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Cone beam computed tomography for dental and maxillofacial imaging: technique improvement and low-dose protocols

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Abstract
Objective The aim of this study was to evaluate images quality and radiation doses of Cone Beam Computed Tomography (CBCT) for dental and maxillofacial imaging testing five different acquisition protocols.
Methods Dose measurements of different acquisition protocols were calculated for Pax Zenith three-dimensional (3D) Cone Beam (Vatech, Korea) and for conventional orthopantomography (OPT) and cephalometric skull imaging Ortophos (Sirona Dental Systems, Bernsheim, Germany). The absorbed organ doses were measured using an anthropomorphic phantom loaded with thermoluminescent dosimeters at 58 sites related to sensitive organs. Five different CBCT protocols were evaluated for image quality and radiation doses. They differed in FOV, image resolution, kVp, mA, acquisition time in seconds and radiation dose. Measurements were then carried out with the orthopantomograph. Equivalent and effective doses were calculated.
Results The reference protocol with large FOV, high resolution quality images, 95 kVp, 5 mA and acquisition time of 24 s resulted in a DAP value of 1556 mGy cm^2 instead the protocol with reduced kVp from 95 to 80 kVp translated into a value of DAP inferior to 35% (from 1556 to 1013 mGy cm^2). Going from a high resolution to a normal resolution, there was a reduction of the acquisition time to 15 s which allowed further dose reduction of approximately 40% (628 mGy cm^2); this protocol resulted in a value of effective dose of 35 microSievert (μSv). Moreover, the effect of changing FOV has been evaluated, considering two scans with a reduced FOV (160 × 140 and 120 × 90 mm, respectively).
Conclusions CBCT low-dose protocol with large FOV, normal resolution quality images, 80 kVp, 5 mA and acquisition time of 15 s resulted in a value of effective dose of 35 microSievert (μSv). This protocol allows the study of maxillofacial region with high quality of images and a very low radiation dose and, therefore, could be proposed in selected case where a complete assessment of dental and maxillofacial region is useful for treatment planning.

Keywords Cone beam computed tomography (CBCT) · Orthopantomography (OPT) · Low-dose protocol · Dental imaging · Dose area product (DAP) · In vitro phantom study

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Introduction

Most dental and maxillofacial procedures require the use of radiographic examinations for proper diagnostic evaluation and treatment planning. The imaging methods most commonly used in dentistry are orthopantomography (OPT) and cephalometric skull. The reason of their frequent use is represented by low costs, ease of execution and low radiation doses to the patient. However, not always the anatomical details of these methods are optimal.

At the time, other imaging methods, such as computed tomography (CT), are used in Odontoiatric Radiology changing the way we look at a variety of common diagnostic and treatment issues in daily dental practice. CT can be used where more anatomical details are needed and in clinical conditions such as pathologies and traumas in the maxillofacial region, pre surgical implant treatment planning and evaluation of the temporomandibular joint.

Despite many benefits of CT compared to the other methods, it is not routinely used in dentistry for the high costs, large space needed, long scanning time and high radiation dose provided to patients.

Cone Beam CT (CBCT) has recently been developed. It allows a shorter scanning time whilst the radiation dose is up to ten times lower compared with helical CT scans [1, 2] and the costs significantly reduced. CBCT uses a cone-shaped X-ray beam instead of the collimated fan beam used in helical CT centered on two-dimensional (2D) detectors. The tube-detectors system performs a 360° rotation around the head of the patient using a constant beam angle. This rotation produces the initial data, the so-called raw data, which are presented as a lateral tomogram. The raw data are used for primary reconstruction. The options for the thickness of the layers to be reconstructed are 0.3, 1.0, and 3.0 mm, and the reconstruction angles are determined by the clinician. The primary images can be used for further secondary reconstructions in all plane and three-dimensional reconstructions. CBCT involves a unit that in size can be comparable with a conventional panoramic radiographic device. It is able to accomplish rapid volumetric image acquisition in a time of exposure in the range of 20 s. The amount of radiation exposure is much lower than helical CT with higher spatial resolution [3, 4], because the voxel size may be as low as 0.2 mm (it is 0.5–1 mm for most fan-beam units).

Since its first applications, CBCT has been increasingly used for three-dimensional volumetric assessment of the craniofacial region and now is considered the examination of choice in many instances, since it provides high resolution imaging and diagnostic reliability with a positive risk–benefit balance [5]. Its use is also recommended in odontoiatric practice for impacted teeth [6], temporomandibular joint evaluations [7, 8], 3D views of the upper airways, assessment of maxillofacial growth and dental age estimation. CBCT has also demonstrated validity for biomechanical simulations, models of bone remodeling, simulations for orthodontic surgical planning [9], and measurements taken by digitizing points in 3D coordinates.

Despite all these advantages, there are still many questions on the use of this method in the routinely evaluation of the patients especially in pediatric age and these concerns focus on the radiation dose that, although considerably less than the helical CT, remains higher than the conventional radiographic studies ones. In literature there are many studies of comparison but they are characterized by an enormous variability in CBCT related doses, ranging from 68 to 1073 μSv [10] depending on the study protocols.

The aim of this prospective study was to evaluate low-dose CBCT protocols regarding images quality and radiation doses.

Methods and materials

Dose measurements in terms of dose area product (DAP) were measured for different diagnostic protocols acquired by Pax Zenith 3D CBCT (Vatech, Korea) and for conventional OPT Ortophos (Sirona Dental Systems, Bernsheim, Germany). Moreover, assessments of effective dose and dose to the organs for a low-dose CBCT protocol have been made. The measurements of DAP were performed by placing a transmission ionization chamber in correspondence of the output window of the X-ray tube. Evaluations of effective dose were made with an Alderson Rando anthropomorphic phantom (The Phantom Laboratory, New York, USA) by placing in the internal seats of measures radiochromic film strips measuring 4 mm × 25 mm. Radiochromic films with good sensitivity in the X-ray diagnostic field have been recently developed and are commercially available as GAFCHROMIC XR-QA and XR-CT (International Specialty Products, Wayne, NJ) [11]. Fifty-eight locations have been used for the measurements in order to have a good sampling for all the involved organs at risk (bone marrow, bone surface, brain, salivary glands, thyroid, oral mucosa, extrathoracic airway, esophagus and lymph nodes). The results were compared with those obtained with a Monte Carlo simulation using the software PCXMC [12, 13]. The calculation of the effective doses was based on the International Commission on Radiological Protection's (ICRP) 2007 recommendations [14].

To obtain dose reduction we tested five different protocols and in particular we reduced kVp from 95 to 80 and acquisition time from 24 to 15 s.

All parameters used for the five different CBCT protocols are reported in Table 1.

The Rando phantom was positioned in such a way as to simulate the actual exam conditions. Fifteen repeated acquisitions were made, so as to obtain values of absorbed dose compatible with the sensitivity of radiochromic film, even for peripheral sites affected only by scattered radiation. The evaluation methodology is described in detail in Rampado et al. [11]. All parameters used for panoramic

Table 1 All parameters of five different CBCT protocols

ID protocol	FOV size selection (mm)	Quality selection	kVp	mA	Acquisition time (s)	Note
1	240 × 190	High resolution	95	5	24	(Prot. reference)
2	240 × 190	High resolution	80	5	24	
3	240 × 190	Normal resolution	80	5	15	(Prot. low dose)
4	160 × 140	High resolution	95	5	24	
5	120 × 90	High resolution	95	5	24	

Table 2 All parameters for panoramic and cephalometric images in lateral and antero-posterior projections

Acquisition	Protocol	kVp	mA	Time acquisit (s)
	Adult	71	8	13
Panoramic	Pediatric	60	6	13
	Adult	84	13	16
Lateral projections	Pediatric	73	15	16
	Adult	84	13	16
Antero-posterior projections	Pediatric	73	15	16
	Adult	84	13	16
Total	Pediatric	73	15	16

and cephalometric images in lateral and antero-posterior projections are reported in Table 2, both for adult and pediatric protocols.

Results

Results of DAP measurements were shown in Table 3 and 4.

The first protocol with 95 kVp (Fig. 1) resulted in a DAP value of 1556 mGy cm^2. The second protocol with 80 kVp (Fig. 2) translated into a value of DAP inferior to 35% (from 1556 to 1013 mGy cm^2). Going from a high resolution to a normal resolution scanning mode (Fig. 3) there is a reduction of the acquisition time from 24 to 15 s which resulted in a further dose reduction of 628 mGy cm^2, equal to 40% of the value obtained with the reference protocol. Finally, the fourth and fifth protocols with medium and small FOVs (Fig. 4) resulted in a DAP value of 988 and 1162 mGy cm^2. For all protocol a voxel size of 0.3 mm was chosen and no corrections were applied for the reduction of metal artifacts.

The DAP values shown by the equipment were compatible only with the values measured for the reference

Table 3 DAP mesurements for five different CBCT protocols

ID protocol	FOV size selection (mm)	Quality selection	kVp	mA	DAP (display) mGy cm^2	DAP (media measure) mGy cm^2	Diff %	Acquisition time (s)	Note
1	240 × 190	High resolution	95	5	1837	1556	18.1	24	(Prot. reference)
2	240 × 190	High resolution	80	5	1761	1013	73.8	24	
3	240 × 190	Normal resolution	80	5	1093	628	74.2	15	(Prot. low dose)
4	160 × 140	High resolution	95	5	117.9	988	−88.1	24	
5	120 × 90	High resolution	95	5	N/A	1162	–	24	

Table 4 DAP measurements for panoramic and cephalometric images in lateral and antero-posterior projections

Acquisition	Protocol	kVp	mA	Time acquisit (s)	DAP (media measure) mGy cm^2
	Adult	71	8	13	36
Panoramic	Pediatric	60	6	13	19
	Adult	84	13	16	47
Lateral projections	Pediatric	73	15	16	40
	Adult	84	13	16	40
Antero-posterior projections	Pediatric	73	15	16	35
	Adult	84	13	16	123
Total	Pediatric	73	15	16	94

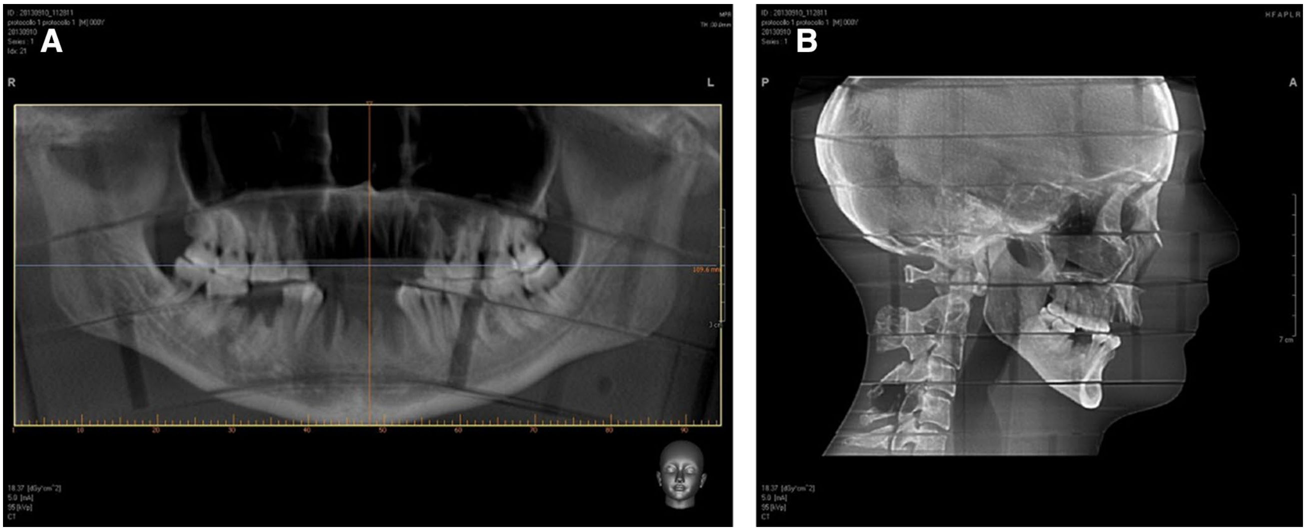

Fig. 1 Panoramic (**a**) and cephalometric (**b**) reconstructed images of the anthropomorphic phantom obtained from CBCT with Protocol 1: FOV of 240 × 190 mm, 95 kVp, 5 mA and acquisition time of 24 s

protocol, with a difference of 18%. In other cases, there are differences in the order of 70%. These results were submitted to the equipment technicians and they were asked to correct the determination methods for this dosimetry indicator.

Indeed, while the measured values are compatible with the dependencies expected by the exposure parameters (quadratic dependence on the voltage value which is linear with the exposure time and the beam section), the values displayed by the machine do not reflect these trends, as noted, for example in the transition from 95 to 80 kV, which translates into a reduction of the DAP displayed only by 7%. In one case, the displayed value resulted also null. This experience underlines the importance of DAP accuracy verification by a medical physicist, as also evidenced in the European Guidelines [15]; it is mandatory to carry out regular quality controls to calibrate the most of the equipment as this problem is often found by medical physicists.

Measurements were then carried out with orthopantomograph equipment with Cefalometro Siemens Ortophos, and the results are showed in Table 4.

As it can be observed, the value of the total DAP obtained for a panoramic acquisition and the two skull projections with adult parameters leads to a value of DAP 123 mGy cm^2, that is equal to about one-fifth of the value of DAP for the low-dose CBCT protocol.

Evaluation of effective dose and dose to organs

Measurements of effective dose and dose to organs were carried out for the third protocol that is the tested protocol proposed for the complete evaluation of the maxillofacial region.

Applying the weight coefficients defined in the ICRP 103, 2007 [14] a value of the effective dose of 35.4 µSv has been obtained.

The calculation made by the program PCXMC, considering the geometrical parameters and the measured value of DAP, gives a result of effective dose of 36.8 µSv, in perfect agreement with the experimental value obtained. The individual assessments of dose to the organs differ less than 30%, which is justified by several factors, and in particular by the different conformation of the Phantom which is geometric and not anthropomorphic in the calculation program.

So, although the results should be validated with at least one repetition of the measurements, the good correspondence with the data obtained through simulation provides a significant confirmation.

The relationship between effective dose and DAP results therefore in 0.056 µSv for mGy cm^2, less than the value of about 0.1 found in other evaluation works for CBCT examinations, with smaller fields of view. This difference is attributable to the different distribution of the dose to the organs with the extended volume of 24 × 19 cm. With the same amount of DAP the dose to the thyroid significantly increases, but the dose to other organs significantly decreases, including the primary beam. Indeed with equal DAP, that is to switch from one volume of 14 × 10 to one of 24 × 19, means to triple the section of the beam and reduce the dose to a third punctual axis.

Because of time constraints, it was not possible to evaluate effective dose of the traditional methods, but it was possible to estimate it on the basis of DAP measurements

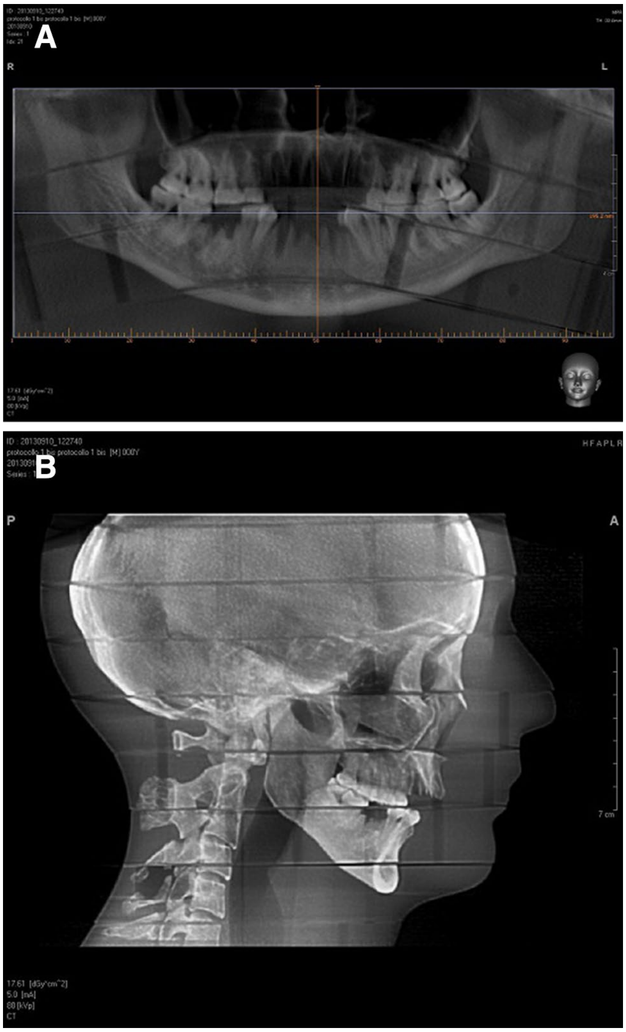

Fig. 2 Panoramic (**a**) and cephalometric (**b**) CBCT reconstructed images of the anthropomorphic phantom obtained with the some protocol of Fig. 1 with reduced kVp from 95 to 80

made and conversion coefficients published in literature. In the study of Lofthag-Hansen et al. [13], a coefficient from DAP to effective dose for panoramic examinations of 0.08 μSv mGy cm^2 was considered, so that for our panoramic examination there would be an effective dose of about 3 μSv. For the two cephalometric projections we could assume a coefficient similar to the one found for the CBCT, thereby contributing to about 5 μSv. In total we obtain about 8 μSv, equivalent to about one-fourth of the effective dose associated with CBCT.

Discussion

CBCT software can manipulate the Digital Imaging and Communications in Medicine (DICOM) data to visualize anatomic structures and accurately display relationships within the craniofacial complex. A combination of volumetric reconstruction and multiplanar views can provide useful information to dentistry, orthodontic and maxillofacial clinicians about skeletal hard tissue, dentition and airway status. Nonstandard orthodontic cases, such as impacted tooth, supernumerary odontomas, or unexpected radiologic observations, such as pathologic lesions or incidental findings, are best visualized with the 3D CBCT scan. CBCT is also be indicated when conventional radiographs suggest a direct inter-relationship between a mandibular third molar and the mandibular canal or for cross-sectional imaging prior to implant placement. Moreover, CBCT has a role in facial trauma for maxillofacial fracture assessment and in orthognathic surgery planning for obtaining three-dimensional datasets of the craniofacial skeleton. Advanced CBCT software applications can also be used to quantify airway space (relevant for sleep apnea cases), to perform superimpositions of objects at different time points to semiquantitatively visualize changes (e.g., mandibular growth, temporomandibular joint, airway), and generate digital dental models to streamline the workflow in the dental clinic.

Patient radiation dose is one of the main issues in dental CT examinations and it was investigated in several studies. Although the related effective dose is lower than most other CT examinations involving thorax and abdomen anatomical districts, there is concern about radiation dose in dental CT as a consequence of the frequency of dental examinations and of the repetition on the same subject, especially for pediatric patients. Therefore, it is important to know the dental CT patient dose for all machines and protocols, in order to optimize acquisition parameters and to minimize the related radiological risk. Several studies compare the Multi-slice Computed Tomography (MSCT) patient dose with the CBCT patient dose. Generally the results show doses for MSCT equipment ranging from eight to ten times the CBCT doses, but it must be underlined that there is a great variability in the CBCT protocol definition and often there are possibilities of optimization which have been not completely investigated [16].

CBCT imaging protocols should take into consideration the relative advantages of this technology over routine radiography, including the quality of the information derived, its potential impact on diagnosis and treatment planning, the ease of use and financial costs. This subjective benefit-to-risk assessment may be termed "value proposition" for taking CBCT scans for any given case [17, 18]. As stated in the Guidelines on CBCT for dental and maxillofacial radiology published by various Scientific Societies in Europe and America, CBCT should be used when the question for which imaging is required cannot be obtained adequately by lower dose

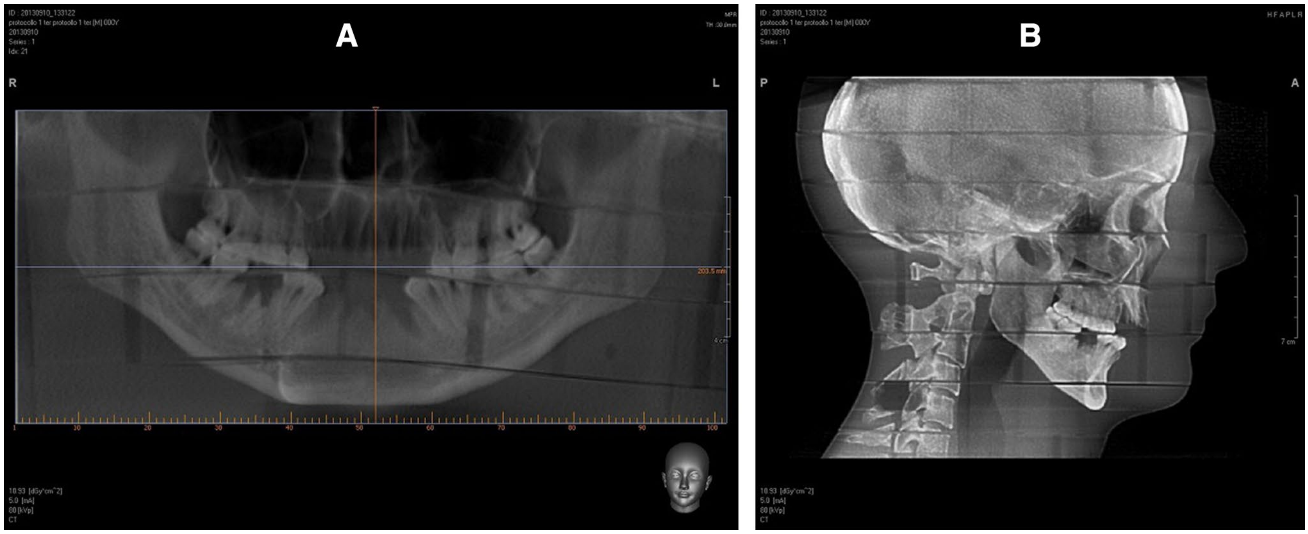

Fig. 3 Panoramic (**a**) and cephalometric (**b**) reconstructed images of the anthropomorphic phantom obtained from CBCT with low-dose protocol (Protocol 3): FOV of 240 × 190 mm, 80 kVp, 5 mA and acquisition time of 15 s

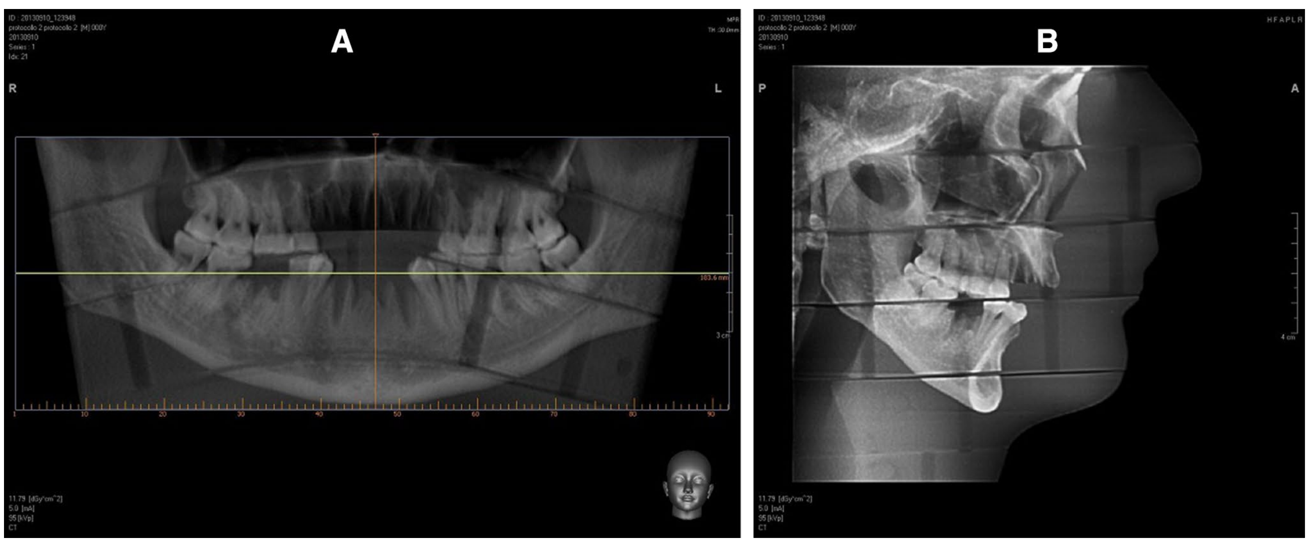

Fig. 4 Panoramic (**a**) and cephalometric (**b**) reconstructed images of the anthropomorphic phantom obtained from CBCT with a reduced FOV of 120 × 90 mm

conventional radiography. It is obvious that all stakeholders have a responsibility to deliver radiographic technology to patients in a responsible way so that the diagnostic accuracy is maximized and radiation doses kept as low as achievable. For these reasons CBCT protocol should be optimized according to the clinical indication in terms of kVp, mA, exposition time and FOV. CBCT equipment should offer a choice of volume sizes and examinations have to use the smallest that is compatible with the clinical situation if this provides less radiation dose to the patients.

Our study is not finalized to evaluate guidelines for CBCT or to suggest protocols according to the clinical indication, as defined by Scientific Societies, but to demonstrate that CBCT good quality images can be obtained using low-dose protocols with an effective dose to the organs as low as 35 microsievert even when a full FOV is needed for clinical purposes. Obviously, the dose will be even lower in cases where it is not necessary to use a large FOV as our study confirms that, with the same parameters used, the radiation dose is reduced when using a restricted FOV (protocols 4 and 5 versus protocol 1).

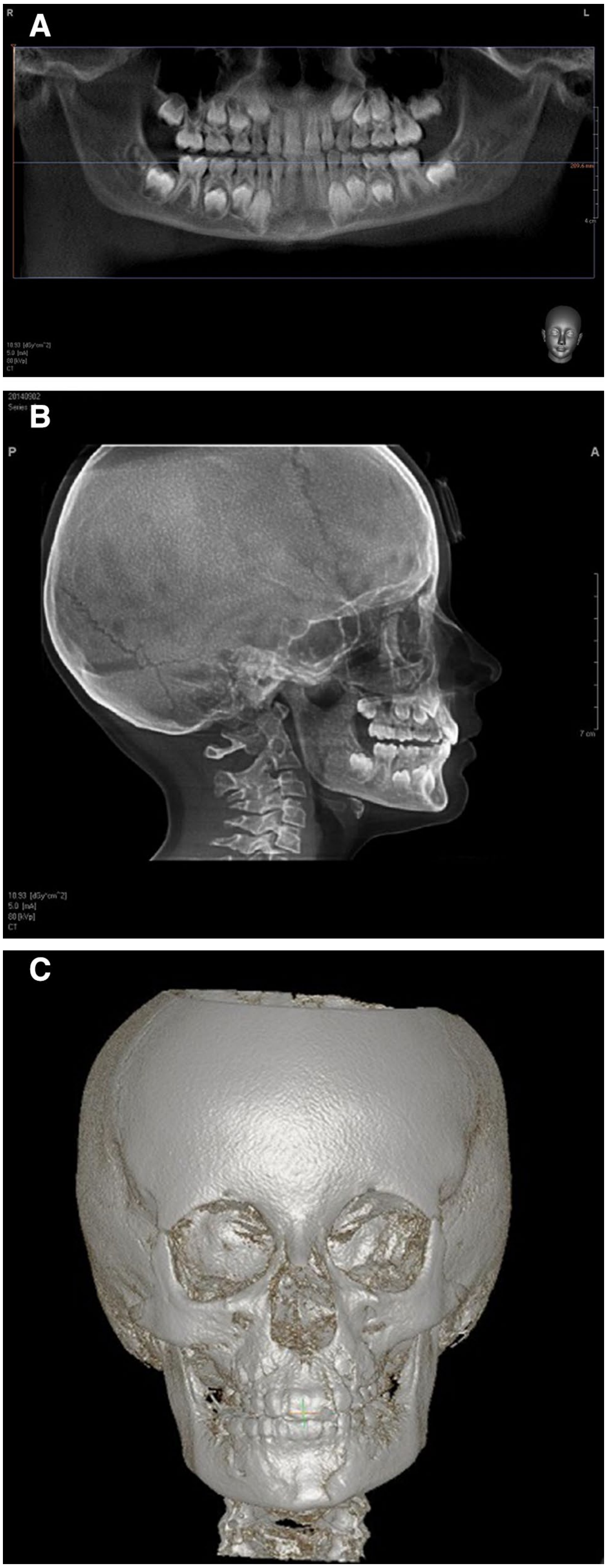

Fig. 5 Seven years old patient underwent CBCT examination with low-dose protocol: notice the good quality of the panoramic (**a**), cephalometric (**b**) and 3D (**c**) images

The current study confirms the CBCT low radiation dose and optimal quality of images (Fig. 5) obtained with the following protocol parameters: FOV of 240 × 190 mm, normal resolution quality images, 80 kVp, 5 mA and acquisition time of 15 s. Applying the weight coefficients defined in the ICRP 103 a value of the effective dose of 35.4 μSv has been obtained. For the conventional radiography technique, in this study we found a total effective dose of about 8 μSv. This is a relative low-dose value, considering that European Guidelines [18] report a range only for panoramic of 2.7–24.3 μSv. Another comparison study report a cumulative effective dose of 26 μSv for a digital panoramic and one lateral cephalogram. This means that the effective dose of the optimized CBCT protocol of this study is four times higher of our conventional imaging and comparable with part of the range of literature values for conventional radiography.

Further developments of the project may be directed to repeat similar assessments on other types of equipment for a selected sample and discuss the opportunity for further dose reduction, conducting pre-assessments of the quality obtainable on suitable phantoms and the dose associated with the variation of the selected parameters.

Conclusion

CBCT performed with low-dose protocol has a very low radiation exposure and good quality of images and, therefore, could be proposed for dental, orthodontic and maxillofacial studies in cases where a complete evaluation of the maxillofacial region is essential in order to set the proper treatment.

Compliance with ethical standards

Funding There are any source of funding or financial interest.

Conflict of interest The authors declare no conflicts of interest.

Ethical standards This article does not contain any studies with human participants or animals performed by any of the authors.

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