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Different Models of Dual-Energy Bone DXA Scanners: A Comparative Study

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Background. Dual-energy X-ray absorptiometry (DXA) is an effective method for bone mineral density (BMD) and subcutaneous fat percentage estimation. The constant development of new densitometry techniques, the demographic change and the higher potential of artificial intelligence in healthcare enhance requirements for the high-quality measurements in DXA.

This study aimed to develop a quality control method for DXA scanners and compare four DXA systems with different X-ray geometries and manufacturers when simulating fat-water environments.

Methods. We evaluated the accuracy (relative error (ε%) and precision (CV%)) of the bone mineral density (BMD) measurements, performed by the four DXA scanners: 2 with narrow-angle fan beam (64- and 16-channel detectors (DXA-1, DXA-2)); 1 with wide-angle fan beam (DXA-3); 1 with pencil beam (DXA-4). We used a PHK (PHantom Kalium) designed to imitate spine. The PHK contained four vertebras filled with a K_2HPO_4 solution in various concentrations (50-200 mg/ml). The PHK also included paraffin patches (thickness 40 mm) to simulate the fat layer.

Results. DXA-1 and DXA-2 demonstrated the best CV% ranged from 0.56% to 1.05%. The least ε% was observed when scanning PHK with fat layer on DXA-1 and DXA-2 (1.74% and 0.85%) and DXA-4 (1.47%). DXA-3 produced significantly lower BMD (ε = -14.56%, p = 0.000). After removing the fat layer, we observed reduction (p = 0.000) of BMD for DXA- 1 and DXA-2 (ε = -5.11% and -6.12% respectively) and weak deviation (p = 0.80) for DXA-4 (0.87%). For DXA-3, removal of the fat layer also resulted in a significant reduction in BMD (ε = -16.44%, p = 0.000). The subcutaneous fat modeling showed that all these DXA systems automatically determine the percentage of fat in the scanned area with weak underestimation: for DXA-1, DXA-2 and DXA-4 the ε% were -5,9%, -6,3% and -2,3% respectively. CV% were 0.15%; 0.39%; 1.6%, respectively.

Conclusions. We proved a significant underestimation of the BMD measurements across the entire range of simulated parameters for the DXA scanners when the model did not include the subcutaneous fat layer. All models demonstrated high accuracy in measuring the fat layer, with the exception of the DXA-3 model, which was not assessed in these studies.

Keywords: DXA, dual-energy X-ray absorptiometry, densitometry, bone mineral density, osteoporosis, precision, relative error.

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Сравнение двухэнергетических денситометров различных моделей

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Актуальность. Двухэнергетическая рентгеновская абсорбциометрия (ДРА) — это эффективный метод оценки минеральной плотности костной ткани (МПК) и подкожно-жировой клетчатки (ПЖК). Постоянное развитие новых методов денситометрии, старение населения и высокий потенциал применения технологий искусственного интеллекта в здравоохранении усиливают потребности в получении высококачественных измерений МПК в ДРА.

Цель исследования — разработать средства и методы контроля ДРА сканеров и провести сравнение четырех денситометров разной геометрии и фирм-производителей при моделировании различного водно-жирового окружения.

Материал и методы. В ходе работы проведена оценка точности (относительной погрешности (ε%) и воспроизводимости (CV%)) измерений МПК четырех рентгеновских денситометров: два — с узковеерным пучком рентгеновского излучения с 64- и 16 рядами детекторов (DXA-1, DXA-2), один — с широковеерным пучком (DXA-3); один — с пучком карандашного типа (DXA-4). Для сравнения использовался фантом РНК (PHantom Kalium), моделирующий МПК поясничной области: четыре модели позвонков от нормы до остеопороза, содержащие гидрофосфат калия в различной концентрации — 50–200 мг/мл. РНК также включал парафиновые накладки (толщиной 40 мм), имитирующие ПЖК.

Результаты. DXA-1 и DXA-2 имеют наилучшую CV%, определенную в диапазоне от 0,56% до 1,05%. Наименьшая ε% отмечена при сканировании РНК с ПЖК для DXA-1 и DXA-2 (1,74% и 0,85%) и DXA-4 (1,47%). При исключении ПЖК наблюдаются снижение МПК для DXA-1 и DXA-2 (ε = -5,11% и -6,12% соответственно) и небольшое отклонение (p = 0,80) для DXA-4 (ε = 0,87%). DXA-3 демонстрирует существенно заниженные данные измеренной МПК (ε = -14,56%; p = 0,000) при сканировании РНК с ПЖК. Однако исключение ПЖК также приводит к значительному (p = 0,000) снижению МПК (ε = -16,44%; p = 0,000). При анализе точности определения жирового слоя для DXA-1, DXA-2, DXA-4 отмечалась незначительная недооценка заданных показателей на -5,9%, -6,3% и -2,3% соответственно. При этом CV результатов составила 0,15%; 0,39%; 1,6%.

Заключение. Результаты исследования подтвердили значительную недооценку МПК для всего диапазона возможных значений при сканировании РНК без ПЖК. Модели продемонстрировали высокую точность измерения жирового слоя за исключением DXA-3 сканера, для которого этот параметр в исследовании не оценивался.

Ключевые слова: ДРА, двухэнергетическая рентгеновская абсорбциометрия, денситометрия, минеральная плотность кости, остеопороз, воспроизводимость, относительная погрешность.

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BACKGROUND

Dual-energy X-ray absorptiometry (DXA) is an effective method for bone mineral density (BMD) and subcutaneous fat percentage estimation. High-accuracy measurement of BMD is considered an important criterion to diagnose osteoporosis and to monitor the treatment progress [1]. The International Society for Clinical Densitometry (ISCD 2019) suggests assessing the precision in volunteer studies by calculating the least significant change (LSC) using the ISCD calculator [2]. A similar approach (involving the LSC calculation) was suggested for cross-calibration of various scanner models. The suggestions also addressed phantom studies, recommending to assess the stability of the scanner performance in general and when replacing scanners with similar models. Fat layer measurements are relevant for body composition estimation that is recommended for children, the diagnosis of sarcopenia, and other diseases [3].

The comparison of DXA scanners about the measurement accuracy and phantom studies designed to assess various scanner models has been conducted during the entire DXA history [2, 4, 5, 6]. However, recently, there has been growing interest in precision assessment. Firstly, it is associated with the constant development of new densitometry techniques that requires providing comparisons with previous methods [7]. Secondly, the population becomes older, and with that, the distribution of this technique and its application rise [8]. The suggested resupply of the DXA equipment to meet the European targets (1 scanner per 100 thous. people) would secure population coverage with the screening measures based on the risk factors and treatment monitoring needs [9]. Thirdly, the higher potential of artificial intelligence in healthcare requires receiving robust medical data for using it in a decision support system, to provide patient-oriented medicine [10, 11], and for providing the population studies by osteoporosis.

Following the European Union initiative, the Committee d'Actions Concertes — BioMedical Engineering (COMAC-BME) developed a procedure to improve cross-calibration and enhance the BMD measurement standards that utilize semi-anthropomorphic phantoms (ESP — European Spine Phantom) [12, 13]. Some phantoms contain as well as test objects for BMD modelling, a permanent fat layer. For example, the standard ESP configuration is designed to simulate a 9% fat layer [14], whereas Bona Fide Phantom, BFP simulates a 26% fat layer [15]. However, the embedded fat layer of these phantoms cannot be modified. Although this phantom was presented in many studies, its construction doesn't allow adding or deleting a fat layer. The above makes it reasonable to compare the measurement technique of various DXA scanners to assess the impact produced by the fat layer and to obtain data on CV precision and accuracy when modelling fat-water environments.

Our study aimed to compare the accuracy and precision parameters for BMD and fat percentage measures acquired by four DXA scanners using a self-developed phantom solving the describing above limitations. During our study, the alternative phantom was presented and the precision and accuracy parameters of four DXA scanners were measured and compared.

METHODS

PHK phantom

A detailed description of the PHK (Phantom Kalium) is available in the previous paper [7] (Fig. 1).

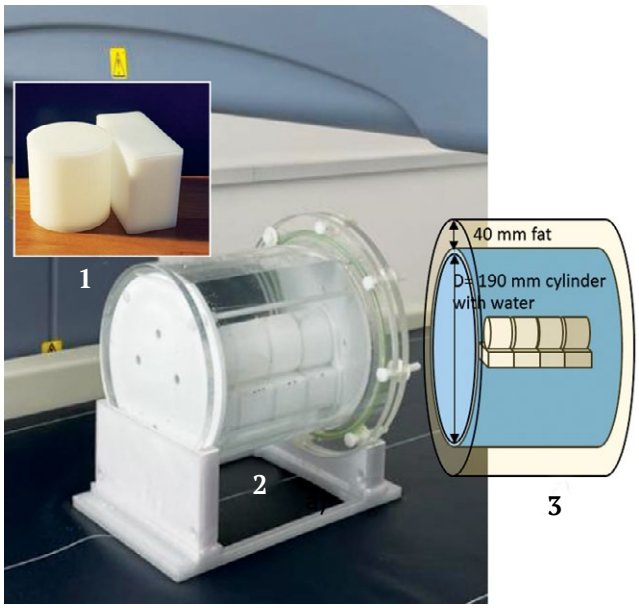

Fig. 1. PHK design:
1 — vertebrae section made of a cylinder that simulates the vertebra body, and a parallelepiped imitating a cortical layer;
2 — during the w/ fat scan the 'vertebrae' were placed inside a cylinder with a diameter of 190 mm filled with water;
3 — around the cylinder walls it was possible to place 40 mm thick paraffin patches to simulate the fat layer

The phantom is designed to simulate the lower back region. Depending on the configuration, the phantom body can be made of polypropylene or polymethyl methacrylate (to results presented in this paper were obtained using a polypropylene phantom. The phantom is cylinder in shape with an internal diameter of d = 190 mm and length 230 mm. Wall thickness — 5 mm. Using high-precision milling on ultra-high-molecular-weight polyethylene fiber we made 4 vertebra models consisting of a cylinder (a vertebra body) and a parallelepiped (a cortical layer).

The vertebrae sections are filled with a dipotassium phosphate solution (K_2HPO_4) in various concentrations. Table 1 contains set values of volumetric BMD and projected areal density (cylinder + cortical layer). The "vertebra" area of 17.5 cm^2 is defined by the area of a parallelogram pertaining to a denser cortical layer. According to the evaluation of the expanded uncertainty for the set values the error for the set volumetric BMD is ± 0.21%; projected areal density — ±0.9%. The highest difference between the volumetric and set BMD values for both L1 sections is 0.26%. The accuracy of the set BMD values for this phantom is as good as that for ESP phantoms. The PHK phantom can be used both for DXA measurement accuracy evaluation and for QCT. To simulate the fat layer, we used 40 mm thick circular paraffin patches that covered completely the phantom outer side (See Fig. 1). During the imaging with fat condition, the fat percentage was 32.14%; for scanning without fat, it was 5%, due to consideration of the thickness of the polypropylene wall in the fat percentage.

Table 1

The PHK features for set volumetric and projected BMD

Vertebra	Set volumetric BMD (cylinder), mg/mL	Set volumetric BMD (cortical layer), mg/mL	Set projected BMD, g/cm^2	Set T-score for Lunar DXA, SD
L1	50.13	250.65	0.586	-5.08 (osteoporosis)
L2	100.19	350.79	0.886	-2.58 (osteoporosis)
L3	150.38	450.10	1.177	-0.16 (normal)
L4	200.49	551.21	1.475	2.33 (normal)

Scanning technique

The phantom study was performed using DXA scanners with four different types of fan beam:

– two DXA scanners with narrow-angle beam and a detector array: 64-channel detector Lunar iDXA (hereinafter – DXA-1) (GE HealthCare, USA); 16-channel detector (DXA-2) (Lunar Prodigy, GE HealthCare, USA);

– one DXA scanner with wide-angle beam (DXA-3) (Discovery, Hologic Inc., USA);

– one DXA scanner with pencil beam (DXA-4) (DEXXUM-3, OsteoSys Co., Ltd., Republic of Korea).

The imaging was performed using the standard clinical protocol. The phantom scanning technique is described in previous studies [4, 16]. Each phantom scan was repeated five times for each of the two configurations: with (w/) and without (w/o) fat layer.

During the image processing, the automated segmentation was corrected manually (since there was no high X-ray density layer, the automated segmentation showed lower reliability) which eliminated the possible bias [7]. The rectangular configuration of the cortical block allowed to perform the correction effectively (Fig. 2). In addition, as per the DXA scanning procedures, we have been recording the results of the fat percentage estimation in the regions that imitated soft tissues.

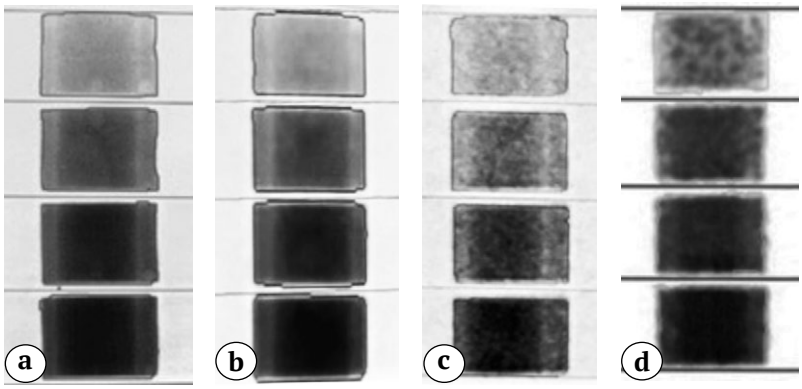

Fig. 2. The images were obtained from a PHK phantom w/o fat using the following DXA scanners:
a — DXA-1; b — DXA-2;
c — DXA-3; d — DXA-4

Evaluation of accuracy (precision and relative error)

When comparing the DXA scanners, we analyzed the following results of the DXA study: the area, the bone mineral composition (BMC), and the derived areal BMD (calculated as the ratio between BMC and the object area). The measurement was performed for each vertebra section and the average scores for L1–L4.

Following the results of the five-fold scanning, we calculated an average value ($\overline{BMD}_{L1-4}$) and a standard deviation (SD_{L1-4}) that were later used to access the study accuracy scores: precision (CV%, formula 1) and relative error (ε%, formula 2):

$$CV = \frac{SD_{L1-4}}{\overline{BMD}_{L1-4}} \times 100\%, \quad (1)$$

where:

SD_{L1-4} — standard deviation,

$\overline{BMD}_{L1-4}$ — average BMD values for L1-4;

$$\varepsilon = \frac{\overline{BMD}_{L1-4} - BMD_0}{BMD_0} \times 100\%, \quad (2)$$

where:

BMD_0 — average BMD values for L1-4 set during the making of the phantom;

$\overline{BMD}_{L1-4}$ — average BMD values for L1-4.

Considering that the measured BMD, BMC, and the area values are linearly dependent from the set values, to compare the measurements from different DXA scanners we analyzed the corresponding linear approximation parameters. The comparison was performed using the generalized linear model (GLM) method for w/ and w/o fat conditions. A significance level was set to <0.05.

RESULTS

Figure 2 shows images, obtained from a PHK phantom w/o fat. The borders that surround the BMD measurement area were corrected manually.

Figure 3 shows graphs of BMD measured with different DXA scanners using the PHK phantom in w/ and w/o fat configurations. It shows the mean values, which are ± 2 SD for each L1-4 vertebra model.

For the Lunar DXA scanners (DXA-1 and DXA-2), the CV,% during the scanning w/ fat was 0.68% and 1.0%, and 0.56% and 1.05% w/o fat, respectively. The mean ε,% for the DXA-1 and DXA-2 w/ fat was 1.74% and 0.85% (Table 2). The measured BMD values were lower w/o fat and the average ε values were -5.11% and -6.12% for the DXA-1 and DXA-2, respectively. The lower BMD for the DXA-1 and DXA-2 were significant (p = 0.000 for both models), as determined by the multiple regression for w/ fat scans. This underestimation was caused by a significant decrease in BMC measurements (p = 0.000 for both models), while no significant differences in the area measurements were observed (p = 0.430 for the DXA-1 and p = 0.360 for the DXA-2).

The Hologic DXA scanner (DXA-3) generated reproducible data during w/o fat scans (CV = 0.91%) and less precise data for w/ fat scans (CV = 2.60%) (See Table 2). Assessment of the relative error for the DXA-3 indicates a significantly lower BMD across the entire range of values: the mean ε% were (-16.44%) w/o fat and (-14.56%) w/ fat (See Fig. 3c). This model showed a significantly lower BMD (p = 0.000) w/o fat, due to a significant decrease in BMC (p = 0.000), without a significant underestimation of the measured area (p = 0.220).

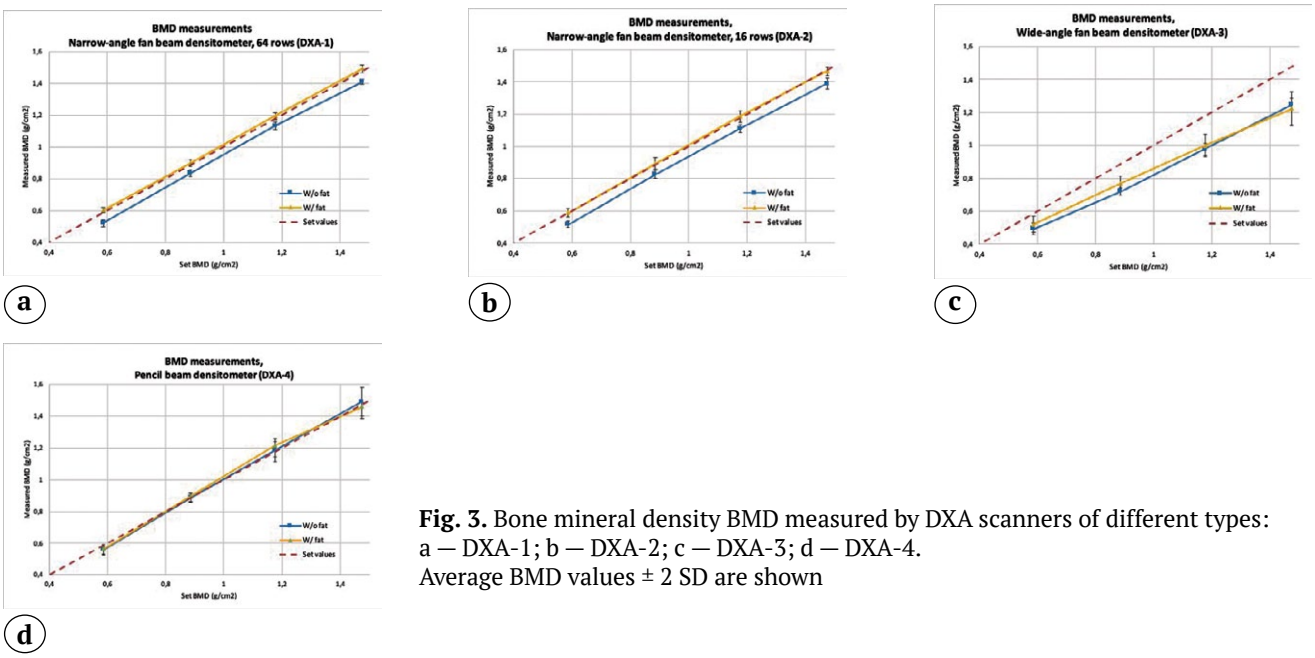

Fig. 3. Bone mineral density BMD measured by DXA scanners of different types:
a — DXA-1; b — DXA-2; c — DXA-3; d — DXA-4.
Average BMD values ± 2 SD are shown

Table 2

Specified values, precision (coefficient of variation CV), accuracy (relative error ε) of BMD, BMC, and areas for various models of DXA scanners (mean values for L1-4), calculated using the formulas 1, 2

Set values	DXA scanner	Measured mean values (L1-4)		Precision, CV% L1-4, %		Accuracy, relative error (ε), %	
		W/o fat	W/ fat	W/o fat	W/ fat	W/o fat	W/ fat
BMD, g/cm^2 1.031	DXA-1	0.978	1.049	0.56	0.68	-5.11	1.74
	DXA-2	0.968	1.039	1.00	1.05	-6.12	0.85
	DXA-3	0.861	0.881	0.91	2.60	-16.44	-14.56
	DXA-4	1.038	1.040	2.10	1.47	0.71	0.87
BMC, g 72.17	DXA-1	67.73	72.86	0.34	0.85	-6.16	0.95
	DXA-2	66.11	71.47	0.47	0.87	-8.40	-0.97
	DXA-3	58.21	60.91	1.33	1.31	-19.35	-15.6
	DXA-4	67.64	67.88	0.86	0.57	-6.29	-5.95
Area, cm^2 70	DXA-1	69.18	69.45	0.44	0.97	-1.16	-0.78
	DXA-2	68.51	68.74	0.70	0.67	-1.01	-1.78
	DXA-3	67.57	69.17	1.26	2.90	-2.5	-1.18
	DXA-4	65.18	65.29	2.37	1.40	-6.90	-6.73

The OsteoSys DXA scanner (DXA-4) produced fairly low-reproducible results. The CV was 2.10% for w/o fat, and 1.47% for w/ fat condition. At the same time, the measured BMD values closely corresponded with the set values (See Fig. 2 d) for L1-L4: the relative error (ε%) was 0.71% and 0.87% w/o fat and w/ fat, respectively. It should be noted that these scanning modes showed no significant differences in BMD measurements ($p = 0.800$). Also, no differences were observed in BMC values ($p = 0.48$), and in the vertebrae area ($p = 0.870$).

At the same time, both the measured area (on average) and BMC values (6.8%) were underestimated for both scanning options (see Table 1), while the calculated BMD value was close to the set one.

The accuracy of the fat percentage estimation was compared for three devices. The subcutaneous fat modeling showed that all these DXA systems automatically determine the percentage of fat in the scanned area quite well: 30.24 ± 0.05% for the DXA-1; 30.53 ± 0.12% for the DXA-2 and 31.4 ± 0.54% for the DXA-4 (CV% were 0.15%; 0.39%; 1.6%, respectively) for a given 32.14% fat environment, including the paraffin patches and the polypropylene casing. We obtained identical results by scanning the phantom without the patches for all three DXA scanners: 4% with a relative error of 20%.

DISCUSSION

Analysis of the precision (CV%) showed that the lowest CV values (the best reproducibility) were observed for both Lunar DXA scanners: from 0.56% (for the DXA-1 w/o fat) to 1.05% (the DXA-2 w/ fat). The presence of the fat layer simulant contributed to lower precision for the DXA-1 and the DXA-2, an even more significant decrease for the DXA-3 DXA scanner, and a decrease for the DXA-4 DXA scanner (Table 2). Previously we obtained comparable results. Scanning an ESP phantom with similar DXA scanners produced: 0.78% for the DXA-3 (80 measurements, 10 DXA scanners); 2.46% for the DXA-4 (50 measurements, 10 DXA scanners) [4].

According to other data, when scanning the ESP phantom with the DXA-1 and the DXA-2, we obtained the coefficients of variation of 0.42% and 0.50%, respectively [15], which also matches well with our data. In-vivo measurements (30 patients) by Krueger D. et al. produced slightly larger coefficients of variation for these DXA scanner models: 1.81% for the DXA-1 and 1.41% for the DXA-2 [5].

Scanning of the PHK phantom using various DXA scanners showed that the BMD parameters correspond the most with the set values when measured using the DXA-1 and the DXA-2 in the w/ fat mode. According to the scientific papers, scanning of the ESP phantom

produced overestimated BMD values in comparison to the set values for the Lunar DXA scanners, so according to different authors, the BMD value was 11.75% [4], 4.08% [17] in the L1- L3 section. We noted a slight relative overestimation of the measured BMD values (by 0.85% w/o fat and 1.01% w/fat) for the measurements using the DXA-1 DXA scanner compared to the DXA-2 DXA scanner. A similar overestimation by 1.5% was observed for the DXA-1 compared to the DXA-2 in the study in phantoms and in patients earlier [3].

The DXA-3 DXA scanner also showed a significant underestimation of the BMD measurements compared to the set values, both when scanning with and without subcutaneous fat (See Fig. 3c). Without subcutaneous fat, the measured BMD values were slightly lower (-1.9%) compared to the Lunar DXA scanners. According to the scientific papers, the average relative error for the ESP phantom was -3.91% in the L1-L3 section [4].

We obtained relatively elevated (13.71%) BMD measurements for the DXA-2 DXA scanner in comparison to the DXA-3 DXA scanner in the L1-L4 sections. This is in good agreement with the 15.66% difference [4] in the results for similar DXA scanners.

The difference in relative errors for the DXA-1, the DXA-2 and the DXA-3 may be caused by different technologies for bone structure contouring [4]. According to our data, this discrepancy is largely caused by different methods for BMC measurements (See Table 2): the MSC values for the Hologic DXA scanner are lower by 10.9% (without subcutaneous fat) and 14.6% (with subcutaneous fat) compared to the Lunar DXA scanners, although the difference in the determined area is insignificant.

According to our data, the Osteosys DXA scanners ensure the most accurate BMD measurements, regardless of whether the fat simulant was there. However, this was achieved by a systematic decrease both of the area and the BMC values by about 6% with manual adjustments (Table 2). Without an automated adjustment of the area measurements, the ESP scanning with this DXA scanner model produced lower BMC values (by 7%) for the L1-L3 section [2]. This can be explained by an increased area of objects with automatic segmentation and lower BMC values.

A study of 102 patients showed a relative underestimation of the BMD values measured using the DXA-4 DXA scanner compared to the DXA-2 DXA scanner (the same models) [18].

Elevated measured BMD values with an increased fat environment were recorded for DXA scanners when scanning the phantoms [19]. We observed a significant decrease in BMD in patients after different types of weight reduction surgeries [20]. A true decrease in BMD, which may cause fractures as a complication from the obesity treatment, must be differentiated from an artifact decrease in BMD when measuring the volume of fat tissue [21]. Therefore, it is important to determine the relative error when modeling the fat environment.

The study showed that all DXA scanners determine the percentage of fat in the scanned area quite well. When scanning with subcutaneous fat, the volume of adipose tissue is slightly lower by -5.9%, -6.3%, and -2.3% when using the DXA-1, the DXA-2 and the DXA-3 DXA scanners, respectively. When scanning without subcutaneous fat the results were the same across all the devices and studies, therefore the underestimation is 20%. These studies are relevant for estimating the human body composition accuracy (fat, muscles, bones) using modern DXA scanners [14]. This technology is used in paediatrics [22, 23], and the diagnosis of sarcopenia [24]. Cross-calibration of DXA scanners when determining the composition of the human body [25] may be feasible when using a special phantom that simulates the shape of the human body.

The results of this study are perspective also for providing ex-vivo samples experiments based on DXA [26]. On the other hand, the high-accuracy measurements of BMD and fat percentage are seemed to be applied in the decision-making systems including systems based on the artificial intelligence. Robust data develop the prognosis accuracy that is actually in the situation of the life duration increasement.

The developed PHK phantom is limited by its inability to correctly outline the edges of vertebra models in an automatic mode when using the phantom, which calls for manual adjustment. A promising idea is adding high- density boundary inserts to the cortical block models. The study is also limited to four devices. Different devices of these models are required for a more comprehensive understanding of the observed differences.

CONCLUSIONS

The study showed the effectiveness of the developed PHK phantom based on vertebra models using potassium hydrogen phosphate and modeled subcutaneous fat for determining the accuracy of the densitometry studies.

The impact of the fat environment on the DXA studies was evaluated for four DXA scanners (various models and manufacturers). We proved a significant underestimation of the BMD measurements across the entire range of simulated parameters for the iDXA, Prodigy (Lunar GE), and Discovery (Hologic) DXA scanners when the model did not include the subcutaneous fat layer. The Discovery model (Hologic) underestimates BMD compared to the iDXA and Prodigy (Lunar GE) models, which is consistent with

the results of other studies. The BMD values obtained using the Dexxum 3 DXA scanner (Osteosys) showed they were close to the standard, while the BMC and the area were systematically underestimated.

All models demonstrated high accuracy in measuring the fat layer, with the exception of the Discovery (Hologic) model, which was not assessed in these studies.

The best precision was demonstrated by the iDXA and Prodigy (Lunar GE) models (below 1%).

DISCLAIMERS

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Author contribution

Petraikin A.V. — concept and methodology, consulting during experiments, preparing and review of the manuscript.
Akhmad E.S. — data analysis, preparing and editing of the manuscript.
Semenov D.S. — performing experiments, participation in the development of the phantom.
Artyukova Z.R. — accumulate and processing the data of the study, preparing of the manuscript.
Kudryavtsev N.D. — accumulate and processing the data of the study.
Petriaikin F.A. — concept of the study and data analysis.
Nizovtsova L.A. — editing the manuscript.
All authors have read and approved the final version of the manuscript of the article. All authors agree to bear responsibility for all aspects of the study to ensure proper consideration and resolution of all possible issues related to the correctness and reliability of any part of the work.

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