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Review paper

Development of a high resolution voxelised head phantom for medical physics applications

V. Giacometti [a], S. Guatelli [a,*], M. Bazalova-Carter [b], A.B. Rosenfeld [a], R.W. Schulte [c]

[a] Centre for Medical Radiation Physics, University of Wollongong, Australia
[b] Department of Physics and Astronomy, University of Victoria, BC, Canada
[c] Department of Basic Sciences, Division of Radiation Research, Loma Linda University, Loma Linda, CA, USA

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ABSTRACT

Computational anthropomorphic phantoms have become an important investigation tool for medical imaging and dosimetry for radiotherapy and radiation protection. The development of computational phantoms with realistic anatomical features contribute significantly to the development of novel methods in medical physics. For many applications, it is desirable that such computational phantoms have a real-world physical counterpart in order to verify the obtained results.

In this work, we report the development of a voxelised phantom, the HIGH_RES_HEAD, modelling a paediatric head based on the commercial phantom 715-HN (CIRS). HIGH_RES_HEAD is unique for its anatomical details and high spatial resolution (0.18×0.18 mm^2 pixel size). The development of such a phantom was required to investigate the performance of a new proton computed tomography (pCT) system, in terms of detector technology and image reconstruction algorithms.

The HIGH_RES_HEAD was used in an ad-hoc Geant4 simulation modelling the pCT system. The simulation application was previously validated with respect to experimental results. When compared to a standard spatial resolution voxelised phantom of the same paediatric head, it was shown that in pCT reconstruction studies, the use of the HIGH_RES_HEAD translates into a reduction from 2% to 0.7% of the average relative stopping power difference between experimental and simulated results thus improving the overall quality of the head phantom simulation.

The HIGH_RES_HEAD can also be used for other medical physics applications such as treatment planning studies.

A second version of the voxelised phantom was created that contains a prototypic base of skull tumour and surrounding organs at risk.

Contents

* Corresponding author at: Centre for Medical Radiation Physics, School of Physics, Faculty of Engineering, Building 4, Room G69, University of Wollongong, Northfields Ave, NSW 2522, Australia.

E-mail address: susanna@uow.edu.au (S. Guatelli).

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1. Introduction

The development of anthropomorphic phantoms, both physical and computational, is an active field of investigation in medical physics [1]. Anthropomorphic computational phantoms have undergone an evolution from simple stylized phantoms to voxelised phantoms and, more recently, to hybrid phantoms offering a mixture of surface-based and voxelised representations [2–4]. Stylized mathematical phantoms [3], which are based on 3D surface equations for internal organs definition, provide only a rough approximation of the true anatomy of individual patients. Voxelised [4] and hybrid phantoms [2] are usually generated from CT and/or MRI data of patients or volunteers. They provide a better anatomical detail, but are frequently compromised by image noise, partial-volume averaging and imaging artefacts. Despite these drawbacks, it has been well established that voxelised phantoms can be successfully used in a wide range of medical physics applications [5–10].

In this work we describe the development and use of a novel high resolution voxelised head phantom, called here HIGH_RES_HEAD, based on a high resolution CT acquisition of a physical paediatric head phantom (HN715, CIRS).

The HIGH_RES_HEAD was initially created for proton computed tomography (pCT) studies when it became clear that simple geometrical phantoms such as, for example, the Catphan® 600 series (The Phantom Laboratory, Salem, New York, USA) were not sufficient to fully characterize pCT, but that an accurate representation of the human anatomy was necessary. pCT is a promising imaging technique that could add to or substitute for X-ray CT in treatment planning and in-room image guidance applications, as it allows for direct reconstruction of proton relative stopping power (RSP) from proton energy loss measurements [11].

2. Material and methods

2.1. Development of the HIGH_RES_HEAD

The HIGH_RES_HEAD was created from the CT scan of a commercially available tissue-equivalent dosimetry phantom (ATOM®, Model 715 HN, CIRS Inc., Norfolk, VA) (Fig. 1a).

The physical phantom provides very realistic anatomical details of the head and spine of a 5-year-old child including skeletal and soft tissue features, intra-cranial and paranasal sinuses, ear canals, and outer head contours (Fig. 1b). The physical phantom is composed of the following seven tissue-equivalent materials (density in g/cm^3): soft tissue (1.055), brain (1.07), paediatric spinal disc (1.10), paediatric trabecular bone (1.13), 5-year-old compact bone (1.75), tooth dentine (1.66), and tooth enamel (2.04). All materials of the real phantom are homogeneous in their density and composition; a few minor defects such as small cavities can be present, which were not included in the HIGH_RES_HEAD. The proprietary atomic composition of each material is available from CIRS upon request.

Eight separate helical CT scans of the entire physical head phantom were acquired with a 64-detector-row CT scanner (Lightspeed, GE Healthcare, Waukesha, WI) using an image matrix size of 512 $\times$ 512 pixels and a display FOV of 9.6 cm, corresponding to a pixel size of 0.1875 mm $\times$ 0.1875 mm. The slice thickness was 1.25 mm. The display FOVs were partially overlapped so that each part of the phantom was covered by at least one display FOV (Fig. 1c). A single DICOM study with 128 slices and matrix size of 1024 $\times$ 1024 pixels was generated from the CT scan with a segmentation study performed with Matlab (The MathWorks Inc., Natick, MA, USA).

Another voxelised virtual phantom, called here CONVENTIONAL_HEAD, was created scanning the same physical head phantom with the same X-ray CT scanner at Loma Linda University Medical Center using an image matrix size of 512 $\times$ 512 pixels and a display FOV of 37 cm, in order to cover the entire phantom with one scan. Its spatial resolution is lower than the case of the HIGH_RES_HEAD. The pixel size was 0.72 mm $\times$ 0.72 mm, the slice thickness was 1.25 mm and 171 slices were collected in a single DICOM study. The CONVENTIONAL_HEAD was not subjected to any image segmentation process but was developed to be used as a term of comparison to quantify the effect of adopting a high spatial resolution and a noiseless virtual phantom, such as the HIGH_RES_HEAD, when characterising a pCT system.

2.2. Segmentation of the anatomy of the HIGH_RES_HEAD

The different tissue regions of the phantom were segmented in each CT slice using ImageJ version 1.46r (http://imagej.nih.gov/ij). The Hounsfield unit (HU) values of the outer air and most of the tissue regions were found to be well described by well-separated Gaussian distributions with mean and standard deviations listed in Table 1.

The first step of the segmentation process consisted in identifying continuous boundaries between the voxelised phantom and the surrounding air, and between the different tissues of the head itself by means of a thresholding process. To detect entire tissue regions and their boundaries, different windows of HU were selected using a custom thresholding macro in ImageJ. Imperfections in the boundaries were manually edited as guided by anatomical knowledge or by the fact that they were obvious artefacts.

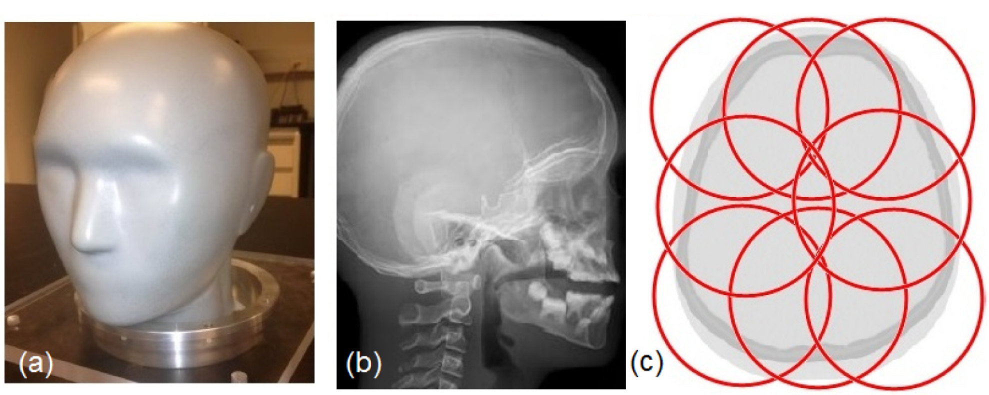

Fig. 1. (a) Head phantom (HN715, CIRS); (b) lateral X-ray radiograph of the head phantom demonstrating its anatomical detail; (c) arrangement of eight partially overlapping FOVs represented by the red circles of 9.6 cm diameter.

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