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Low-dose computed tomography: A solution for in vivo medical imaging and accurate patient-specific 3D bone modeling?

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Abstract

Background. The number of in vivo clinical biomedical experiments based on computed tomography is increasing. International radiation-protection bodies are promoting the use of low-dose computed tomography to reduce radiation absorption by the subject undergoing imaging. On the other hand no data exist in the literature to quantify whether or not low-dose computed tomography would lead to a decrease of result quality when used for three-dimensional bone modeling and related measurements.

Methods. This paper aimed at finding a consensus between minimal X-ray radiation of the subject, and satisfactory image data quality, especially for accurate three-dimensional bone modeling. Several standard computed tomography and low-dose computed tomography sequences were analyzed in three tests and statistically compared.

Findings. Absence of significant difference between standard and low-dose computed sequences indicated that the low-dose setting would not produce less accurate three-dimensional models, while it decreased the effective X-ray dose up to 90% compared to standard settings.

Interpretation. Low-dose computed tomography seems suitable for accurate three-dimensional bone modeling, while the related effective X-ray radiation is low. Such setting is therefore advised for any in vivo medical imaging aiming to collect bone data.

Keywords: Low-dose computed tomography; LDCT; 3D; bone

1. Introduction

During the last two decades, the number of biomechanical applications using computed tomography (CT) increased to perform three-dimensional (3D) joint modeling. In vitro registration methods using CT for bone modeling have been previously developed for joint (Belsole et al., 1988; Van Sint Jan et al., 1997; Cripton et al., 2001; Fischer et al., 2001) and limb motion analysis (Sholukha et al., in press) without paying attention to minimize radiation. In vivo joint modeling for research purposes have been reported as well (Bresina et al., 1986; Van Sint Jan et al., 2006). Magnetic Resonance Imaging (MRI) offers a non-invasive alternative that has been previously used for joint kinematics analysis (Udupa et al., 1992; Stindel et al., 2001). Unfortunately, post-processing of MRI image datasets is time-consuming because of the low contrast between the anatomical tissues (i.e., bone vs. soft tissue). MRI is also relatively expensive and imaging installations are not so widely available as CT systems. Some of the above systems are now being improved for clinical patient-specific applications; such improvements of the clinical usefulness of current modeling methods will therefore probably largely depend on CT imaging (Van Sint Jan, 2005). On the other hand, CT technology is based

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on X-ray, whose side effects are raising ethical concerns, even if there is no consensus in the specialized radiation assessment literature, when applied in vivo because of potential side-effects. Several recognized North American and European radioprotection bodies advise therefore the use of Low-Dose CT (LDCT) (Nagel et al., 2000; US Food and Drug Administration, 2005). No strict threshold value between Standard Dose CT (SDCT) and LCDT has been found in the literature. LCDT stands for CT settings that allow considerable dose reduction to the patient, but still providing adequate image quality (Nagel et al., 2000). Other sources mention that LDCT settings "may adjust the radiation dose used to levels less (by factors such as 1/2–1/5) than those typically used for diagnostic CT procedures" (US Food and Drug Administration, 2005).

Few biomechanical studies advised use of low X-ray dose, but without quantifying the effect of dose reduction on the data quality (Crisco et al., 1999; Snel et al., 2000). To the authors' knowledge only one paper in the field proposed radiation reduction and assessment (Lattanzi et al., 2004). It was unfortunately limited to the control of both pitch and detector collimation. Recent work showed that LDCT did not interfere with the detection of clinical abnormalities of nasal soft tissue (Tack et al., 2003). No similar work was found in the literature for bone modeling to estimate if LDCT could have an adverse impact on the image quality produced (US Food and Drug Administration, 2005).

This paper analyzed the effect of LDCT on various aspects of 3D bone modeling. Several CT settings, including SDCT and LDCT were statistically compared regarding anatomical realism and accuracy of the 3D models. Another goal of this paper is promoting LDCT during in vivo imaging to answer official recommendations aiming to protect public health (Nuis, 1997; ICRP, 2000; Nagel et al., 2000; Wrixon et al., 2004; US Food and Drug Administration, 2005).

2. Methods

Various successive CT trials were performed to find a consensus between minimal X-ray radiation and satisfactory image data quality for accurate modeling. Trial differences have been statistically compared by evaluating various aspects of 3D modeling (i.e., anatomical realism, volume and morphological measurements). Medical imaging datasets collected for this study can be found at: http://homepages.ulb.ac.be/~sintjans/ct_assessment.htm.

2.1. Parameters required for X-ray radiation assessment

For each collected trial, radiation assessment was performed using the method advised by the European Coordination Committee of the Radiological and Electromedical Industries, or COCIR, (Nagel et al., 2000) based on CT hardware characteristics and CT protocol setting. The CT installation used for this study was a Somatom Volume Zoom 6 (spiral system, Siemens Medical Solutions®, Erlangen, Germany) with the following hardware characteristics (found from manufacturer hardware specifications): tube potential reference (U_{ref}) = 120 kV, normalized dose free-in-air ($nCTDI_{air}$) = 0.17 mGy/mA s and scanner factor (K_{CT}) = 1.0. Radiation assessment is also dependent on several parameters that are customizable from the protocol setting (Table 1): tube potential U (in kV), tube current intensity I (in mA), exposure time t (in s, this is the time

Table 1
Spiral CT parameters of the various bone trials (trial index in first row)

	1	2	3	4	5	6
h	$P,D = 0.125$; $C = 0.3$	$P,D = 0.15$; $C = 0.3$			$P,D = 0.15$; $C_1, C_2 = 0.3$	
N	$P = 175$; $C = 74$; $D = 229$	$P = 69$; $C = 78$; $D = 111$	$P = 67$; $C = 87$; $D = 95$	$P = 73$; $C = 85$; $D = 94$	$P = 69$; $C_1 + C_2 = 19$; $D = 98$	$P = 65$; $C_1 + C_2 = 29$; $D = 102$
I	254		187	134	94	
U			120			80
t				0.75		
F_{mean}				$P = 0.002$; C (or C_1, C_2), $D = 0.00029$		
E_s	$P = 1.42$; $C = 0.21$; $D = 0.27$	$P = 0.67$; $C = 0.22$; $D = 0.16$	$P = 0.48$; $C = 0.18$; $D = 0.10$	$P = 0.37$; $C = 0.13$; $D = 0.07$	$P = 0.25$; $C_1 + C_2 = 0.02$; $D = 0.05$	$P = 0.08$; $C_1 + C_2 = 0.01$; $D = 0.02$
E	1.89	1.05	0.76	0.57	0.32	0.12

Effective dose (E_s, in mSv) per sequence and effective dose per trial (E, in mSv) were determined from Nagel et al. (2000) (see Eqs. (1)–(5)). For each trial, several sequences were collected according the current anatomical areas-of-interest. Epiphyses ($s = P$ and D for proximal and distal epiphysis, respectively) support joint surfaces, and need to show higher resolution than at diaphysis level ($s = C$). For all trials the following parameters remained constant: slice collimation (P and D = 1 mm; C = 2.5 mm), feed rotation (P and D = 4 mm; C = 10 mm), image dimensions (512^2 voxels), field-of-view (310 mm), exposure time t (0.75 s). Final slice stacks were reconstructed from the collected raw slices using constant slice intervals (P and D = 1 mm; C = 3 mm) and medium reconstruction filter (B50) for all trials. F_{mean} value was 0.002 mSv/mGy cm for each proximal sequence P, and 0.00029 mSv/mGy cm for C and D sequences. See text for further explanations.