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Individual chronobiological control of the reproducibility error by using the DEXA method for evaluation of mineral density in the periprosthetic zone of patients after total hip arthroplasty

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Purpose Using chronobiological methodology and on the basis of individual analysis, to determine the character of changes in the reproducibility error (RE) of double-energy X-ray absorptiometry (DEXA) by assessment of the projection bone mineral density in the Gruen zones in patients after total hip arthroplasty in the early postoperative period. **Materials and methods** Eight men and two women were examined. **Results** RE value was changed in oscillation manner. It was hypothesized that it is caused by tremor. On this basis, a theoretical physical model was proposed which considers the mechanisms of X-ray radiation attenuation by passing through bone tissue. According to the model, the tremor changes the length of X-ray path in the bone tissue. The fact that bone structure is characterized by parts with high and low atom density was taken into account in the model. It is especially strongly manifested in the areas of the trabecular bone. Theoretical modeling allowed us to suggest the physical mechanisms of tremor effect on X-ray radiation passing through bone structures as well as to demonstrate the dependence of the study results on tremor-related spatial vibrations of bone structures. **Conclusions** These findings should be taken into account when investigating the projection mineral density of bone tissue in the periprosthetic zone after hip arthroplasty.

Keywords: total hip arthroplasty, double-energy X-ray absorptiometry, Gruen zones, reproducibility error

INTRODUCTION

Roentgenologic technologies are the basic methods of diagnosis and efficiency control in clinical orthopaedics. One of them is double-energy X-ray absorptiometry (DEXA) that enables to realize an objective quantitative control of projection bone mineral density (PBMD) in the zone of interest, and, in particular, in the periprosthetic zone of the femur in patients after total hip arthroplasty [1, 2]. In every specific case, representation of the study results depends on the reproducibility error (RE) of the method. Therefore, the knowledge of the reason of its occurrence will allow not only an adequate assessment of the results but also a reduction of the risks of unreasonable indications of that or those therapy measures. According to previous studies, the RE can be caused by [3, 4, 5, 6, 7, 8]:

– Intrinsic errors in the complex of software and apparatus [3, 5, 8, 9];

– Specific features of the structure of a study object [5, 10];

– Improper positioning [4, 5, 11];

– Weekly physiological fluctuations in the mineral density caused by metabolic processes [12, 13, 14, 15].

However, the role of patients' individuality on the RE value has not been defined yet. The necessity to establish it has become imminent due to the fact that in the practical conditions of the densitometry chamber and by a strict implementation of the rules of patient's positioning, some patients show considerable outlying PMBD data that are higher than the limit boundaries when the studies are repeated without any change in the body position on the device table. These outlying data cannot be referred to the violations of the position rules as far as the position of the body does not change during the entire study cycle. Our work presents a part of the findings of the study that was conducted for the first time with the use of chronobiological technology and investigated an individual PBMD dynamics in the periprosthetic zone (**Fig. 1**) in patients after total hip arthroplaty in the early postoperative period.

Purpose Using a chronobiological methodology and on the basis of individual analysis, to determine the character of changes in the reproducibility error (RE) of double-energy X-ray absorptiometry (DEXA) by assessment of the PBMD in the Gruen zones in patients after total hip arthroplasty in the early postoperative period.

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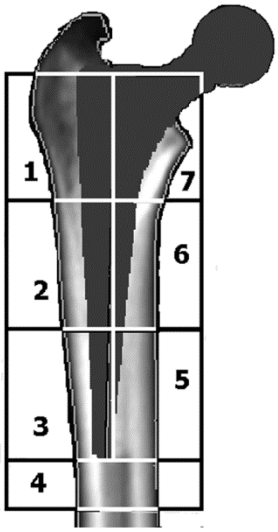

Fig. 1 Diagram image of Gruen zones

MATERIAL AND METHODS

Patients' group included eight males in the age between 54 and 71 years (mean age: 60 years) and two females in the age of 40 and 48 years. Nine patients had total hip replacement due to hip joint coxarthrosis and one was operated due to pseudarthrosis of the left femoral neck. Postoperative period ran without any abnormalities.

Evaluation of BMD in the periprosthetic zone Patients were examined with the PRODIGY (GE Medical Systems LUNAR) densitometer daily at one and the same time from 9.00 to 10.00 a.m. The examination was conducted during 10 days in eight patients and during 8 days in two patients. Densitometric scanning was repeated five times with an interval of 2 to 4 minutes between the scans. The position of the body on the device table did not change.

Voluntary informed consent of patients The preliminary study of the radiation exposure [16] showed that the operating dose of external radiation by densitometry study with the PRODIGY (GE Medical Systems LUNAR) densitometer is relatively low and corresponds to the average level of a daily natural radiation [5, 6]. These data were presented to the Ethical Board of the Vreden Scientific Institute for Traumatology and Orthopaedics and its permission was obtained to conduct this densitometry study. Written informed consents of 10 participants of the study were received.

Statistical processing of the findings Based on the examination of each patient, values of average mineral density in every Gruen zone were calculated and findings of every study were presented in percentage from these values. Then the results of each of the five repeated findings were defined as a mean squared deviation (σ) and the width of the reliable interval 4σ in each Gruen zone was determined on every study day in each patient. In fact, this index is an RE of the method for every day of patient's study. Wilcoxon-Mann-Whitney U-test was used for a statistical check of the hypothesis on the uniformity of two samples (difference in the means for independent samples).

Statistical mathematical modeling On the basis of the results obtained by examination of each Gruen zone, dynamic rows were formed that approximated by the polynominal spline of fourth order and statistical mathematical models were built (significance level $p < 0.05$) of the oscillation curve with the approximation parameters $p=0.95$. Average period of RE oscillation was assessed.

RESULTS AND DISCUSSION

This study of PBMD in the periprosthetic zone in the patients with total hip arthroplasty established that the RE of the DEXA method (**Fig. 2**) is characterized by the following:

– Its value changes in the oscillation manner;

– RE fluctuations have an individual character and their amplitude does not exceed 10% in the majority of cases;

– by comparison of the Gruen zones between each other, it was revealed that RE fluctuations happened with a shift in a phase in 9 patients while the fluctuations were synchronized in phase in one patient (patient 5) with a maximum RE amplitude that reached 30%.

The analysis of RE values (**Table**) showed that their value is within 5% limit. It exceeded 10% only in 4 subjects.

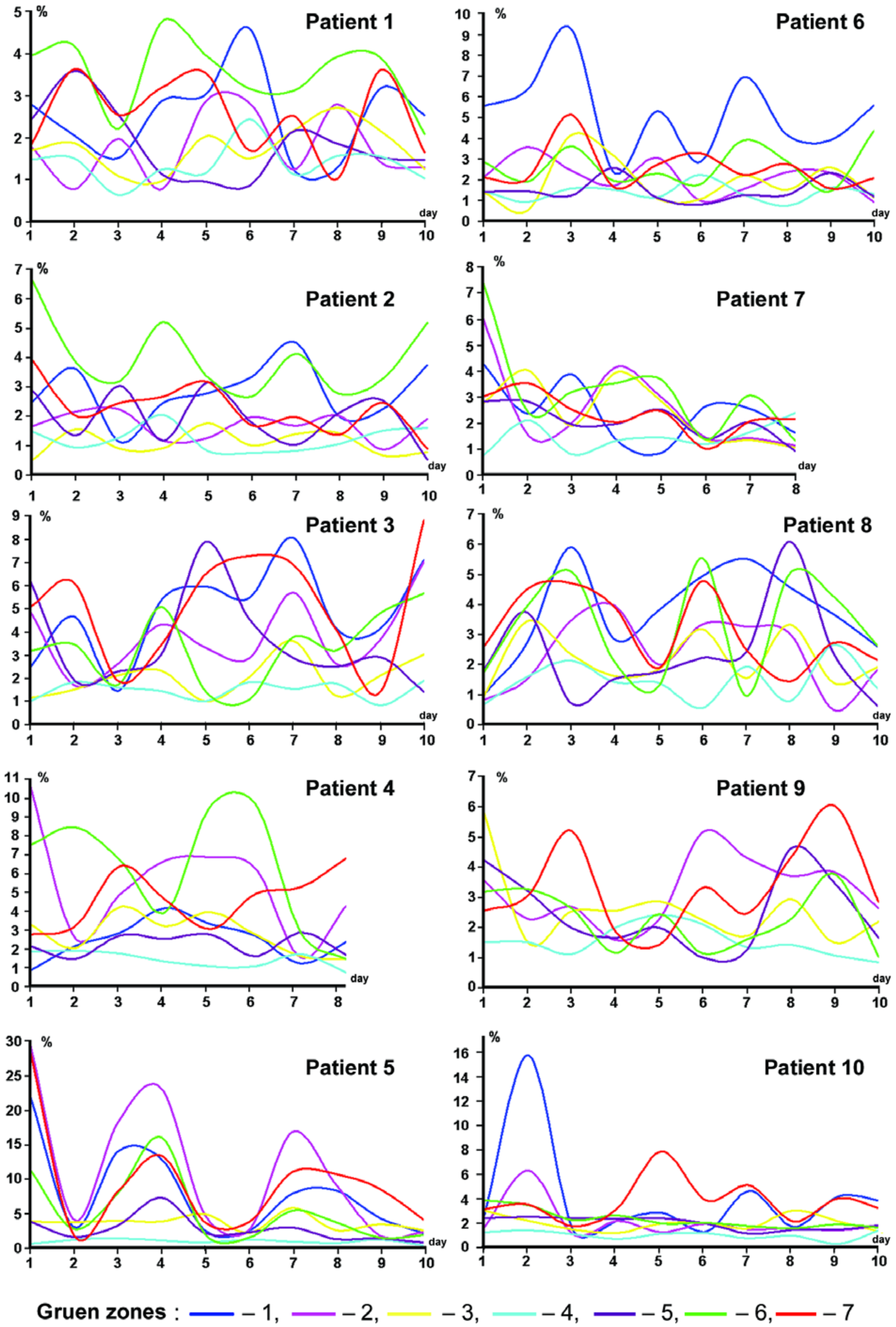

Fig. 2 Individual characteristics of RE oscillation by determination of PBMD in the Gruen zones with DEXA method in patients after total hip arthroplasty in the early postoperative period

Table

Incidence of different RE values by individual analysis (%)

RE value	Patients									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Up to 1.0	11.4	21.4	5.7	3.6	8.6	8.6	8.9	14.3	4.3	10.0
1.1–2.0	41.4	35.7	28.6	28.6	18.6	40.0	39.3	28.6	32.9	47.1
2.1–3.0	25.7	21.4	18.6	25.0	18.6	28.6	30.4	22.9	32.9	24.3
3.1–4.0	17.1	14.3	11.4	10.7	15.7	8.6	14.3	17.1	14.3	10.0
4.1–5.0	4.3	2.9	11.4	10.7	7.1	4.3	3.6	10.0	7.1	4.3
5.1–6.0	–	2.9	10.0	1.8	2.9	5.7	1.8	5.7	8.6	–
6.1–7.0	–	1.4	7.1	10.7	–	2.9	–	1.4		1.4
7.1–8.0	–	–	4.3	1.8	4.3	–	1.8			1.4
8.1–9.0	–	–	2.9	1.8	4.3	–	–			–
9.1–10.0	–	–	–	3.6	1.4	1.4	–			–
10.1–11.0	–	–	–	1.8	2.9	–	–			–
11.1–30.0	–	–	–	–	15.7	–	–			1.4

It was required to answer the following questions by explanation of the occurrence of the phenomena described above:

– What mechanism initiates RE change in the oscillation mode?

– Why are the RE values shifted in phase in the majority of patients by comparison of the study results in the Gruen zones while they are synchronized in phase in one patient with the maximum RE amplitude of RE wave fluctuation?

– Why do the RE oscillation values not exceed 5% in some patients while they are much higher in others?

To answer these questions, one should first consider a possible influence of each of the reasons of RE occurrence mentioned above.

Reproducibility error in the complex of soft-ware and apparatus by the study of the phantom Lunar Prodigy (version Encore) (Prodigy) was assessed basing on the many-years studies of the phantom supplied with the device. It was established that its maximum value is 0.4% and it does not change during the entire period of operation [8].

Influence of physiological fluctuations of the mineral density caused by metabolic processes on the RE value was shown earlier [13, 14, 15, 17]. Though these studies referred only to circaseptan periodicity of the changes in the metabolic activity of the skeleton, it is obvious that mineral density of bone structures should change also in other scaling of time correspondingly to the spatial and temporal organization of the organism. However, it is doubtful that the metabolic processes could cause local changes in mineral density by 5% and more during 5 minutes in the Gruen zones that are situated close to each other. This doubt is first based on the fact that such effects have not been described by the literature and, second, the mechanisms that are able to cause them have been still unknown.

Influence of study object features and improper positioning The proximal femur has a more complex and flattened organization with different protrusions in the Gruen zones while the distal femur is of a simpler cylindrical organization. Moreover, the spatial sizes of these protrusions are individual in each patient. Therefore, they also differ in the projection on plane. As a result, due to the change in patient's positioning with femoral bone rotation, RE is higher in the proximal parts and lower in the distal ones [6, 7, 11], and may reach 74.5% [6].

Hypothesis on the causes of RE value oscillation in the periprosthetic zone While formulating the hypothesis we considered the following facts:

Repeated studies in each time-point were conducted without the change in the positioning, that is the patient was in one and the same position during the entire study time (about 20 minutes);

Change in the RE values occurs in the oscillation mode;

RE values are higher in the proximal parts then in the distal ones;

RE oscillations by the study of different Gruen zones have an asynchrony character in 9 patients while they are synchronized in phase with the maximum RE value in one patient.

Having considered the above stated, it was logical to suppose that by the occurrence of oscillation changes in RE the magnitude of spatial shifts of bone structures in the zones of interest should change in a similar manner. In order to reveal the mechanisms that cause spatial shifts we analyzed the literature and on its basis we came to a supposition that they occur due to muscle tremor.

Theoretical substantiation of possible effect of the physiological muscle tremor on the RE value

Tremor is an involuntary oscillation of limbs with synusoidal features [18]. It is hardly visible with eyes and consists of two different oscillations measuring from eight to 12 Hz that are added on the background of irregular oscillation muscle contractures and limb shifts [19]. Physiological tremor is hardly notable in young healthy persons and its mean amplitude is from one to 3 mm [20]. By aging and under the influence of surgical trauma, the amplitude may increase significantly [19, 20]. As **Figure 3** shows, numerous muscles that provide hip joint functions as well as the complexity of their attachments suggest that their contraction should cause various types of deformities in different parts of the femur. The fact that tremor causes deformities of bone structures was confirmed by W.C. de Jong and co-authors [21] who, by daily monitoring of frequencies of bone structure deformities, revealed the expressed peaks in the zones ≈5 Hz, ≈9 Hz and ≈13.0 Hz. The authors noted that bone deformations[1] with frequency of ≈9Hz have a cyclic character and, in the authors' opinion, are caused by the physiological tremor of muscles that is characteristic for all superior vertebrates.

According to the authors, the surface of bone is subjected to $2.9 \pm 1.4 \times 10^3$ events of deformations per hour. Having considered these data, we developed a theoretical and physically substantiated model that describes the tremor effect on RE of the DEXA method.

The theoretical model deals with the issues of attenuation of roentgenologic radiation by its way through the bone tissue. In general, this attenuation is provided with three mechanisms: reflection from its surface, dissipation and absorption. Reflection from the bone surface is commonly neglected by the use of X-ray absorption spectroscopy for studying spatial distribution of the atom density in the bone tissue. In this case, the relation of the intensity of the falling (I_0) and passed (recorded) (I) radiation is determined by its absorption (attenuation) in the bone tissue and depends upon its quantity: $I = I_0 e^{-\mu x}$. In the formula, μ is a linear coefficient of absorption that is determined by the density of bone tissue atoms and x is the length of the X-ray way in the chosen direction of its study. If x is permanent, then the measurement of the radiation absorption coefficient enables to define the atom density along the direction chosen.

Tremor changes the length of the way x of the recorded radiation. In *in-vivo* model, the value x becomes an oscillation variable that may be described with the formula: $x(\Omega) \approx x_0 + \Delta \sin \Omega t$, where x_0 is an average length of the X-ray way in the bone tissue in the chosen direction in view of tremor, $\Omega \approx 9$ Hz is a corresponding frequency of oscillations, and Δ is an amplitude of changes in the length of the path due to tremor. As it was noted above, the value Δ depends on the patient's condition and experiences weekly variations with frequencies ω_j. Taking into consideration the tremor and low frequency changes in its amplitude, the intensity of the recorded radiation could be presented in such a way:

$$I \approx I_0 e^{\ \mu x_0} e^{\ \Theta(\omega)} . \qquad (1)$$

Tremor factor $e^{-\Theta(\omega)}$ appears only in *in-vivo* model and describes the decrease in the radiation intensity caused by tremor. This factor depends on the index

$$\Theta(\omega) \approx \tfrac{1}{4} \mu^2 \sum_j \Delta_j (\omega)^2 . \qquad (2)$$

In the formulas (1) and (2), weekly fluctuations of the amplitude of tremor oscillations have been considered. According to the assumptions of this work, it is $e^{-\Theta(\omega)}$ that is responsible for the RE oscillations presented in **Figure 2**. The analysis of the tremor factor effect requires further studies. First of all, a Fourier-analysis of the measured PBMD should be conducted.

Due to the fact that bone architecture is characterized by the areas of high and low atom density as well as taking into account the proportionality of the value μ of atom density, we can see that tremor may cause considerable deviations in the bone tissue density that is to be determined. Thereby, the value Δ, and consequently the factor $e^{-\Theta(\omega)}$ depend upon the direction of the X-ray relative the study object, Gruen zone and patient's condition.

Brief discussion of the data obtained with the presented model As seen on the diagrams, RE oscillations in the Gruen zones ran with the shift in phase (asynchrony) in the majority of cases (nine patients from the total of 10), and were synchronic in one patient. Moreover, the amplitude of RE oscillations in this patient was maximal and reached 30%. One can suppose that the shift in phase was caused by an asynchronic occurrence of tremor in various muscle groups that are attached to the proximal femur (**Fig. 3**). And on the contrary, the effect of RE oscillations under tremor is probably associated with the peculiarities of the surgical trauma in the patient that provided a synchronic tremor of muscle groups that cause rotation of the femur. The phenomenon should be further investigated as far as it may appear to be a considerable diagnostic and prognostic event.

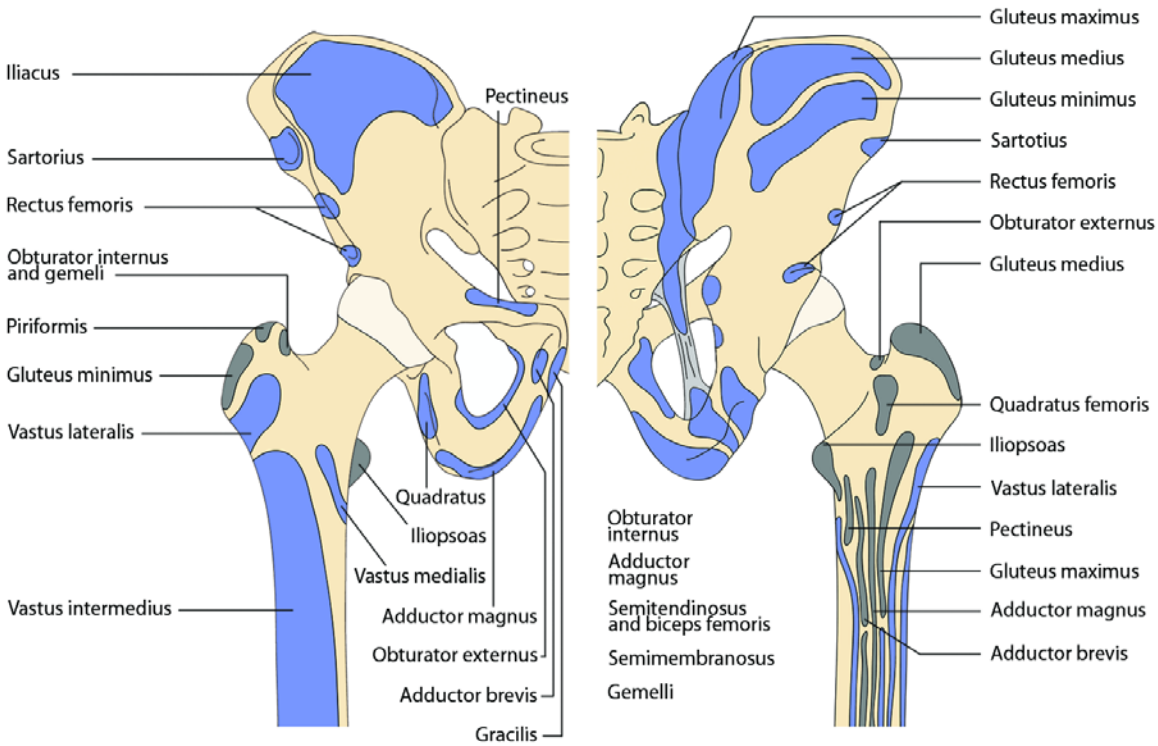

Fig. 3 Muscle attachment sites in the region of pelvic bone of the proximal femur: **a** front view; **b** rear view [22]

CONCLUSION

Possible influence of tremor on the reproducibility error (RE) value should be considered in the study of projection of bone mineral density (PBMD) with the double-energy X-ray absorptiometry (DEXA) method.

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