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ORIGINAL PAPER

Quality control in cone-beam computed tomography (CBCT) EFOMP-ESTRO-IAEA protocol (summary report)

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Dedicated to our deceased colleague and friend Wil van der Putten, who co-founded this group.

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ABSTRACT

The aim of the guideline presented in this article is to unify the test parameters for image quality evaluation and radiation output in all types of cone-beam computed tomography (CBCT) systems. The applications of CBCT spread over dental and interventional radiology, guided surgery and radiotherapy. The chosen tests provide the means to objectively evaluate the performance and monitor the constancy of the imaging chain. Experience from all involved associations has been collected to achieve a consensus that is rigorous and helpful for the practice.

The guideline recommends to assess image quality in terms of uniformity, geometrical precision, voxel density values (or Hounsfield units where available), noise, low contrast resolution and spatial resolution measurements. These tests usually require the use of a phantom and evaluation software. Radiation output can be determined with a kerma-area product meter attached to the tube case. Alternatively, a solid state dosimeter attached to the flat panel and a simple geometric relationship can be used to calculate the dose to the isocentre. Summary tables including action levels and recommended frequencies for each test, as well as relevant references, are provided.

If the radiation output or image quality deviates from expected values, or exceeds documented action levels for a given system, a more in depth system analysis (using conventional tests) and corrective maintenance work may be required.

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1. Introduction

Cone-beam computed tomography (CBCT) is now an essential image modality in different fields of diagnostic and planning digital imaging. After the publication of the first document on 'Quality Controls in digital mammography' in 2015, a specific EFOMP International Working Group started a strong cooperation with the International Atomic Energy Agency (IAEA) and the European Society for Radiotherapy and Oncology (ESTRO) to prepare a similar document on CBCT. A group of 20 authors and 28 consultants from a total of 19 countries have collaborated. This paper is a summary of the resulting second book of this series: 'Quality Controls in Cone-Beam Computed Tomography'. These books are freely available online at efomp.org and can be used as both in-depth working guides to everyday practice and up-to-date reference sources for medical physicists engaged in quality control of medical imaging systems.

Current guidelines for quality control (QC) of CBCT and general documents on radiology physics regard the different CBCT applications (dental, radiotherapy, interventional radiology and guided surgery) as different entities [1,2]. However, the data acquisition, reconstruction and the test parameters for image quality and dose evaluation are mostly the same. The guideline presented in this paper unifies the test parameters for all CBCT systems. A further unification with multi slice CT systems, which are closely related to CBCT, is planned for the future.

The aim was to search for test parameters and methods that can be used to assess the image quality and the exposure related to any CBCT device. Detailed procedures using free software have been included for image quality evaluation. Action levels and frequency of the tests are indicated together with references wherever possible. However, due to a lack of long term worldwide experience with applications of CBCT in radiotherapy, interventional radiology and image-guided surgery, the recommended action levels for these modalities are still not as well established as in the dental field [3–5].

In the particular case of external beam radiotherapy, patients undergo treatments with high energy X-rays or charged particles with total absorbed doses in the range of several tens of Grey (Gy). In addition, for image-guided radiotherapy (IGRT) several CBCT scans could be performed on the patient during treatment [6]. In this regard, the guideline focuses on the quality control of the CBCT system and not the whole IGRT system.

The next section (a summary from Chapter 2 of the guideline) presents references that were useful for the present work. The main body of the guideline is devoted to the measurement of image quality using objective methods (Section 3) and phantoms (Section 4) and the measurement of practical dosimetric quantities to check the radiation output (Section 5).

2. Previous work

The International Commission on Radiological Protection (ICRP) in its publication 129 on Radiological protection in cone beam computed tomography (CBCT) [7] and the Criteria for acceptability of medical radiological equipment used in diagnostic radiology, nuclear medicine and radiotherapy[2] by the European Commission are the most recent international efforts to provide guidelines for quality control of CBCT. The most detailed and practical documents, focused on dental CBCT only, are the German standard DIN 6868-161 [5] Acceptance testing of dental radiographic equipment for digital cone beam computed tomography and its complementary DIN 6868-15 [8], the British guidelines Guidance on the safe use of dental CBCT equipment [4], and the European Guidance on the safe use of dental CBCT equipment [3].

In the field of radiotherapy, the only dedicated references we could find were the French Radiothérapie guidée par l'image - contrôle de qualité des équipements à rayons X - Rapport SFPM N° 29 [9] and the AAPM guideline Quality assurance for image-guided radiation therapy utilizing CT-based technologies [10].

The conventional tests mentioned in most guidelines for X-ray devices involve X-ray tube potential, X-ray tube leakage, total filtration and/or of half-value layer, repeatability and reproducibility of radiation output, beam collimation, image display, image artefacts and radiation protection of the staff and public. These tests are briefly described in the guideline and accompanied by references and tolerances. To keep compatibility with current guidelines, the conventional test of "image slice thickness" is maintained as an alternative measurement, but the actual measurement of z-resolution is now possible using software and it should be preferred in future national regulations.

The most relevant tests for efficient quality control evaluate *image quality* and *radiation output*. Ensuring a balance between both is the main goal of our work (Fig. 1).

3. Objective measures of image quality

A summary of the methods, test frequencies and action levels is shown in Table 1 and briefly described below. Although frequent tests are desirable for all modalities, in general the test frequencies (and action levels) proposed are stricter for radiotherapy applications. This is because the CBCT images are often used in the context of IGRT to aid the accuracy of the delivery (patient/tumour positioning before the delivery and/or within treatment fractions) and could also be used for dose accumulation and to re-plan a treatment in adaptive radiotherapy (ART) [11].

Fig. 1. An example of the experimental setting used to measure image quality (left) and radiation output (right). The importance of objectively measuring both, as inseparable entities, for complete and efficient quality control is especially stressed in the Chapters 3 and 5 of the guideline.

Table 1
Summary of recommended image quality tests.

Parameter	Procedures	Frequency*			Action level		
		Dental	Interventional radiology	Radiotherapy	Dental	Interventional rad.	Radiotherapy
3.1 Uniformity	XYZ uniformity curves	Annual		Monthly	Manufacturer specifications, or >10% difference air water		Deviation from baseline >10 HU
	DIN method				Uniformity parameter U < 5		
3.2 Geometrical precision	Geometrical accuracy Linearity	Annual (or none)		Monthly	>1 mm	>2 mm	>2 mm for conventional
	Spatial Stability	(not relevant)		Monthly (coincidence of isocentres daily)	(not relevant)	(not relevant)	treatments, >1 mm for SRS/SBRT
3.3 Voxel density values	Voxel values for different materials	Annual		Monthly	Manufacturer specifications, or >25% difference air water	Deviations >50 HU from the baseline value (still under research)	
3.4 Noise	ROI standard deviation	Annual		Monthly	Differences from baseline >20%		
3.5 Low contrast resolution	Contrast-to-noise ratio	Annual			Differences from baseline >40% Acceptance indicator <100§		
3.6 Spatial resolution	Frequency at 10% of the modulation transfer function	Annual			<10 lp/cm (high resolution mode)	<5 lp/cm	

* Depending on the complexity of the treatment techniques used and the weight of CBCT for image guidance, the monthly tests in radiotherapy facilities may be carried out quarterly or every half a year. In addition to the indicated frequency, the tests should be performed at acceptance of the device as well as after maintenance work or upgrades that could affect the integrity of the system.

3.1. Uniformity

Regular evaluation of the axial uniformity is one of the simplest methods to make sure that there are no errors (appearing as artefacts) affecting the reconstruction. With CBCT equipment, a lack of uniformity is usually unavoidable though, because of several factors such as radiation heel effect, beam hardening, partial rotation acquisition and parts of the volume outside the FOV.

The two recommended methods make use of five ROIs placed as shown in Fig. 2a. The first method (xyz uniformity curves) evaluates the mean grey values (or Hounsfield units, HU) of those ROIs against the z-coordinate. The second method [5] calculates the maximum differences between the ROI values and the average of them all, scaling the results by the contrast-to-noise-ratio. This procedure enables a direct comparison between values obtained with different grey scales.

3.2. Geometrical precision

The value of CBCT relies on its ability to produce a three-dimensional description of the anatomy of the patients. In this respect, it is essential that the relative spatial relationship of the internal structures in the image is representative of the imaged structures, and that the image is rigidly related to the coordinate system of the machine. The latter aspect is especially important for radiotherapy applications, where mismatches between the imaging isocentre and the treatment isocentre must be avoided in order to ensure that the strict positioning requirements are met. Both mechanical sag and flex of the CBCT arms, and limitations of the reconstruction algorithms, are responsible for limitations of the geometrical accuracy of CBCT images. Therefore, it is essential to regularly check the geometrical calibration of the CBCT.

The purpose of the test is to monitor the geometrical accuracy and the linearity of the CBCT image. For radiotherapy, a further test is recommended aimed at monitoring the position of the imaging isocentre in relation to the treatment isocentre. Phantoms with known internal structures or grids are required for these tests (e.g. Fig. 2b).

3.3. Voxel density values

It is important to be able to distinguish between the different electronic densities of materials in a radiographic image, in order to perform accurate clinical diagnoses. Accurately relating physical density to voxel density values is particularly important when these values are used to perform a clinical diagnosis, such as assessing bone density. It is also essential to accurately relate the voxel density (in Hounsfield units) to the electron density of the material if the CBCT images are used to perform dose computations in ART, which is currently an active area of research [12].

The purpose of this test is to check whether the system is able to reproduce the voxel density values that are expected for the given materials. If the system does not claim conformity with the HU scale the purpose of this test is just to check that the density values assigned to a certain material do not deviate from the baseline values. A test phantom containing a number of materials with different electronic densities is required. An example is shown in Fig. 2c.

3.4. Noise

Quantum noise represents the pixel variations associated to the stochastic nature of radiation. A measurement of noise is a simple method to detect failures in the performance of the X-ray device, by comparing the values with a measured baseline of performance.

The purpose of this measurement is to ensure that the noise in the images does not compromise the visibility of relevant structures or lesions. The same phantom used for the uniformity is required (Fig. 2d). However, the measurement of noise is an integral part of the contrast-to-noise ratio (CNR), involved in the test described below. Advanced methods of evaluation, such as the noise power spectrum, are dealt with in the appendix of the guideline.

3.5. Low-contrast resolution

The cone beam of CBCT systems is associated with high levels of scatter radiation, with a consequent degradation of soft tissue differentiation and loss in low-contrast resolution (decrease in CNR) [13]. Measured variations of this parameter are an indirect

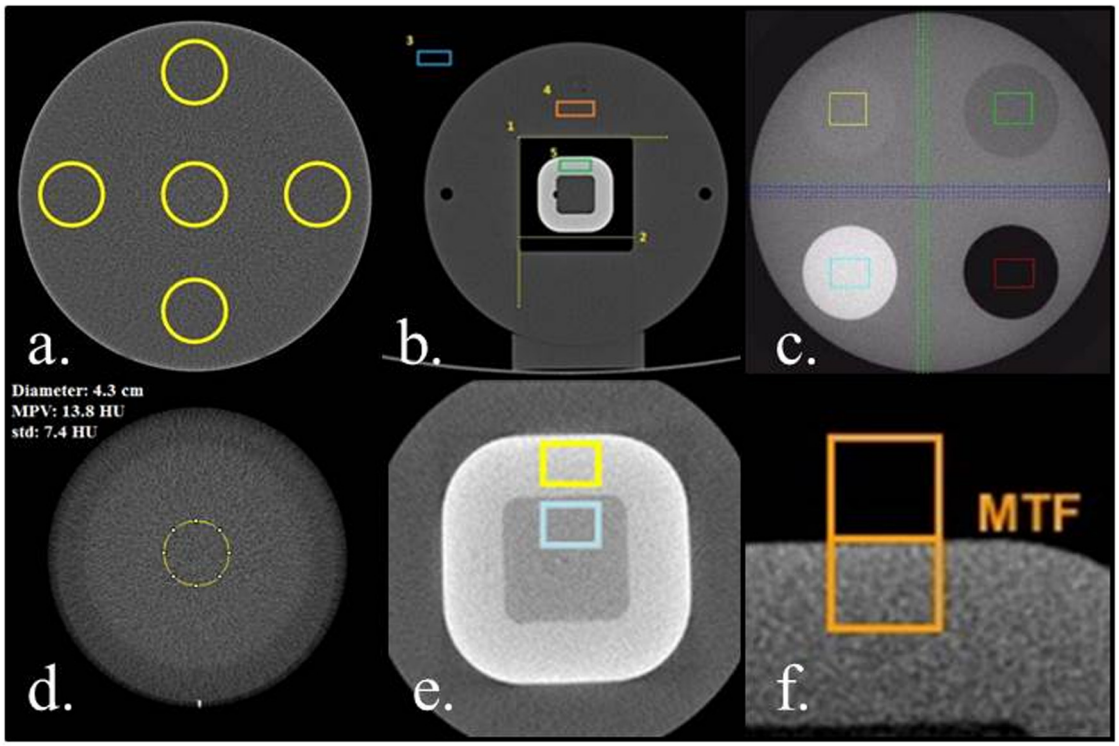

Fig. 2. An example of the measurement of uniformity (a), geometrical linearity (b), density values or Hounsfield units (c), noise (d), contrast-to-noise ratio (e) and modulation transfer function (f).

indicator of changes in tube performance, as low-contrast resolution is linked to the peak-voltage (kVp) of the X-ray tube and consequently to patient dose (see Section 6.2.7.1 in Ref. [1]).

The traditional method to evaluate low-contrast resolution is based on detecting subtle signals within a noisy but uniform background. The drawback of this method is that it is highly subjective. Different observers, and even the same observer on different occasions, can give different results when they are presented the same signals [14]. Although costly human observer studies are valid under certain circumstances of performance, the results can be biased and/or be difficult to reproduce. Thus, substituting subjective methods for objective techniques is a high priority when determining procedures for image quality control.

The purpose of this test is to objectively quantify the low-contrast resolution. The most practical method is to measure the CNR between two ROIs of well-defined positions and electronic densities (see Fig. 2e), as recommended in the guideline. Model observers have also been suggested for specific detection tasks [15]. Such advanced methods are dealt with in the appendix of the guideline.

3.6. Spatial resolution

The relative high spatial resolution is one of the main advantages of CBCT technology, and it is particularly important in dental clinical applications and peripheral vascular applications. Its value depends on the technical characteristics of the equipment, such as focal spot dimension and detector performance, which could change over the time. In CBCT the voxel usually has equal dimensions along all three Cartesian axes, and as a consequence spatial resolution should be assessed along the three axes, and similar values should be expected.

The purpose of this test is to provide a quantitative evaluation of the size of the smallest object that can be resolved in a volumetric dataset from a tomographic acquisition. Although this size is limited by the voxel dimensions, it does not coincide with it. The limiting spatial resolution is usually associated with the frequency at which the modulation transfer function (MTF) falls to a defined level (usually 10%) of its maximum value. The line-pair value corresponding to 50% of the MTF maximum is usually also indicated (Fig. 2f). The conventional test of "image slice thickness" was up to now the only method to study the resolution in the longitudinal axis direction (the "z-direction"), which is the relevant parameter. To assess spatial resolution along this axis, images of a plane perpendicular to the axial plane (eg. a sagittal or coronal slice) and appropriate software should be used.

For dental and interventional radiology applications annual tests are suggested as a minimum requirement (in addition to the acceptance tests and the tests after changes in the device). However, we support the decision of some countries to enforce the tests on a monthly basis [8]. Indeed, with the help of dedicated software it is possible and desirable to perform the indicated tests on a monthly basis.

4. Image quality phantoms

An image quality phantom should allow the user to evaluate the different aspects of the imaging chain in a standardised, reproducible and consistent way. The use of simple but reliable software is essential for this task.

Phantoms intended for medical physics testing are used for comprehensive assessment of a wide range of image quality aspects of the equipment, e.g. uniformity, spatial and contrast resolution, noise, artefacts, image density values, geometric accuracy and reconstruction for a range of clinical protocols, usually on an annual basis. However, monthly, quarterly or half-yearly tests are aimed to highlight issues that require immediate attention. These tests are usually simple, time efficient and can be readily

performed by the local clinical team. The phantoms used for these test are designed to assess a limited number of image quality parameters (such as uniformity, noise and spatial resolution) and their main role is to ensure constancy of performance.

Phantoms dedicated to CBCT should allow the assessment of the 3D performance of the system and therefore, should be designed to allow the evaluation of the image quality parameters across the axial, sagittal, coronal planes and for the volume rendering mode of the system. The size and shape of the phantoms should be optimised for the particular clinical application. In particular, for applications dedicated to paediatric imaging, dose optimisation and image quality assessment with adult phantoms is far from ideal, especially for young children. The manufacturers of phantoms and CBCT scanners need to address this issue in the near future.

The guideline includes a review of the current status and challenges for phantoms in dental, interventional radiology and radiotherapy CBCT, as well as a table summarizing the available phantom properties.

5. Radiation output

In-phantom dosimetry, traditionally used for CT, raises two kinds of problems: 1) the formalisms use phantoms that are too small to properly represent radiation scatter from the large X-ray fields commonly used in CBCT applications, and 2) the positioning and weight of the phantom can be an obstacle in particular for dental CBCT [16]. However, measurements without phantoms may be used with a complete description of the X-ray beam geometry of a CBCT unit, to characterise the radiation output and even derive estimates of patient radiation dose for a given unit. The air kerma shall be used for periodic (and fast) constancy measurements of the X-ray tube output.

The two methods that are suggested in the guideline for quality control are the kerma-area product (KAP), which is measured with a KAP meter (Fig. 3) and, as a practical alternative, the dose to the field of view (D_{FOV}) or "dose to the isocenter" [5] (Fig. 4), which is obtained by the procedure described below. Table 2 lists the

Fig. 3. A kerma-area product meter attached to a dental scanner, a C-arm and a guidance system of a linac (from left to right). To avoid contact between the meter and the tube case of the guidance system it may be necessary to add a polystyrene separation.

Fig. 4. A solid-state probe attached to the flat panel of a dental CBCT, a C-arm for angiography and a guidance system of a linac (from left to right). The position of the meter must be marked for the sake of reproducibility.

Table 2
Summary of the recommended tests of radiation output.

Parameter	Frequency			Action level		
	Dental	Interventional radiology	Radiotherapy	Dental	Interventional radiology	Radiotherapy
KAP (Kerma area product)	Annual			KAP larger than 250* mGy cm^2	Not available	Not available
$K_{a,i}$ (FDD) (incident air kerma at the detector)				D_{FOV} larger than 50* mGy (calculated by Eq. (1))		

* The action level for the KAP corresponds to imaging prior to the placement of a maxillary molar implant in a standard adult patient. The action level for the dose to the field of view (D_{FOV}) corresponds to default scan protocols in all modalities (however, a reference value of 10 mGy may be used for low dose protocols in linacs and a reference value of 90 mGy may be used for high dose protocols in C-arms).

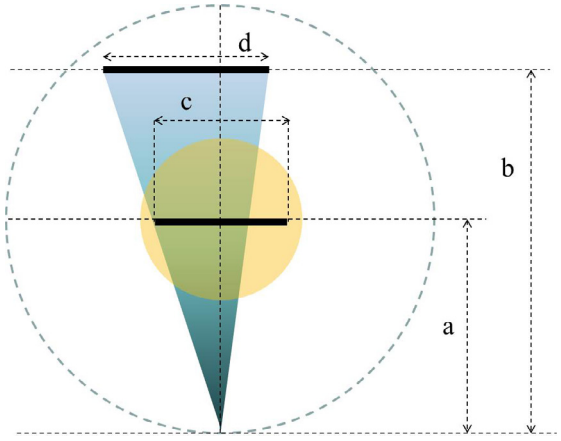

Fig. 5. Description of the quantities *a*, *b*, *c* and *d* required to apply equation 1 in the case of symmetric scan geometry (left) and asymmetric scan geometry (right).

suggested tests of radiation output, together with the recommended test frequency and action levels.

The D_{FOV} is an estimation of the average dose over the diameter of the FOV, and it is calculated from the accumulated incident air kerma at the source-to-detector distance, $K_{a,i}(SDD)$ using a simple geometrical relation [5]:

$$D_{FOV} = K_{a,i}(\mathrm{SDD}) \cdot \frac{b}{a} \cdot \frac{d}{c'} \quad (1)$$

where *a* is the distance from the focal spot to the isocentre, *b* the distance from the focal spot to the place of measurement (slightly smaller than the SDD), *c* the horizontal diameter of the scanned volume, and *d* the horizontal diameter of the radiation field at the place of measurement (Fig. 5).

6. Conclusion

Guidelines have been developed to bridge the gap of performance measurements for CBCT, aiming to achieve a consensus that is rigorous and helpful for the practice. Experience from all participant associations, in particular EFOMP, ESTRO and IAEA, but also AAPM and EURADOS, has been put together to state feasible requirements for image quality and dosimetry measurements.

This guideline includes a wide variety of tests, aimed at basic system functionality as well as more advanced procedures that may be helpful in the optimization of examination protocols. The tests have been limited to analysis of image quality and radiation output, which are straightforward to apply either by medical physicists or radiographers with basic knowledge of quality assurance. This provides the means to evaluate the performance and monitor the constancy of the whole imaging chain. If the radiation output or image quality deviates from expected values, or exceeds documented action levels for a given system, a more in depth system analysis and corrective maintenance work may be required.

The guideline will be offered for free from the website of EFOMP (www.efomp.org). To keep track of downloads from one central server ESTRO and IAEA will include the link in their websites. Any societies that may want to endorse the initiative are more than welcome to also include the link in their websites. A revised version of the guideline will be published if necessary in 2020.

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