Eur Radiol (2015) 25:1752–1760
DOI 10.1007/s00330-014-3560-8

PEDIATRIC

Low-dose biplanar radiography can be used in children and adolescents to accurately assess femoral and tibial torsion and greatly reduce irradiation

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Received: 27 May 2014 / Revised: 5 October 2014 / Accepted: 5 December 2014 / Published online: 23 December 2014

Abstract
Purpose To evaluate in children the agreement between femoral and tibial torsion measurements obtained with low-dose biplanar radiography (LDBR) and CT, and to study dose reduction ratio between these two techniques both *in vitro* and in vivo.
Materials and methods Thirty children with lower limb torsion abnormalities were included in a prospective study. Biplanar radiographs and CTs were performed for measurements of lower limb torsion on each patient. Values were compared using Bland-Altman plots. Interreader and intrareader agreements were evaluated by intraclass correlation coefficients. Comparative dosimetric study was performed using an ionization chamber in a tissue-equivalent phantom, and with thermoluminescent dosimeters in 5 patients.
Results Average differences between CT and LDBR measurements were –0.1° ±1.1 for femoral torsion and –0.7° ±1.4 for tibial torsion. Interreader agreement for LDBR measurements was very good for both femoral torsion (FT) (0.81) and tibial torsion (TT) (0.87). Intrareader agreement was excellent for FT (0.97) and TT (0.89). The ratio between CT scan dose and LDBR dose was 22 in vitro (absorbed dose) and 32 in vivo (skin dose).
Conclusion Lower limb torsion measurements obtained with LDBR are comparable to CT measurements in children and adolescents, with a considerably reduced radiation dose.
Key points
- *LDBR and CT lower-limb torsion measurements are comparable in children and adolescents.*
- *LDBR considerably reduced radiation dose necessary for lower-limb torsion measurements.*
- *LDBR can be used for evaluation of lower limb-torsion in orthopaediatric patients.*

Keywords Pediatrics · Radiation Dosage · X-ray · Lower extremity · CT

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Abbreviations and acronyms

CTDI	Computed tomography dose index
TLD	radiothermoluminescent detectors
DLP	dose-length product
LDBR	Low dose biplanar radiography
FT	Femoral torsion
TT	Tibial torsion

Introduction

Accurate evaluation of femoral and tibial torsion is essential for children or adults with a lower limb deformity. Defects in leg morphogenesis can lead to abnormalities. As soon as symptoms arise, orthopaedic referral is needed [1]. Objective radiological measurements as well as clinical examination are essential in decision making [2]. These measurements help physicians to achieve successful derotational osteotomies. Computed tomography (CT) imaging is particularly accurate and is considered the gold standard [3, 4].

Use of x-rays requires optimizing the radiation dose [5]; as such, reducing patient irradiation via low-dose biplanar radiographs is appealing. This method uses conventional x-ray tubes associated with multiwire proportional chambers displaced together along the patient to provide two orthogonal projections of bony structures without distortion. By adapting parametric models during a semiautomatic process, the software delivers a 3D model of bones from the interest region and automatically provides various measurements. Based on the research of Charpak (French physicist, Nobel prize in physics, 1992), low-dose biplanar radiographs require a very low dose of radiation [6]. In studies of scoliosis, dosimetric evaluation shows the dose is reduced by a factor of nearly 20 when compared with standard spine radiographs [7]. Compared with CT, the reduction is expected to be much higher. Even if radiological measurements of tibial and femoral torsion mainly irradiate the lower limbs, the pelvis and, therefore, the gonads are nonetheless exposed. Lower irradiation using this technique seems particularly applicable to children, since their tissue radiosensitivity is higher [8].

In adults, it has been shown that measurements of femoral and tibial torsion via biplanar radiography are equivalent to standard CT measurements [9]. However, low-dose biplanar radiography requires correct identification of anatomic landmarks used to produce 3D models of the lower limbs. The presence of cartilage may hinder identification of bony structures and alter the accuracy of the tibial and femoral torsion measurements based on these 3D reconstructions.

The purpose of this study was to evaluate in children the agreement between femoral and tibial torsion measurements obtained with low-dose biplanar radiography and CT, and to investigate the dosimetric characteristics of these methods both in vitro and in vivo.

Materials and methods

This was a single-centre prospective study. Thirty patients were included, all referred from orthopaediatric clinics for evaluation of lower limb torsion in view of possible derotational osteotomies, from June 2012 to June 2013. Patients with major limb deformities were, therefore, not included in this study. There were 23 girls and 7 boys (sex ratio= 3.3). The mean age was 14 years (range, 8–18).

We used our routine protocol for lower limb torsion evaluation, which included both CT and low-dose biplanar radiography. Ordinarily, these methods are used to assess lower-limb torsion (CT) and lower-limb length (low-dose biplanar radiography). Both were performed the same day. All 30 patients were imaged under the same conditions and with the same parameters. As in routine evaluation, readers were not blinded from clinical information.

The study was conducted with the approval of our institutional review board. The institutional review board waived the requirement for informed consent, since patient care was not modified by the study design.

Imaging technique

A 32-slice CT scanner (Lightspeed™ Pro 32, GE, Chalfont St. Giles, UK) was used. The topogram was centred on the lower limbs. The protocol used sequential acquisition of the joints. Images of the hip, knee, and ankle joints were acquired without moving the patient. Axial image parameters were as follows: tube voltage, 120 kV; tube current, 200 mAs/slice; matrix 512×512; reconstruction thickness 5 mm; reconstruction increment 5 mm. Image overlay was used to measure femoral and tibial torsion.

Femoral torsion was defined as the angle between a line passing through the centre of the femoral head and parallel to the cortical bone of the femoral neck and a tangent line to the posterior contour of the femoral condyles [3]. Tibial torsion was defined as the angle between the tangent line to the posterior contour of the tibial plateau and the line passing through the midpoint of the articular surfaces of the medial and lateral malleoli [4]. These measurements were routinely obtained by senior radiologists with more than five years experience (Fig. 1). The measurements were taken directly from their records.

The EOS imaging system (EOS-Imaging, Paris, France) was used for low-dose biplanar radiography. Perpendicular anteroposterior and lateral projections were acquired simultaneously (anteroposterior parameters: tube voltage 85 kV, tube current 200 mA; lateral parameters: tube voltage 110 kV, tube current 320 mA). Every child was able to stand upright and still and there was no need for repeat examinations. SterEOS software (EOS Imaging) uses both projections to create 3D models of the lower limbs. This requires identification of specific anatomic landmarks by a software-guided, step-by-step fitting process of a 3D parametric model. These landmarks include the greater trochanter, the posterior contours of the femoral condyles, the posterior contours of medial and lateral aspects of the proximal tibia, and the malleoli of the ankle joint (Fig. 2). The software then automatically provides the femoral and tibial torsion measurements. One technician performed the set of measurements used for comparison with CT. Secondarily, the same technician produced another set of measurements to assess intraobserver agreement. A second technician produced separately a third set of measurements to assess interobserver agreement. Each technician was specifically trained in the use of sterEOS.

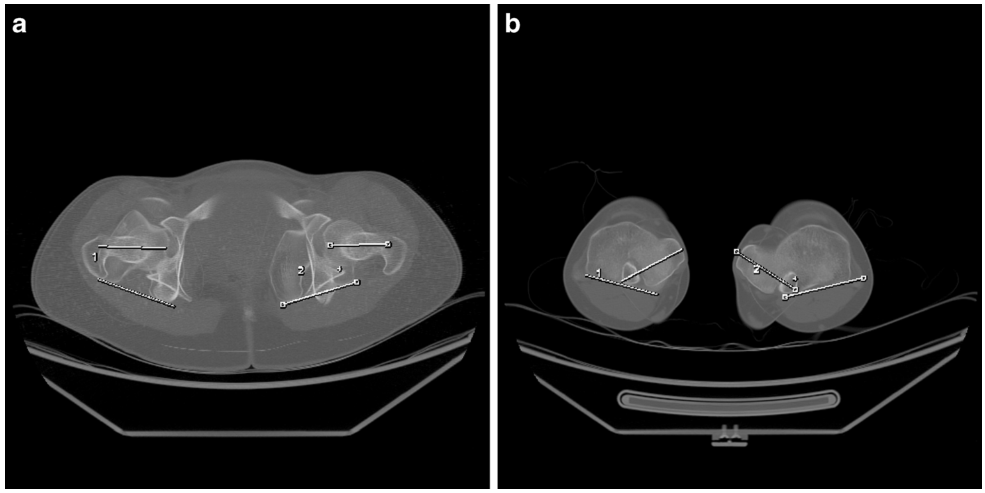

Fig. 1 CT scan measurements of tibial (**a**) and femoral (**b**) torsion.

Dosimetric study

For in vitro dosimetry, a pencil ionization chamber was used (8202041-c XI CT, Unfors Raysafe, Billdal, Sweden) inserted in a standard tissue equivalent phantom (methyl polymethacrylate, diameter 32 cm) used for the CT dose index (CTDI) quality control. Two water cylinders were attached, simulating thighs for scatter radiation. Measurements were taken in five different positions (central, anterior, posterior, left, right). Irradiation parameters were the same as those used with children. We used two sequential acquisitions five cm long. One was on the phantom, one on the extremities of the water cylinders, simulating acquisition of hip joint and knee joint images (Fig. 3). We did not simulate acquisition of the ankle joint since scatter radiation is very low for both CT or biplanar radiography. Results were delivered in units of mGy.cm.

For in vivo dosimetry, radiothermoluminescent detectors (TLD) with lithium fluoride were used. TLDs were placed on 5 patients (mean age 13.7 years). They were positioned beside the pubis and changed between examinations. Two separate TLDs were used as controls for natural radiation. An automatic reader delivered equivalent skin dose (Hp 0.07) estimation in mGy units.

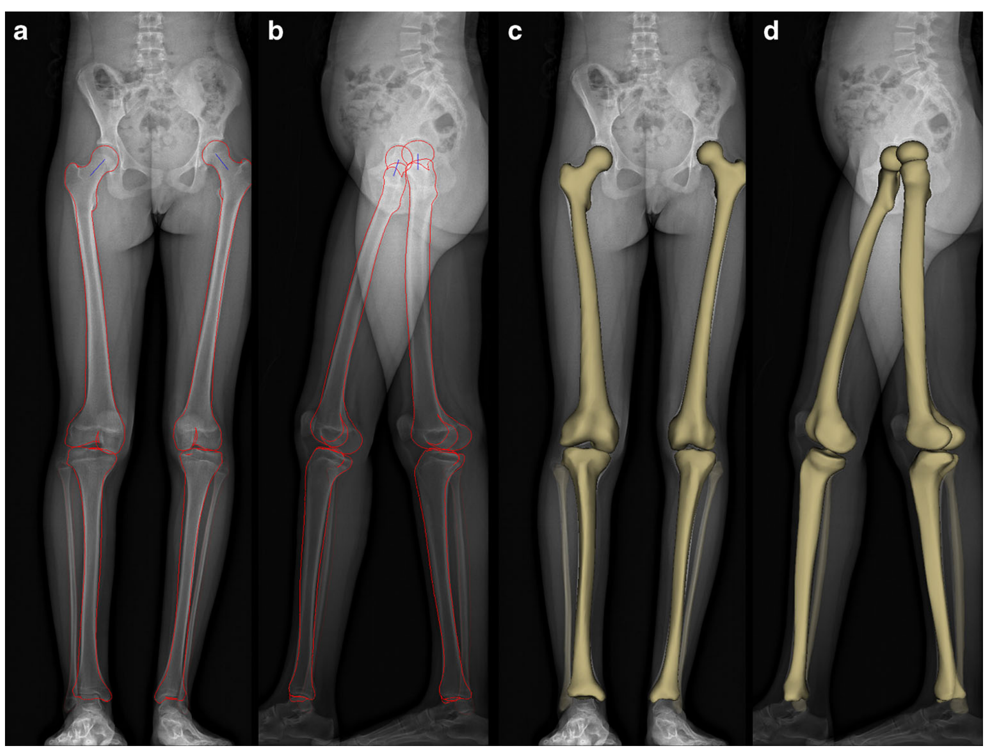

Fig. 2 Low-dose biplanar radiography anteroposterior (**a**) and lateral (**b**) projections used for reconstruction of the 3D parametric model (**c** and **d**)

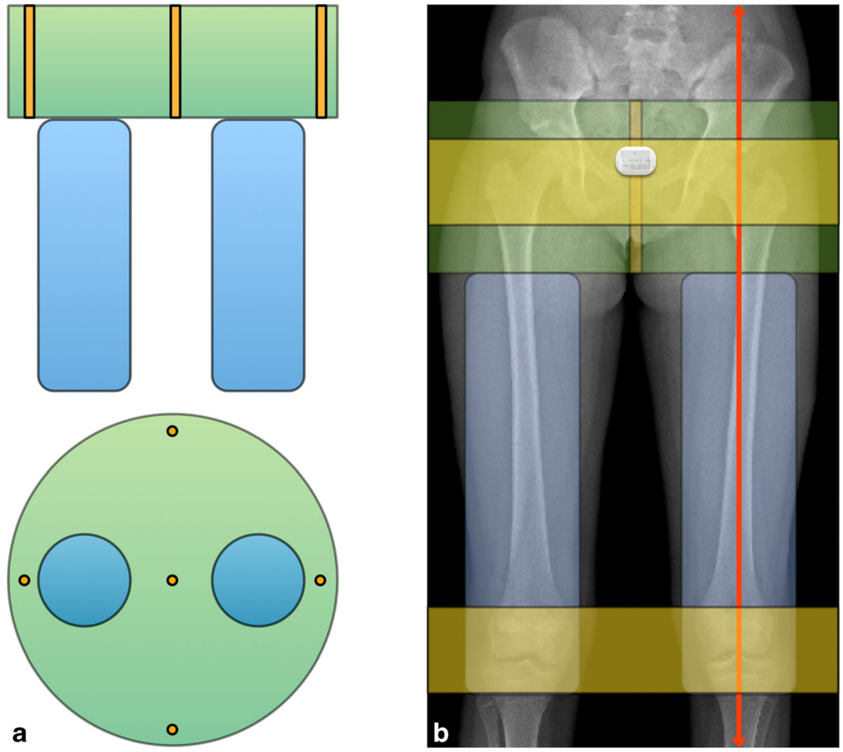

Fig. 3 (**a**) Schematic phantom representation with both front and top view. The standard tissue equivalent is in green, the water cylinder is in blue, and the ionization chamber insert positions are in orange. (**b**) Phantom representation overlay on an anteroposterior projection of lower limbs for the low-dose system. CT acquisition was sequential (yellow boxes) while biplanar radiography acquisition required irradiation of the pelvis and the whole limbs (red line). The TLD placed just beside the pubis (white box, shown enlarged) was less likely to reflect irradiation of the whole pelvis because of its shape. The ionization chamber (orange, here in central position) collected irradiation on its whole length

Statistical analysis

All differences between CT and biplanar radiograph measurements used CT as a reference. A negative value indicated that biplanar radiographs gave a lower measurement, while a positive value indicated a higher measurement. The measurements of femoral and tibial torsion obtained by the two modalities were compared using Bland-Altman plots [10, 11]. This was preferred to correlation coefficients since high correlation does not imply good agreement between the two methods. Inter-reader and intra-reader agreement for low-dose biplanar radiography measurements were evaluated by intra-class correlation coefficients. The relationship between CT-biplanar radiography differences in absolute values and age or degree of deformity was evaluated using Pearson correlation coefficients. Analyses were carried out with MedCalc © version 12 (MedCalc Software bvba, Ostend, Belgium).

Results

The average differences between CT measurements and biplanar radiograph measurements were –0.1° ±1.1 (range, –10 - +8) for femoral torsion and –0.7° ±1.4 (range, –17 - +12) for tibial torsion (Fig. 4, Table 1). There was no significant relationship between the CT-biplanar radiograph differences and the degree of femoral (P=0.17) or tibial torsion (P=0.63). Inter-reader agreement for biplanar radiograph measurements was very good for both femoral (0.81, 0.69–0.88) and tibial torsion (0.87, 0.77–0.93). Intra-reader agreement was excellent for both femoral torsion (0.97, 0.95-0.98) and tibial torsion (0.89, 0.82-0.93).

There was no relationship between CT-biplanar radiograph differences and patient age for either femoral (P= 0.09) or tibial (P=0.19) torsion. The mean difference for femoral torsion for the 14 patients younger than 14 years old was –0.61° ±1.51 versus –1.2° ±1.7 for the 16 older patients. For tibial torsion, mean differences among younger patients were similar at –0.9° ±2 versus –0.4° ±1.9 among older patients.

Regarding in vitro dosimetry of irradiation, regardless of the position of the ionization chamber, the CT dose was higher than the bi-planar radiography dose (Fig. 5). The arithmetic mean was 69.01 mGy.cm for CT vs 3.16 mGy.cm for biplanar radiographs (ratio=22). Irradiation from the topogram represented less than one percent of the total irradiation (0.55 mGy.cm).

Regarding in vivo dosimetry analysis with TLD, the skin dose was 13.448 mGy (standard deviation=6.76) for CT versus 0.596 (standard deviation=0.12) for biplanar radiographs. Natural radiation levels measured on controls were 0.17 mGy. Compared with low-dose biplanar radiography, CT increased the radiation delivered to the children by a ratio of 31.9.

Discussion

Mean differences between CT and biplanar radiographs were –1° for femoral torsion and –0.7° for tibial torsion. Biplanar radiography inter-reader and intra-reader agreements were, respectively, very good and excellent. In vitro and in vivo dosimetric analysis showed, respectively, dose reduction ratios of 22 and 32 for biplanar radiographs compared with CT.

The incompletely ossified skeleton did not alter the viability of the bony landmarks used to assess bone torsion with biplanar radiographs. Authors found similar results in adults, with 0° and 3° differences for femoral and tibial torsion, respectively [9], and slightly greater differences of 4.9° and 5.5° in children and in adolescents, possibly due to the younger age of their sample [12]. Surprisingly, in our population, the CT-biplanar radiograph measurement difference was lower among younger patients, possibly because of sampling error. Differences between CT and biplanar radiographs measurements ultimately discussed with our orthopaedists were considered as clinically acceptable since most of them are below 12°. In one case, femoral torsion differed by 17°. This was because senior radiologists, sometimes not involved in the study design, did the CT measurements routinely. In this particular case, biplanar radiography measurements were closer to clinical measurements than CT measurements. On a second examination, the CT measurements were found to be inaccurate. Compared with CT, biplanar radiography provides an overall view of the limbs and precise length measurements of lower limb segments. It yields further insight into lower limb coronal statics and this information is relevant to planning surgery [1, 13].

Investment in low-dose biplanar radiography appears worthwhile for seeking dose reduction and there are increasingly numerous indications for this new modality in both adults and children. Its application in scoliosis is particularly interesting [14, 15]. However, dosimetry data on biplanar

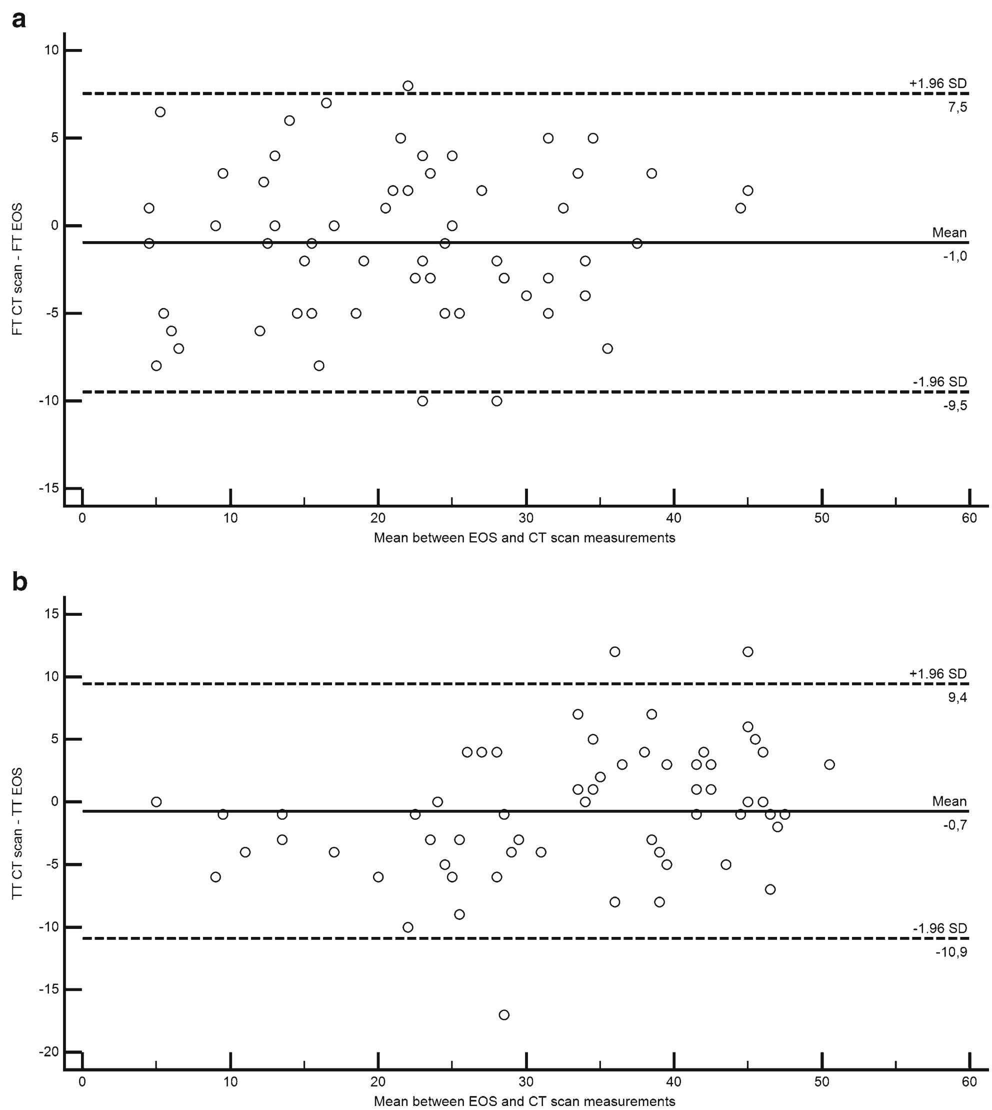

Fig. 4 Bland-Altman plots for femoral (**a**) and tibial (**b**) torsion show similar measurements from CT and biplanar radiography

Table 1 CT can and low-dose biplanar radiography (LDBR) measurements and differences

ID	AGE	SEX	SIDE	FT CT SCAN	FT LDBR	FT difference	TT CT SCAN	TT LDBR	TT difference
1	12.7	F	right	40	37	3	22	27	-5
	12.7	F	left	45	44	1	27	31	-4
2	10.2	M	right	37	38	-1	5	5	0
	10.2	M	left	33	35	-2	9	10	-1
3	13.7	F	right	9	9	0	43	42	1
	13.7	F	left	3	8	-5	42	41	1
4	12	F	right	32	36	-4	52	49	3
	12	F	left	33	32	1	41	38	3
5	13.6	F	right	21	20	1	24	27	-3
	13.6	F	left	23	28	-5	9	13	-4
6	14.4	F	right	28	26	2	40	36	4
	14.4	F	left	26	18	8	35	43	-8
7	15.5	F	right	21	24	-3	46	48	-2
	15.5	F	left	32	36	-4	44	45	-1
8	17.1	M	right	12	20	-8	47	48	-1
	17.1	M	left	25	22	3	48	42	6
9	17.9	M	right	27	23	4	20	37	-17
	17.9	M	left	25	25	0	21	30	-9
10	11.9	M	right	18	20	-2	51	39	12
	11.9	M	left	24	19	5	41	46	-5
11	16.1	F	right	8.5	2	6.5	37	42	-5
	16.1	F	left	13.5	11	2.5	35	34	1
12	14.1	F	right	25	21	4	41	42	-1
	14.1	F	left	20	13	7	37	40	-3
13	17.7	F	right	22	20	2	15	19	-4
	17.7	F	left	27	29	-2	12	15	-3
14	13.4	F	right	46	44	2	17	27	-10
	13.4	F	left	37	32	5	22	28	-6
15	13.8	F	right	32	39	-7	42	30	12
	13.8	F	left	34	29	5	32	40	-8
16	15.1	F	right	27	30	-3	48	43	5
	15.1	F	left	35	32	3	37	32	5
17	12.4	F	right	28	32	-4	34	33	1
	12.4	F	left	22	24	-2	22	25	-3
18	14.7	F	right	9	15	-6	44	41	3
	14.7	F	left	13	18	-5	46	46	0
19	17.3	F	right	3	10	-7	36	34	2
	17.3	F	left	11	8	3	37	41	-4
20	8	F	right	17	11	6	25	31	-6
	8	F	left	12	13	-1	13	14	-1
21	14.6	F	right	30	33	-3	45	45	0
	14.6	F	left	22	27	-5	29	33	-4
22	15	M	right	23	33	-10	28	29	-1
	15	M	left	29	34	-5	28	31	-3
23	10.9	F	right	5	4	1	17	23	-6
	10.9	F	left	4	5	-1	6	12	-6
24	13.4	F	right	18	28	-10	43	40	3
	13.4	F	left	16	21	-5	46	45	1
25	14.2	M	right	1	9	-8	42	35	7

Table 1 (continued)

ID	AGE	SEX	SIDE	FT CT SCAN	FT LDBR	FT difference	TT CT SCAN	TT LDBR	TT difference
	14.2	M	left	3	9	-6	37	30	7
26	14.9	F	right	12	17	-5	44	40	4
	14.9	F	left	15	16	-1	28	24	4
27	10.8	M	right	15	11	4	38	35	3
	10.8	M	left	13	13	0	34	34	0
28	11.5	F	right	14	16	-2	24	22	2
	11.5	F	left	17	17	0	24	23	1
29	14.3	F	right	23	21	2	30	26	4
	14.3	F	left	22	25	-3	29	25	4
30	15.1	F	right	24	25	-1	48	44	4
	15.1	F	left	27	30	-3	43	50	-7

radiography essentially comes from comparison with standard spine radiography [16]. Biplanar radiography greatly reduced the absorbed dose by organs by a ratio of 100 to 600 compared with CT. However, this appears to be the result of theoretical calculations and not true measurement. Also, it appears to compare the dose between 3D modelling from biplanar radiographs of the spine with 3D reconstructions from CT, which are not used in standard scoliosis follow-up. *A contrario*, CT is considered the reference in evaluation of lower limb torsion and protocols have been optimized for minimal irradiation. However, a lower dose of radiation must be sought when acquiring the data necessary for decision making [17]. So, we needed a comparative analysis between biplanar radiographs and CT in this particular indication to assess if introduction of this new modality would not be at the expense of irradiation.

Rigorous comparison of radiation doses between two different modalities using x-rays is quite difficult. Manufacturers only provide dose estimations. The CTDI and dose-length product (DLP) from CT are obtained by calculation, as is the dose area product from radiographs. Furthermore, we cannot compare them directly. The effective dose expressed in sieverts (Sv) is used in radiation protection to estimate the impact of irradiation on the whole body. However, the International Commission on Radiological Protection (ICRP) does not recommend its use in studies of patient exposure. They advise using the absorbed or equivalent dose [18]. Both can be measured and not merely calculated. The limbs are considered to have low radio sensitivity, but in our particular case we also irradiate the hip joint. At the level of the femoral metaphysis and epiphysis are the gonads, which are highly radiosensitive organs in children [19]. Therefore, we targeted the pelvis for our dosimetric analysis. In vitro measurements have shown a dose reduction ratio of 22 for biplanar radiographs compared with CT. In vivo measurements indicate an equivalent skin dose reduction ratio of 32. The difference between the two ratios may arise from the shape of the detectors. Biplanar radiographs need continuous acquisition on the whole pelvis, compared with the 5-cm window acquisition of CT protocol. Inside the phantom, the ionization chamber is a 10-cm long cylinder that collects the dose over its entire length. On a patient, the TLD can be assimilated to a point placed in the centre of the acquisition window of the hip joint (Fig. 3). The ionization chamber probably gives a more accurate estimation of the dose reduction ratio since it collects data from the larger

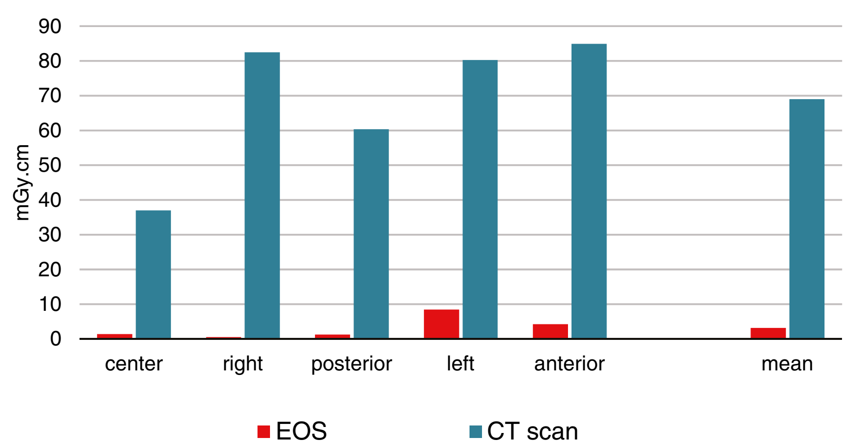

Fig. 5 Ionization chamber measurements in vitro for biplanar radiographs (red) and CT scans (blue) show greater irradiation to the pelvis by CT. Higher values of left and anterior positions are due to the position of the two sources required for biplanar radiography acquisition

irradiation window of biplanar radiographs. Accordingly, with a different and solely in vitro methodology Delin et al. reported similar values of gonad dose reduction, ranging between 4.1 and 24 [20]. Even if the ratio is lower than previous estimations, this still represents a massive dose reduction.

One cost-effectiveness analysis comparing biplanar radiographs with standard x-rays found no evidence of significant benefits in terms of health outcomes. Since the risk of radiation-induced cancer associated with standard x-rays is minor, biplanar radiographs did not give patients a significant health advantage over x-ray from the UK health service perspective [21]. A similar dose reduction ratio (18.8) [7] was used for simulation in this study and most indications concerned scoliosis or other spine deformities. Since we do not repeat measurements for lower limb torsion as often as for spine follow-up, benefits may be minimal in terms of public health. However, the relevance of this kind of analysis varies greatly between countries since the cost of each modality differs from one national health service to another.

A limitation of our study is the small sample size. Also, no patient was younger than 8 years old and the mean age was around 14 years. Nevertheless, some authors describe spontaneous remodelling in most cases below 8 years old and advise postponing surgery until the child is more than 8–10 years old [22]. Fourteen years old is close to skeletal maturity and, for some surgeons, this is the recommended time to proceed with surgery if needed [1]. Also, we did not use a low-dose scanner using iterative reconstruction algorithms. Nonetheless, the expected dose reduction would be between 30 to 80 % [23]. Finally, biplanar radiography requires patients to be still and upright, but this should not influence bone torsion which is independent of posture.

Our study has shown that lower limb torsion measurements obtained with biplanar radiographs are comparable to CT measurements in children and adolescents with a considerable radiation dose reduction. These measurements can be used for planning orthopaedic management.

Acknowledgments We have greatly appreciated the kind help and support of the whole Toulouse children hospital radiology department, especially Barjorie, Barracca, Maryse and Marie Claire.

The scientific guarantor of this publication is Dr Christiane Baunin. The authors of this manuscript declare relationships with the following company: ALRA Expertise. The authors of this manuscript declare no relationships with any companies whose products or services may be related to the subject matter of the article. The authors state that this work has not received any funding. One of the authors Dr Agnes Sommet has significant statistical expertise and provided statistical advice for this manuscript. Institutional Review Board approval was obtained. Written informed consent was waived by the Institutional Review Board. Methodology: prospective, observational and experimental on phantom, performed at one institution.

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