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FULL PAPER

Development of a paediatric head voxel model database for dosimetric applications

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Objective: To develop a database of paediatric head voxel models intended for Monte Carlo (MC) dosimetric applications.

Methods: Seventeen head and neck CT image data sets were retrieved from the picture archiving and communicating system of our hospital and were reformed into voxel models. 22 organs were segmented at each data set. The segmented organ masses were compared to the respective age- and gender-specific ICRP reference mass value. Adjustments were made such that segmented and reference mass values coincide within a tolerance of 10%. A dental cone beam CT cleft palate simulation study was set up to demonstrate the applicability of our database to MC frameworks and to investigate the need for age- and gender-specific paediatric models.

Results: The designed database covers the age range from 2 months to 14 years old. Each model represents a reference head voxel phantom for its corresponding age and gender category. The simulation study revealed absorbed organ dose differences larger than 50% among the 5, 8 and 12 years old models when exposed to identical conditions.

Conclusion: Children cannot be represented by one average phantom covering the entire age range like adults due to the fact that their organs change rapidly in size and shape. A database of paediatric head voxel models was designed to enable dose calculations via MC simulations.

Advances in knowledge: The application of each model of the database to MC frameworks provides age- and gender-specific organ dose estimations from medical exposures in the head and neck region.

INTRODUCTION

Anthropomorphic phantoms which mimic the anatomical features of human body have always been useful in all scientific fields where radiation exposures are involved. Either in a physical or in a computational form, these phantoms, stated also as models, have been employed to optimize exposures, to calculate organ doses and to subsequently estimate the radiation induced risk.

The use of thermoluminescent dosimeters (TLDs), positioned in organ-specific locations within the phantoms, has been a traditional dosimetry method in medical imaging for many years. However, this approach is expensive and time consuming as it requires the application of a large number of TLDs to perform trustful measurements. Furthermore, since the TLD placement at each organ occurs in the dedicated dosimetry holes which occupy a small region and not the entire organ, the dose calculations become cumbersome. The dose to radiosensitive organs like salivary glands, oral mucosa and extra thoracic tissues (ETs)

are in most cases calculated from the dose to surrogate or substitute organs and not directly. Moreover, the paediatric physical phantoms which are available nowadays represent specific age categories and hence they cannot be considered as average ones for the entire paediatric population since they do not adhere to the sharp changes in organ shape and size which take place in early childhood.

Monte Carlo (MC) dose simulation studies with the use of computational phantoms is the software alternative approach for organ dose calculations. Initially in a stylized form, based on quadratic mathematical equations to design the organs in the body, computational phantoms evolved to more anatomically realistic voxel models when powerful computers and tomographic imaging became available. Since early 1980s until today, a large number of voxel models have been developed based on CT, MRI imaging and/or cross-sectional photographic imaging.¹⁻³ Xu et al reported a total number of 84 voxel models in 2014². These phantoms, being compatible to most MC transport

codes, have been extensively used in several dose studies; from internal and external experimental particle dosimetry in health physics to dose studies in medical imaging, nuclear medicine and radiotherapy.⁴⁻¹¹

Among these voxel phantoms, there are only a few which are paediatric ones.¹²⁻²¹ There is an intrinsic difficulty in building paediatric voxel models; it is relatively difficult to retrieve whole body or partially irradiated, mainly in the head and neck region, paediatric CT scans which will undergo the voxelization procedure to design the model. Although the voxelization procedure consists of concrete steps, regardless of the multiple software tools which are used to carry out the tasks, the paediatric voxel models differ between each other; in gender and age; in the methodology which is followed as most of them are based on paediatric image data sets whereas some others emanate from adult models deformation;²⁰ even in the number of segmented tissues and organs. The shortcoming of non-segmented organs/tissues in the model is usually circumvented in dose studies by specifying and estimating the dose to substitute organs, *i.e.* the tongue has been reported as a surrogate for the salivary gland;²² the absence of oral mucosa has been confronted by splitting the weighting factor to the rest remainder organs;²² blood vessels, muscles alone or in combination with residual tissue have been used as surrogate for lymph nodes;²³⁻²⁵ pharynx and larynx for the extrathoracic region.²⁶ According to World Health Organization (WHO) and Vassileva *et al* head CT accounts for nearly 75% of all paediatric CT examinations while CT examinations are responsible for the 43.2% of the collective dose in all ages.²⁷⁻²⁹ Furthermore there is an increasing use of dental cone beam CT (CBCT) imaging over the last few years; this relatively new imaging modality has been reported to be associated with lower doses compared to CT, yet higher than panoramic and intraoral radiography.³⁰ Therefore, even if diagnostic radiology is a relative low risk field in medical exposures, it is of great importance to carry out dose calculations for head applications. The aim of this work was to develop a database of paediatric head voxel models dedicated for MC dose estimations in the head region. A dose simulation study was finally carried out to clarify the need for different head voxel models for paediatric dose studies.

METHODS AND MATERIALS

Selection of CT image data sets

Our voxel model database is based on head and neck CT image data sets which were retrieved from the PACS database of our hospital. It covers a large range of ages from 2 months to 14 years old and consists of 18 head voxel models of males and females. The same voxelization procedure was followed for each model. Interpolation algorithms were applied to ICRP 89 reference mass values to extract reference values for each age and gender category; the segmented masses were subsequently adapted to the reference ones.³¹ This was to correct for any segmentation errors due to similar tissue densities and to ultimately create age and gender reference models. Each image data set had to strictly meet several requirements in order to be eligible for undergoing the voxelization procedure. A first prerequisite was that the scanned volume should have been imaged in one sequence. This was to attain uniform z-resolution across the image volume, defined by

Figure 1. Head circumference of the male paediatric head voxel models.

the slice thickness, and to avoid any overlap of anatomical regions in cases of poor stitching of two consecutive sequences acquired with different slice thickness. Only full head CT acquisitions, from the crown of the head up to at least the C5 spinal segment, were promoted. This was to ensure that the thyroid would at least be partially included in the voxel models. Furthermore, image data sets with severe artefacts that could hinder organ segmentation were rejected, along with those data sets of patients with severe trauma injuries.

For each promoted data set, the occipitofrontal circumference was measured. This was to check whether the circumference of each model was in accordance with the respective reference values for each age category; only those heads whose circumference was calculated to be within the 3rd and 97th percentile of the reference circumference values were promoted³² (Figures 1 and 2). The circumference was estimated by calculating the area of the head at the respective image plane in ImageJ (version 1.48 x Java 1.6, National Institutes of Health, Rockville, MD) and by subsequently assessing an effective diameter and an effective circular circumference.

Figure 2. Head circumference of the female paediatric head voxel models.

Segmentation procedure

Each image data set was uploaded to ImageJ to create a corresponding initial image tiff file. The image stack was initially cleaned to get rid of anything non-related to the patient anatomy, *i.e.* the table of the scanner in the field of view (FOV). A whole head mask was created by converting the stack of images to 8-bit binary ones. The skin was obtained as a one-voxel thick outline of the mask. Air cavities-sinuses in the head, bone-skeletal mixture, mandible and teeth were all segmented in a semiautomatic way by thresholding the grey values which corresponded to each organ. Blood (arteries), brain, cartilage, connective tissue, oesophagus, eyes, eye lenses, fat, muscle, ET, spinal cord, tongue, trachea, thyroid, salivary glands and oral mucosa were segmented manually by delineating each organ on an image by image basis. The extrathoracic tissue was segmented as the outline of the pharynx and the larynx whereas the oral mucosa was considered to be the outline of the mouth cavity. The spongiosa and the cortical bone were segmented as a unified skeletal mixture. The resolution of most CT scanners nowadays is not adequate to allow for the segmentation of the medullary cavities where the red bone marrow (RBM) resides. Therefore, RBM was not segmented and was not included in the voxel models, yet the dose to RBM can be calculated in an indirect way, as mentioned in the following paragraphs.

A particular grey value was given to every voxel of the same organ such that each organ has a specific grey value—identification number. The organs were added one by one to build the voxel model. After each organ had been segmented, any unsegmented regions which have not been attributed to any organ, were named residual tissue.

Matching with reference values

The segmented mass of each organ was calculated by multiplying the number of segmented voxels by the voxel volume and the respective organ density obtained from ICRP publication 1,10.³³ The segmented masses were compared to reference mass values published in ICRP publication 89 such as to investigate the magnitude of deviations from reference values. Due to the fact that the reference values are only available for newborns, 5, 10,15 years old and adults, a shape preserving algorithm was fitted to ICRP values in Matlab (MathWorks, Natick, MA) to extract reference data for the entire paediatric age range. For those organs entirely located in the head region such as brain, eyes, eye lenses, salivary glands, teeth and tongue, the number of voxels was adjusted by adding to or removing voxels from the periphery of the segmented organ until the segmented mass matches the corresponding value within $\pm 10\%$. For oral mucosa, we only tried to keep an increasing mass pattern with increasing age, as reference values do not exist. Except for skin, for those organs which are partially found in the head, we calculated the ratio of the segmented organ/tissue mass in the head to the total mass in the body. To estimate the skin segmented fraction, we calculated the skin segmented surface by multiplying the surface area of each voxel, obtained as the product of the in-plane and the z-voxel size, with the number of skin voxels. The total skin surface of a human of the respective age and gender was calculated based on a formula described by Haycock et al.³⁴ The

formula requires reference weight and height values which were obtained by the WHO.³⁵ The ratio of the segmented to the total skin surface was calculated.

Monte Carlo Simulation study for cleft palate patients in dental CBCT imaging

A MC dose study was set up to investigate the difference in organ doses between males and females of the same age and to examine the impact of the age on the dose values. An EGSnrc MC framework previously developed in our group, capable of modelling the entire imaging chain from X-ray production to image formation, was applied to simulate a cleft protocol in a Promax 3D Max (Planmeca, Helsinki, FI).^{22,36} The cleft palate protocol for paediatric patients is carried out at 96 kV, 25 mAs and is performed in a FOV of $100 \times 55 \text{ mm}^2$ (diameter x height), with the imaging centre axially positioned in the centre of the mouth cavity and vertically in the roots of the teeth of the upper jaw. Six male and female voxel models, corresponding to three pairs of 5, 8 and 12 years old were employed to the framework and the absorbed organ doses were calculated. The dose to the bone marrow was calculated based on the Mass energy absorption coefficient method, *i.e.* three factor scaling of the homogeneous skeletal mixture.^{37,38} To extract the RBM mass fraction in the head and to find the density of the skull, a method previously proposed by Kramer et al was applied.³⁹ In all cases the skull density was found to be 1.83 g cm^{-3} , corresponding to an RBM mass fraction of 0.1 in the skull skeletal mixture. The elemental composition of the bony mixture of such density was calculated based on a formula proposed by Zhou et al.⁴⁰ To calculate the dose to the bone surface the following equations 1 and 2, proposed by the National Bureau of Standards and applied in dental dose studies, were used^{41,42}:

$$\text{Bone surface dose} = \text{RBM dose} \times \frac{\text{bone muscle mass}}{\text{energy coefficient ratio (MEACR)}} \quad (1)$$

$$\text{MEACR} = -0.0618 \times (2/3) \text{ kVpeak} + 6.9406 \quad (2)$$

RESULTS

Database

Eight image data sets of males, aged from 3 to 12 years old, and nine data sets of females, aged from 2 months to 14 years old, fulfilled the requirements to undergo the voxelization procedure. Table 1 illustrates the characteristic of each data set. These characteristics are preserved throughout the voxelization procedure and hence they can also be considered as the specifications of the resulting voxel models. The in-plane resolution corresponds to the x-y voxel size and the z-resolution to the distance between two consecutive reconstructed images. Specific names were given to each model. Figures 1 and 2 depict the head circumference of the head voxel models embedded to specific growth curves. In all voxel models, the head circumference lies between the 3rd and 97th percentile.

Organ and tissue masses

Table 2 presents the segmented mass values of the organs which are totally found in the head region. Next to each organ, the respective reference mass value, as extracted by fitting an interpolation algorithm to ICRP reference values is also illustrated

Table 1. Specifications of the promoted for segmentation image data sets and of the resulting voxel models

Voxel model	Gender	Age (years)	In-plane resolution (mm)	z-resolution (mm)	x, y number of voxels	Number of slices	Head circumference (cm)
John	Males	3	0.41	1.9	512	92	47.9
Dejan		5	0.22	2.75	1024	60	50.5
Joris		6	0.49	1.95	512	108	52.1
Guozhi		7	0.21	3	1024	64	51.4
Peter		8	0.62	0.7	512	330	51.3
Benjamin		9	0.43	0.6	512	370	50.8
Andrew		10	0.49	0.6	512	342	53.7
Mike		12	0.49	2	512	126	52.3
Lina	Females	2 months	0.33	2	512	77	37.2
Demi		5	0.41	0.6	512	355	49.2
Viktoria		6	0.43	2	512	113	49.3
Xoch		8	0.49	3	512	76	52.2
Louisa		10	0.45	0.7	512	305	50.2
Hilde		11	0.43	2	512	99	53.9
Vivian		12	0.41	1	512	230	51.8
Irene		13	0.45	0.6	512	367	53.2
Georgia		14	0.49	2.05	512	113	55.8

along with the percentage difference between them (%Δ). [Table 3](#) depicts the segmented mass values of the organs which are partially located in the head along with the respective segmented fraction to the total mass of the organ in the entire body. The organs which are not radiosensitive according to ICRP 103, yet they have been segmented and are included in our voxel models, are illustrated in [Table 4](#). The extracted reference values correspond to the 6th month of age for each age category, *i.e.* for the 9-year-old model the reference values were calculated for 9.5 years. [Figure 3](#) displays the 3D contour of four of our voxel models.

MC study

Six voxel models were used in the MC study; Dejan and Demi (5 years old); Peter and Xoch (8 years old) and Mike and Vivian (12 years old). [Figure 4](#) demonstrates on Vivian the cleft palate protocol FOV positioning (in dashed lines) around the clinical volume of interest. [Table 5](#) presents the density and the elemental composition of each organ that was used in the study. The MC calculated absorbed doses to radiosensitive organs are presented in [Table 6](#).

DISCUSSION

The aim of this work was to develop a family of reference paediatric voxel models, dedicated for head MC dosimetry simulation studies. The voxelization procedure was based on the training course from the second European Radiation Dosimetry Group school on voxel phantom development and implementation for radiation physics calculations.⁴⁵ The motivation of this study

was to approximate as accurately as possible the radiation organ doses and subsequently the radiation-induced risk for paediatric patients undergoing head diagnostic medical exposures, mainly in multi-slice CT and dental CBCT imaging. 17 voxel models were finally designed, covering the greater part of the paediatric age range for both genders.

There were intrinsic difficulties in retrieving image data sets, suitable to undergo the voxelization procedure. First of all, paediatric head and neck CT imaging is a rare examination; it is considered a high-radiation risk diagnostic procedure and has been replaced, whenever this is feasible, by lower radiation risk imaging techniques. Furthermore, there were a few data sets of severe trauma patients with broken jaw(s) that were rejected along with data sets with severe beam hardening and metal artefacts in the dental region. Since the ultimate target was to create a database of average-reference models, we decided to keep only those image data sets where the head circumference was within the reference age-specific circumference values.

22 organs were segmented on an image by image basis. The masses were matched as closely as possible to mass reference values. The most corrections in terms of adjusting the number of voxels to get the proper mass values were applied to teeth. This was due to the fact that teeth were initially segmented in a semi-automated thresholding way which was attributing extra voxels to teeth; due to the fact that teeth are high density structures, even a small number of extra voxels assigned as teeth leads to large deviations from the reference mass values. We adjusted

Table 2. Segmented mass values of organs which are entirely present in the head; the respective reference values were extracted by fitting a shape preserving interpolation algorithm to ICRP 89 reference mass values which are available for specific age categories; the percentage difference between the mass values is also illustrated

Voxel model	Gender	Age	Brain			Eyes			Eye lenses			Oral mucosa
			Segmented mass (gr)	Reference mass (gr)	%Δ	Segmented mass (gr)	Reference mass (gr)	%Δ	Segmented mass (gr)	Reference mass (gr)	%Δ	
John	Males	3	1139	1242	-8.3	9.2	9.9	-6.7	0.31	/	/	14.6
Dejan		5	1353	1324	2.2	10.8	11.2	-3.6	0.3	/	/	16.2
Joris		6	1465	1350	8.5	10.7	11.4	-6.2	0.35	/	/	11.6
Guozhi		7	1503	1370	9.7	10.5	11.6	-9.5	0.33	/	/	14.6
Peter		8	1464	1385	5.7	10.7	11.7	-8.5	0.3	/	/	19.4
Benjamin		9	1527	1396	9.4	12.4	11.9	4.4	0.37	/	/	16.3
Andrew		10	1396	1403	-0.5	13.1	12.1	8.3	0.3	/	/	24
Mike		12	1494	1410	6.0	13.2	12.4	6.3	0.36	/	/	18
Lina	Females	2 months	640	590	8.5	6.6	6.3	4.3	0.13	0.13	-1.5	7.3
Demi		5	1264	1187	6.5	12.2	11.2	8.9	0.31	/	/	12
Viktorija		6	1306	1196	9.2	11.4	11.4	-0.5	0.27	/	/	12.9
Xoch		8	1325	1208	9.7	11.2	11.7	-4.0	0.34	/	/	16.9
Louisa		10	1330	1227	8.4	12.3	12.1	1.8	0.37	/	/	18.6
Hilde		11	1329	1245	6.7	13.4	12.3	8.9	0.3	/	/	18
Vivian		12	1215	1267	-4.1	13.3	12.4	7.3	0.35	/	/	19.1
Irene		13	1214	1276	-4.9	13.4	12.4	8.4	0.35	/	/	14.2
Georgia		14	1410	1298	8.6	13.7	12.9	5.8	0.37	0.4	-7.5	19.1
Voxel model	Gender	Age	Salivary glands			Teeth			Tongue			mandible
			Segmented mass (gr)	Reference mass (gr)	%Δ	Segmented mass (gr)	Reference mass (gr)	%Δ	Segmented mass (gr)	Reference mass (gr)	%Δ	

(Continued)

Table 2. (Continued)

Voxel model	Gender	Age	Brain			Eyes			Eye lenses			Oral mucosa
			Segmented mass (gr)	Reference mass (gr)	%Δ	Segmented mass (gr)	Reference mass (gr)	%Δ	Segmented mass (gr)	Reference mass (gr)	%Δ	
John	Males	3	28.3	31.3	-9.5	10.7	11.4	-6.0	16.6	16	3.8	34.2
Dejan		5	35.7	35.1	1.7	18	16.4	9.6	21.8	20.2	7.7	58.2
Joris		6	34.2	36.9	-7.5	18.5	19.3	-4.1	20.5	22.5	-9.1	44.7
Guozhi		7	36.5	38.6	-5.3	24.5	22.3	9.7	27	24.9	8.2	45
Peter		8	37.2	40.6	-8.3	23	25.4	-9.6	25.2	27.5	-8.2	24.1
Benjamin		9	39.4	42.7	-7.7	26.2	28.5	-8.0	28.4	30.4	-6.6	40.8
Andrew		10	46.1	45.6	1.1	28.9	31.5	-8.2	37	33.8	9.6	36.6
Mike		12	50.6	54.8	-7.7	38.5	38.1	1.2	38.7	42.7	-9.4	66
Lina		2 months	12.5	12.7	-1.8	2.3	2.1	7.6	6.4	5.8	9.7	9.6
Demi		5	32.5	35.1	-7.4	14.9	16.4	-9.2	22.1	20.2	9.6	33.8
Viktorija	Females	6	38.8	36.9	5.2	20.1	19.8	1.5	20.5	22.6	-9.2	32
Xoch		8	36.8	40.6	-9.3	28.3	26.5	6.6	27.8	27.6	0.5	47.7
Louisa		10	40.3	44	-8.4	32.2	30.7	4.8	31.3	33.8	-7.3	38
Hilde		11	52.6	49.6	6.0	34.9	31.8	9.6	39.5	38	3.9	51.5
Vivian		12	55.8	54.5	2.4	35.8	32.9	8.8	38.9	42.4	-8.3	48.8
Irene		13	49.4	54.5	-9.4	36.2	33.5	8.1	38.5	42.7	-9.8	50
Georgia		14	58.9	63.6	-7.4	38.3	35.5	7.9	51.4	48.9	5.0	66

Table 3. Mass values of organs which are partially present in the head and neck region and their segmented fraction

Voxel model	Gender	Age	Skin surface (cm ²)	Segmented fraction	Oesophagus mass (gr)	Segmented fraction	Muscles mass (gr)	Segmented fraction	Extrathoracic surface (cm ²)	Segmented fraction	Thyroid mass (gr)	Segmented fraction
John	Males	3	943	0.14	1.0	0.15	295	0.08	134	0.86	0.6	0.24
Dejan		5	1011	0.13	1.7	0.16	313	0.06	103	0.52	0.6	0.18
Joris		6	1253	0.15	2.7	0.22	462	0.07	90	0.39	1.0	0.21
Guozhi		7	1202	0.13	1.8	0.13	430	0.06	90	0.38	0.8	0.15
Peter		8	1295	0.2	1.6	0.11	539	0.06	121	0.49	0.7	0.11
Benjamin		9	1359	0.13	2.7	0.16	548	0.06	126	0.46	1.0	0.14
Andrew		10	1291	0.12	1.8	0.09	452	0.04	105	0.36	0.7	0.09
Mike		12	1518	0.12	5.4	0.23	655	0.04	104	0.30	1.8	0.19
Lina	Females	2 months	720	0.24	0.6	0.19	225	0.20	12	0.20	0.4	0.24
Demi		5	1301	0.17	1.5	0.14	455	0.08	104	0.52	0.6	0.17
Viktoria		6	1249	0.15	3.5	0.29	496	0.07	117	0.52	1.5	0.33
Louisa		10	1347	0.12	2.0	0.11	491	0.04	134	0.46	0.9	0.11
Hilde		11	1249	0.10	2.2	0.10	592	0.05	146	0.46	1.0	0.11
Vivian		12	1312	0.10	2.8	0.12	574	0.04	138	0.41	1.6	0.14
Irene		13	1232	0.09	2.3	0.09	461	0.03	121	0.35	1.4	0.13
Georgia		14	1459	0.10	2.2	0.08	653	0.04	136	0.38	2.2	0.20

Table 4. Segmented mass values for the rest of the organs which are present in the voxel models

Voxel model	Gender	Age	Air cavities (gr)	Blood (gr)	Bone (gr)	Cartilage (gr)	Connective tissue (gr)	Fat (gr)	Spinal cord (gr)	Trachea (gr)	Residual tissue (gr)
John	Males	3	0.02	12.7	411	32.8	218	169	16.1	3.2	25.9
Dejan		5	0.05	16.1	629	9.9	437	155	14.3	3.1	1.4
Joris		6	0.02	22.1	897	44	309	272	19	3.6	0.0
Guozhi		7	0.04	15.3	654	13.5	550	203	20.5	3.1	19.3
Peter		8	0.03	29.1	956	12.5	213	170	23.3	1.9	10.4
Benjamin		9	0.04	35	852	21.4	594	142	43.5	1.7	10.6
Andrew		10	0.06	29	801	23.8	681	367	21	1.9	16.0
Mike		12	0.07	40	768	23.4	770	263	41.8	3.1	6.4
Lina	Females	2 months	0.005	3.6	164	7.3	76	171	7.7	0.9	3.3
Demi		5	0.03	27.8	702	11.9	508	264	14.8	3.1	5.2
Viktorja		6	0.06	16.8	784	11	604	188	18.8	3.6	7.7
Xoch		8	0.06	22.4	952	19.7	779	140	28.3	2.6	3.2
Louisa		10	0.06	30.3	813	21	899	160	37.7	2.3	6.1
Hilde		11	0.05	35.6	784	21.1	738	125	30	2	5.3
Vivian		12	0.06	39.2	802	23.4	772	213	31.1	2.2	3.9
Irene		13	0.06	41.2	614	20.5	442	313	29.2	2.3	3.9
Georgia		14	0.07	29.5	793	26.1	868	179	35.2	2.8	2.1

Figure 3. From the left to the right; Dejan, Guozhi, Xoch and Vivian.

the number of teeth voxels by assigning the inner outline of the teeth to the tongue which is usually in contact with the teeth. The oral mucosa was segmented as the outline of the mouth cavity, yet the parotid gland can also be used as a substitute organ to estimate the dose to oral mucosa. The segmented salivary glands include the parotid, the sublingual and the submandibular glands; all of them were given the same identification number. However, it is straightforward to assign different IDs to each of them such the dose to each gland can be individually calculated.

The current resolution of CT images, even when obtained with the most recent state of the art multislice CT scanners, pose limitations in the segmentation of specific tissues and organs in the head region. The in-plane (x,y) voxel size is too large compared to the thickness of the skin layer and to that of the ET tissue. The radiosensitive wall of the ET₁ region (nasal vestibule) is a squamous epithelium layer which is 50 μm thick; the wall of the ET₂ region, *i.e.* the wall of posterior nasal passages, larynx, pharynx and mouth, has an average thickness of 65 μm (mucous layer and stratified squamous epithelium) according to ICRP 89. By contrast, the lowest in-plane dimension of our images is 210 μm . The skin was segmented as a one-voxel thick outline of the total head frame and the ET tissue as a one-voxel thick outline of the related tissues. Due to the large voxel size, the segmented masses of the skin and the ET region are unavoidably overestimated. To extract the segmented fraction of these tissues, the segmented surface rather than the segmented mass was used.

Figure 4. Cleft palate FOV positioning. The FOV is 55 mm² in height and 100 mm² in diameter. The centre of the FOV is positioned at the centre of the mouth cavity in the axial plane and on the level of the roots of the upper teeth along the vertical axis. FOV, field of view.

The limited image resolution of CT images impedes also the segmentation of the RBM. It would be feasible in high resolution images to distinguish the spongy and the cortical parts of the segmented bones; however, it is impossible to segment the medullary cavities in the trabecular bone where RBM is present. Therefore, in order to follow the same segmentation strategy for each of our phantoms, we decided to segment the cortical bone and the spongiosa as a unified skeletal mixture and apply the well-established 3 factor approach to approximate the dose to the RBM.^{37,38}

A simulation study was set up to demonstrate the applicability of the voxel models in a MC framework. The study was also designed to investigate the dose differences between males and females of the same age, when exposed to identical conditions. We calculated the absorbed doses to the radiation sensitive organs, including the dose to eye lenses which are prone to radiation induced cataract. Translation and rotation corrections were applied to the voxel phantoms to achieve an horizontal Frankfort plane, based on a methodology which has been previously described and which enables the use of CT-based voxel models to dental CBCT MC studies.⁴⁶

The results (Table 6) showed that the percentage difference in organ doses is, in all cases, within $\pm 5\%$ when the two genders of the same age are compared. These slight organs dose differences lie within the overall statistical uncertainty of the MC dose calculations; the latter is considered to be around 5%, given that the maximum % CV on dose calculations is 3% for the number of simulation histories that we used in the study and accounting for an extra uncertainty of 2% in the calibration procedure. The absorbed doses were always slightly lower in males, apart from the dose to the skin, muscles and salivary glands.

When comparing different age categories, there is a well-established organ dose decreasing pattern with age. The only exception is the skin and the muscles which do not display a fixed dose increasing or decreasing behavior with age. There are many factors which contribute to this unstable dose response pattern; for a bigger head circumference and hence for a wider head, the skin surface is slightly closer to the X-ray tube and therefore skin and muscles may receive higher doses; the irradiated part of these tissues compared to the total tissue mass which is present in the voxel model is larger for the younger patient and

Table 5. Organ densities and the elemental composition in terms of % mass fraction

ID	Organ	Atomic number Density (g cm ⁻³)	1	6	7	8	11	12	15	16	17	19	20	26	53
			H	C	N	O	Na	Mg	P	S	Cl	K	Ca	Fe	I
1	Air_internal	0.001	0.0	0.0	80.0	20.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	Blood	1.060	10.2	11.0	3.3	74.5	0.1	0.0	0.1	0.2	0.3	0.2	0.0	0.1	0.0
3	Brain	1.050	10.7	14.4	2.2	71.3	0.2	0.0	0.4	0.2	0.3	0.3	0.0	0.0	0.0
4	Cartilage	1.100	9.6	9.9	2.2	74.4	0.5	0.0	2.2	0.9	0.3	0.0	0.0	0.0	0.0
5	Connective_tissue	1.120	9.4	20.7	6.2	62.2	0.6	0.0	0.0	0.6	0.3	0.0	0.0	0.0	0.0
6	Skin	1.090	10.0	19.9	4.2	65.0	0.2	0.0	0.1	0.2	0.3	0.1	0.0	0.0	0.0
7	Oesophagus	1.030	10.4	22.2	2.8	63.6	0.1	0.0	0.2	0.3	0.2	0.2	0.0	0.0	0.0
8	Eye	1.050	9.7	18.3	5.4	66.0	0.1	0.0	0.1	0.3	0.1	0.0	0.0	0.0	0.0
9	Eye_lens	1.070	9.6	19.5	5.7	64.6	0.1	0.0	0.1	0.3	0.1	0.0	0.0	0.0	0.0
10	Fat	0.950	11.4	58.9	0.7	28.7	0.1	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0
11	Mandible	1.83	5.4	21.6	2.9	38.4	0.0	0.2	9.8	0.2	0.1	0.1	21.3	0.0	0.0
12	Muscle	1.050	10.2	14.2	3.4	71.1	0.1	0.0	0.2	0.3	0.1	0.4	0.0	0.0	0.0
13	ET	1.030	10.5	23.5	2.8	62.2	0.1	0.0	0.2	0.3	0.2	0.2	0.0	0.0	0.0
14	Spinal_cord	1.030	10.5	23.5	2.8	62.2	0.1	0.0	0.2	0.3	0.2	0.2	0.0	0.0	0.0
15	Teeth	2.750	2.2	9.5	2.9	42.1	0.0	0.7	13.7	0.0	0.0	0.0	28.9	0.0	0.0
16	Tongue	1.050	10.2	14.2	3.4	71.1	0.1	0.0	0.2	0.3	0.1	0.4	0.0	0.0	0.0
17	Trachea	1.060	10.1	13.9	3.3	71.3	0.1	0.0	0.4	0.4	0.1	0.4	0.0	0.0	0.0
18	Bone	1.83	5.4	21.6	2.9	38.4	0.0	0.2	9.8	0.2	0.1	0.1	21.3	0.0	0.0
19	Thyroid	1.040	10.4	11.9	2.4	74.5	0.2	0.0	0.1	0.1	0.2	0.1	0.0	0.0	0.1
20	Salivary_glands	1.030	10.4	23.1	2.8	62.7	0.1	0.0	0.2	0.3	0.2	0.2	0.0	0.0	0.0
21	Residual Tissue	0.950	11.4	58.8	0.8	28.7	0.1	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0
22	Oral_mucosa	1.050	10.2	14.2	3.4	71.1	0.1	0.0	0.2	0.3	0.1	0.4	0.0	0.0	0.0

Table 6. Absorbed dose to radiosensitive organs under identical exposure cleft palate protocol conditions for three pairs of opposite gender voxel models, each pair having different age from the other two

Organs	Dejan 5-year-old male	Demi 5-year-old female	Peter 8-year-old male	Xoch 8-year-old female	Mike 12-year-old male	Vivian 12-year-old female
	Absorbed organ doses (μGy)					
Brain	70	77	68	73	61	66
Skin	540	516	584	512	566	514
Oesophagus	716	738	553	588	229	236
Eye lenses	173	204	153	190	131	147
Muscles	1237	1222	1369	1354	1141	1113
ET	1925	2018	1707	1812	1107	1135
Thyroid	429	438	231	236	211	224
Salivary glands	2147	1998	2048	2016	1694	1633
Oral mucosa	2210	2222	1735	1812	1486	1574
RBM	165	182	129	134	120	111
bone surface	493	543	385	400	358	331
Lymph nodes	2410	2428	2234	2230	1899	1904

smaller for the older ones; the dose to the skin is dependent on the in-plane resolution of the voxel model (x-y dimension) and the voxel size of the segmented skin; the scatter distribution is different at each voxel model due to variations in head anatomy among the models. However the maximum percentage difference was very small for both skin and muscles (3.28 and 5.17% respectively). On the other hand, large organ dose differences were observed in the dose to oesophagus, thyroid, ET, RBM, bone surface and eye lenses; the gender averaged dose values to oesophagus and to thyroid are more than three times higher and double, respectively in the 5 years old model compared to 12 years old one. The remaining sensitive organs receive doses which are much higher in the 5 years old models compared to the 8 and 12 years old ones. The results of the study suggest that age-specific voxel models are required to estimate organ doses in the head region. The two opposing gender models at each age category do not lead to large organ differences. However, more than one FOVs and more dental CBCT scanners even different modalities (CT, X-ray tables, even nuclear medicine) shall be

investigated to clarify whether or not gender-specific models are necessary for dose calculations.

CONCLUSION

17 paediatric head voxel models, intended for MC dose simulation studies, were designed. Each model consists of 22 segmented organs in the head and neck region. The organ mass values were compared to the respective ICRP-drawn reference values and were subsequently adjusted to them within a tolerance of 10%, such that they are considered to represent an average-reference male or female at each specific age category. A dose simulation study demonstrated the applicability of the models to a validated dental CBCT MC framework. The study also pinpointed the large dose differences among voxel models of different ages when exposed to identical conditions.

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