Quantitative data standardization of X-ray based densitometry methods

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Abstract. In the present work is proposed the design of special liquid phantom for assessing the accuracy of quantitative densitometric data. Also are represented the dependencies between the measured bone mineral density values and the given values for different X-ray based densitometry techniques. Shown linear graphs make it possible to introduce correction factors to increase the accuracy of BMD measurement by QCT, DXA and DECT methods, and to use them for standardization and comparison of measurements.

Today the diagnosis of osteoporosis (OP) is a relevant issue in Russia and all over the world. Population studies indicate that every third woman and one of four men over 50 years old suffer from OP. More than 40 % of people of both sexes have signs of osteopenia.

Bone mineral density (BMD) is a quantitative parameter used to estimate bone strength and mechanical properties and, therefore, to determine the risk of fracture. BMD measurement is performed using one of the following X-ray methods: dual-energy X-ray absorptiometry (DXA), quantitative computed tomography (QCT), and a new type of computed tomography (CT) – dual-energy computed tomography (DECT).

The wide dissemination of X-ray based densitometry methods both for the diagnosis of OP and for the control purpose during treatment requires the accuracy and reproducibility of BMD measurements. This leads to the need for standardization of BMD determining methods, developing control methods for cross-calibration, which allows comparing the results of the determination of BMD on different devices and different methods [1].

There are cases of inaccuracies in determination of BMD for DXA associated with the type of used equipment, calibration procedure, as well as anatomical features of the patient [1, 2].

The European Spine phantom (ESP) had been developed in 90s to conduct daily quality control and cross-calibration between different devices [1]. It consists of three sections, each of which has the form of a vertebra with different content of bone minerals. This design solution allowed the use of a standard patient scan protocol for both methods: DXA and QCT.

The ESP phantom was used to compare DXA scanners before and after standardization of measurements [1, 4]. The significant differences in the readings of the scanners and the given BMD, as well as the results of comparison of apparatuses with each other, confirmed the need for standardization of measurements during densitometry. The comparable BMD measurement results
were obtained only after the corresponding adjustments. The use of ESP phantom not only increased the quality of routine diagnostic procedures, but also conducted multicenter clinical studies using cross-calibration procedure.

However, CT image errors from beam hardening and X-ray scatter causing inaccuracy of CT numbers, contrast reduction, and cupping artifacts should be taken into account [3] The ESP phantom does not make it possible to move objects freely, simulating different vertebrae position in the plane of the phantom section, since it is filled with epoxy rubber. Thus, it could not be used for modeling of different X-ray density along the cross section of a cylindrical test object. In addition, composites used in the manufacture as an equivalent of water [1] can cause inaccuracies in the decomposition of BMD at DECT.

In order to overcome these, as well as to perform a comparison of various X-ray methods for determining BMD, a special liquid phantom (SL-phantom) was developed. The SL-phantom has 4 cylindrical plastic “vertebras” bodies (diameter and height 3.5 cm, wall thickness 2 mm), manufactured by the method of three-dimensional printing (figure 1(a)). Cylinders were filled with solutions of dipotassium phosphate of various concentrations. This substance is highly soluble and allows to simulate the BMD in a wide range. A bracket of radiopaque material was designed to provide the “vertebrae” positioning. The phantom was immersed in a tank with a physiological solution simulating a human body with a diameter of 32 cm. The vertebrae could move in the bracket, occupying positions in the center of the cylinder with liquid and around the periphery (12 cm from the center). Dipotassium phosphate concentrations were: 29.4 and 60.3 mg/cm³, simulating OP; 92.6 mg/cm³ for simulating osteopenia; 161.4 mg/cm³ for simulating normal BMD values. Threshold values were chosen based on the recommendation of the WHO and ACR.

The CT images of the phantom at the center (figure 1(b)) and at the periphery of the tank with saline were processed using the QCT-program to obtain the mineral density value. CT study was performed on a 64-row CT-scanner (120 kV, 100 mA, FOV 40 cm, FC08 core), software for determining the BMD (QCT with an asynchronous phantom). DXA was performed on X-ray densitometer. Digital radiography was performed on a routing X-ray DR-scanner. DECT with densitometry was performed on a multirow CT-scanner with a tube voltage modulation (80–140 kV) (figures 2(a)–2(d)).

![Figure 1. SL-phantom: (a) – appearance; (b) – CT-image.](image-url)

In assessing the accuracy of quantitative data, the QCT method was used to determine the linear dependence between BMD and the X-ray density values in the investigated range (see figure 2(a)). However, when the phantom is located in the center of the tank simulating the human body, a systematic overestimation in the density by approximately 10 mg/cm³ was observed, which corresponds to an error of up to 34 % for the “vertebra” of the lowest density. The error in measuring the phantom at the periphery of the container did not exceed 6.6 %. Taking into account the strictly linear dependence of the obtained curves (the determination coefficient was $R^2 = 1.0$), these errors can be eliminated by introducing correction coefficients for the corresponding phantom arrangements.
Figure 2. Dependencies between the measured bone mineral density values and the given values for different X-ray based densitometry techniques: (a) – QCT; (b) – DXA; (c) – digital radiography; (d) – DECT (in (a), (d) – blue in center, orange – in periphery).

The results of the study of the phantom by X-ray radiography are shown in figure 2(c). Linear dependence was established at a voltage of 80 kV. Distortions in the shape of the curve and the angle of inclination were observed when choosing other values of the anode voltage. Thus, it is not possible to select a single calibration curve, which makes it impossible to consider this method as promising taking into account the automatic shooting mode.

When scanning the SL-phantom by the DXA method, a linear dependence of the measured BMD values on the set values was established (see figure 2(b)), $R^2 = 0.98$. The correct results were obtained with a decrease in the liquid layer to 15 cm. The error of the DXA method in absolute value is insignificant; however, in the region of low BMD values (cortical mineral density was not taken into account) it can be up to 65.4%. Thus, the parameters of the patient’s body significantly affect the results of DXA, and in the low-density region the error of this method may increase.

In contrast to the QCT method, the dependency graphs of the DECT BMD have different slope coefficients when positioned at the periphery and in the center (see figure 2(d)). DECT study demonstrated a linear dependence ($R^2 = 0.99$) between determined potassium concentration and its true both in the center of the container and on the periphery without using a special calibration phantom. It was established that the DECT method is the least sensitive to the shape of the human body, and the error of this method does not have a clear dependence on the true BMD. However, in the range of values corresponding to osteoporosis, it is quite significant (up to 21.9%).

It is worth noting that the shown linear dependencies make it possible to introduce correction factors to increase the accuracy of BMD measurement by QCT, DXA and DECT methods, and to use
them for standardization and comparison of measurements. Thus, an increase in the number of patients who have a high risk of osteoporotic fractures leads to the need for timely diagnosis using modern X-ray based densitometry methods: QCT, which allows to measure BMD not only from the healthcare organization’s CT data, but also by opportunistic screening, DECT and DXA.

To ensure the accuracy and reproducibility of BMD measurements, it is necessary to develop control techniques that are carried out with the help of appropriate phantoms. The creation and implementation of the standardization of densitometric studies will allow to assess the reliability of the research conducted on various scanners, to determine the factors that affect the accuracy of measurements, and to make appropriate corrections. In this paper, a phantom prototype is presented. It was used for BMD measurement errors estimation for various X-ray based densitometry techniques.

References
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