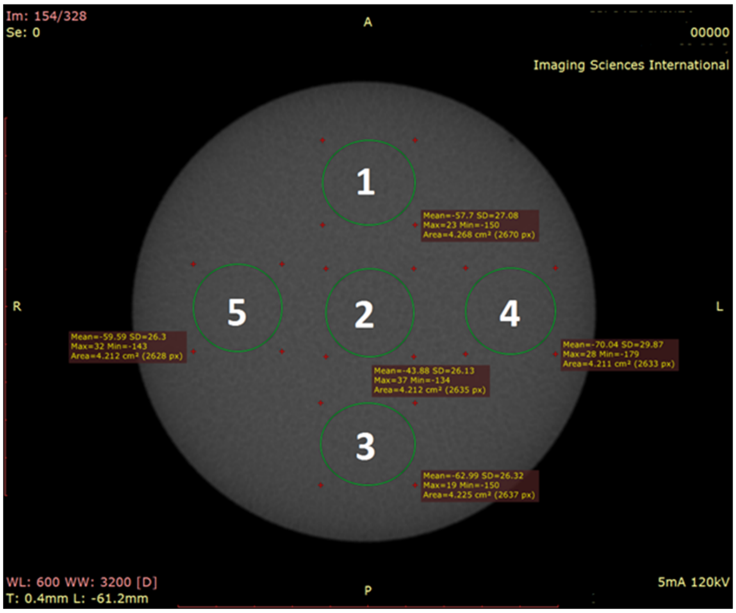


Fig. 4. Example of homogeneity test window with marked ROI areas under analysis (1-5)

Table 1.
Values of the difference between average HU ROI of number 1, 3, 4, 5 from average HU of central 2 for each study presented

Test date	1	3	4	5	Test date	1	3	4	5
01.2018	21.54	36.98	28.6	40.44	11.2018	31.44	19.57	53.95	27.48
02.2018	31.77	43.57	38.28	32.08	12.2018	15.53	29.29	37.37	28.06
03.2018	23.13	40.42	35.12	28.14	01.2019	22.29	24.93	28.96	28.49
04.2018	23.72	28.38	33.9	26	02.2019	33.87	23	40.47	37.31
05.2018	13.88	29.97	39.11	25.09	03.2019	20.48	30.07	28.49	33.75
06.2018	22.07	35.65	38.9	40.1	04.2019	33.81	30.61	29.77	31.98
07.2018	32.1	30.99	37.22	33.58	05.2019	26.76	28.4	38.82	26.77
08.2018	20.83	27.26	39.92	30.21	06.2019	31.11	34.99	32.92	35.74
09.2018	24.48	33.19	30.84	27.07	07.2019	18.69	38.36	25.53	37.45
10.2018	20.8	22.45	29.28	35.63					

The radiological density of the acrylic element was first analysed. Most of the results in this case were in the range between 60 HU and 100 HU, while three measurements went beyond this range, obtaining 127.51 HU and 146.4 HU, and for the second measurement -46.76 HU. A result significantly different from the others was probably caused by a lack of proper calibration of the device or by a technical defect [3, 17]. Nevertheless, the values obtained during this test were in the range of acceptable values set by the manufacturer. The CBCT manufacturer has set limits for this material as acceptable between -50 HU and 200 HU, so the test can be considered as having been performed correctly. The results of the analysis are presented in the diagram of Figure 5.

The following analyses were carried out on the phantom element from low density polyethylene. In this case, the values of HU ranged from - 110.6 HU to - 174.5 HU with the exception of the second in the order of measurement, for which a value of -240.9 HU was assumed. In this case, the second result, as in the analysis of PMMA density tests, is significantly different from the others. This confirmed the need to reschedule the service operations. This may be due to calibration problems, detector failure or impurities in the regions of interest [11]. The values obtained are within the range specified for LDPE are from – 250 HU to -50 HU. The measurement results are shown in Figure 6.

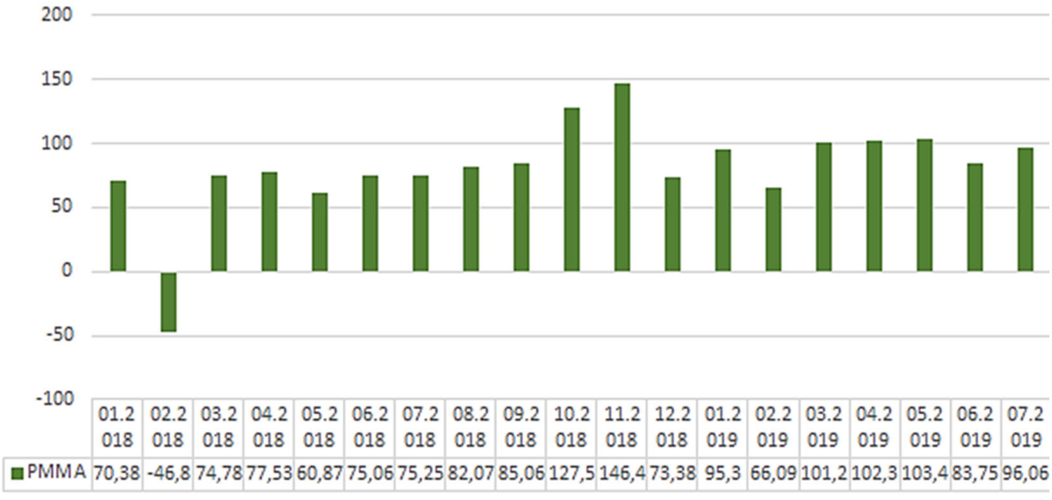


Fig. 5. Average radiological densities of a non-homogeneous phantom PMMA element

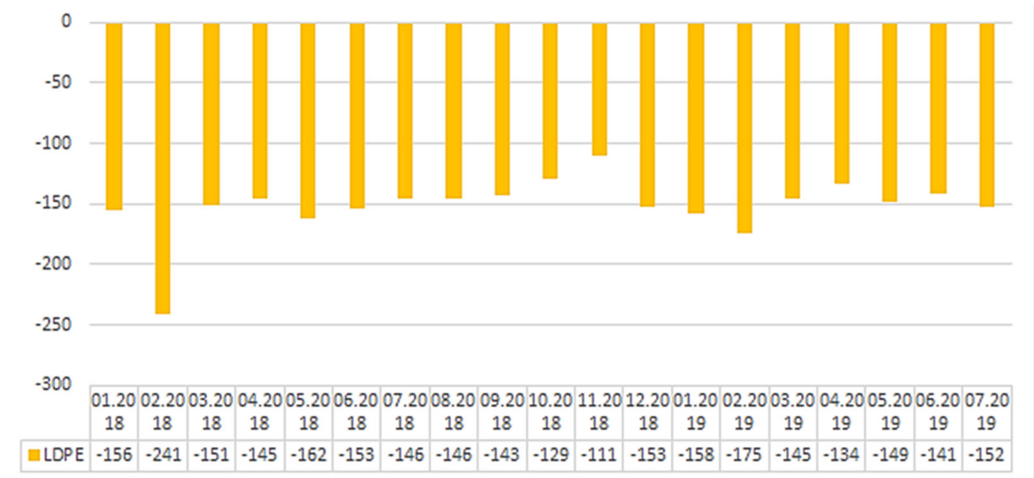


Fig. 6. Average radiological densities of a non-homogeneous phantom LDPE element

During the analysis of the last heterogeneous phantom material element, i.e. polytetrafluoroethylene, it was noted that it takes high values from 810.26.HU to 1077.7 HU. The differences in the subsequent months of testing amounted to a maximum of 150 HU, but in most cases remained at a similar level. According to the manufacturer, polytetrafluoroethylene should take values from 580 HU to 1160 HU. The results of polytetrafluoroethylene radiological density are shown in Figure 7.

The mean values of HU for the air measured during the screening of the heterogeneous phantom were at a very similar level -1000 HU. The maximum differences were 0.4 HU. This is in line with the values that, according to literature sources, air should take. The results obtained during air analysis are presented in Figure 8.

In addition, for each of the comparative analysis of quality control tests, a basic statistical analysis of the results obtained was performed. In this way, the mean value of Hounsfield units of a particular area of interest was obtained, minimum and maximum values obtained for a given ROI, standard deviation showing the measure of variability of the analysed results, their scatter around the mean value, as well as the coefficient of variation determined by dividing the standard deviation by the arithmetic mean. Statistical analysis was carried out in order to determine the correctness of the tested exploitation tests. The results of analytical statistical of individual tests are presented in Tables 2, 3, 4.

Table 2.
Analytical statistics for the study of the noise level of the homogeneous phantom

Arithmetic mean	-33.06
Maximum	-16.51
Minimum	-66.83
Standard deviation	11.86
Coefficient of variation, %	35.87

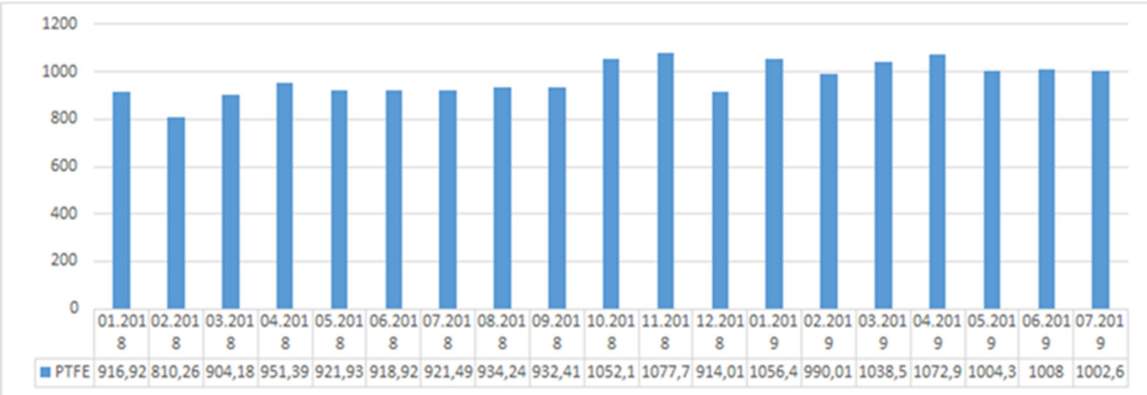


Fig. 7. Average radiological densities of a non-homogeneous phantom polytetrafluoroethylene element

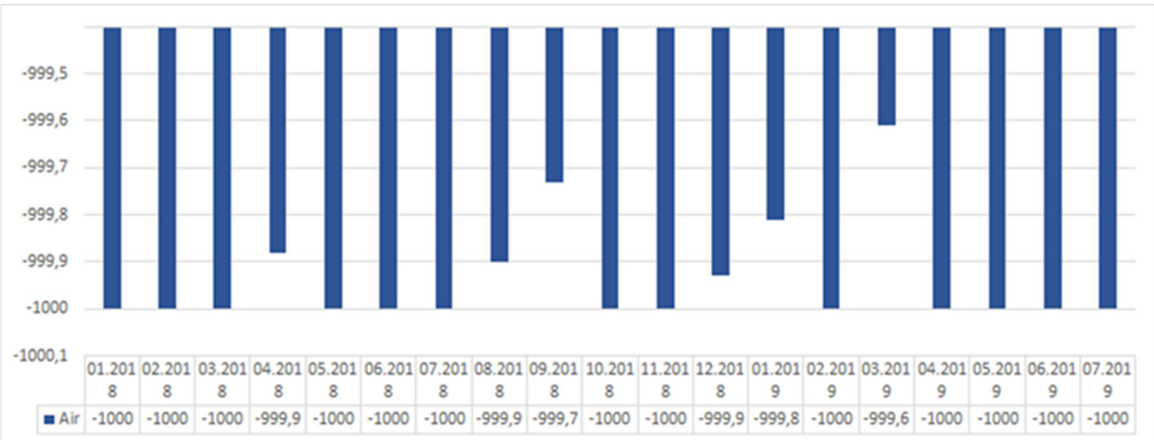


Fig. 8. Average air values of Hounsfield units

Table 3.
Analytical statistics of the constancy of HU measured on homogeneous phantom

ROI	1	2	3	4	5
Arithmetic mean	-58.93	-34.28	-65.24	-69.41	-66.15
Maximum	-40.46	-18.39	-38.20	-53.44	-46.11
Minimum	-97.57	-65.80	-109.37	-104.08	-97.88
Standard deviation	13.74	11.51	13.58	12.47	12.62
Coefficient of variation, %	23.32	33.56	20.82	17.97	19.08

Table 4.
Analytical statistics of the constancy of HU measured on different materials and air

	PTFE	Air	LDPE	PMMA
Arithmetic mean	969.91	-999.94	-152.06	81.56
Maximum	1077.71	-999.61	-110.56	146.4
Minimum	810.26	-1000	-240.92	-46.76
Standard deviation	69.31	0.11	24.63	36.63
Coefficient of variation, %	7.15	0.01	16.20	44.91

By performing statistical analysis of all quality control tests, it can be determined that the arithmetic mean of Hounsfield units for water and other tested materials take values within the ranges defined as acceptable by the CBCT manufacturer. The coefficient of variation determined for the performed tests can be assessed as average for the middle area of the homogeneous phantom (35.87% for the noise level test, 33.57% for the uniformity of projection). For areas of interest other than the middle one in the HU homogeneous phantom constancy test, the coefficient of variation indicated small variability of parameters. The highest value of variability was determined for acrylic, because in this case the coefficient was 44.91%.

4. Conclusions

All performed quality control tests of the CBCT scanner projection were carried out in accordance with the procedures presented by the manufacturer of the device, obtaining results allowing to give a positive opinion on the diagnostic quality of the performed X-rays. All the conducted tests of the projection quality control met the set criteria, falling within the predefined value ranges.

For one test defined as 02.2018, the values taken were close to the limits. In this case, it should be stressed that this was a signal that calibration and other service activities should be performed quickly. Immediately after receiving the results of the operational test presented in this paper, the CBCT scanner and technical service personnel immediately took steps to eliminate the problems in order to prevent deterioration of the diagnostic quality of CBCT scans. An improvement in the stability of Hounsfield units in the analysed areas can already be seen in subsequent phantom quality control tests.

Both the results of the water quality control test and the material phantom screening, after the service activities, remained at similar levels, no disturbing drastic changes were observed in the obtained values of the average Hounsfield units. The cone beam scanner on which the tests were performed can be described as fully operational and capable of performing X-rays of very good diagnostic quality. The cyclic control measurements made it possible to detect a decrease in test parameters and to carry out the necessary service activities in order to remove possible errors in the diagnostic X-rays.

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