Assessment of Bone Mineral Content of Lumbar Vertebrae by Radiographic Densitometry

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X線写真濃度測定による腰椎の骨塩定量

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単純X線写真の濃度を測定することにより，腰椎の骨塩含量をアルミニウム当価として求める方法を研究した．Aluminium step のフィルム濃度が，フィルムの特性曲線の直線部分（濃度が0.8～2.1の範囲）に入ることが，よい検量線を得る必要条件と考え，種々の撮影条件に対して許容できるファントム厚さの範囲を設定する方法を一般化して示した．その結果に基いて，患者の各グループ—性・年齢・mineral loss の有無の点から3つのグループに分類—に最適な撮影条件を定めた．Contrast と aluminium step の厚さの関係を骨塩含量を推定するための検量線として用いたが，最適条件で撮影した場合，ファントムの厚さにほとんど左右されない検量線が得られた．軟組織の厚さの推定—本研究では intervertebral canal の写真濃度によつた—のもつ誤差の影響を少なくすることができる．なお，この検量線は，写真濃度と aluminium step の厚さの関係に比べて，長期にわたる再現性においても優れていた．

本法の再現性は，剖検時に摘出した腰椎を2週間にわたり11回測定して検討したが，変動係数として4～6％（腰椎のアルミニウム当価は3～4 mm）であつた．現在まで若干の正常例と60例以上の osteoporosis と診断された患者を対象に測定した．正常例4例の第3腰椎のアルミニウム当価は平均して約12mm であり，骨粗鬆の進んだ患者では 3mm 前後のものも多くみられた．

Introduction

Quantitative knowledge of the bone mineral content of lumbar vertebrae is expected to provide a useful clinical information. Although some methods which measure bone mineral content in vivo have been developed and widely applied to the bones of extremities, far less adaptation has been reported for axial skeleton. To the authors' knowledge, the measurement of vertebral bone mineral content has been made by radiographic densitometry employing simultaneous exposure technique[1-3], and by dual photon absorptiometry using ^{241}Am and ^{137}Cs sources[4].

In most method of radiographic assessment of bone mineral content, the film density on the bone image is directly compared with that produced by an absorption standard which is radiographed simultaneously. It poses some difficulties when the absorber thickness is not known accurately as in the case of the measurement of vertebral bone mineral content. The surrounding soft tissue and phantom of the same thickness do not always produce the same film density due to the difference of the relative proportions of lean soft and adipose tissues. This makes it difficult to adjust the thickness of phantom in which calibration standard is contained, and to correct the soft tissue absorption of a patient.

In this paper, some improvement will be described for the radiographic densitometry of lumbar vertebrae.

Method

Patients and absorption standard phantoms were radiographed not simultaneously on separate films. The problems contained in the non-simultaneous exposures were solved by radiographing with "optimum exposure technique" and by the improvement in data analysis.

1. Procedure

Patients were radiographed on lateral projection with the legs bent. The phantom consisted of a series of polyacrylate plates of 10 mm thickness. An aluminium step wedge, each step of which was 1 mm thickness, was used as a calibration standard of bone mineral content. It was embedded in the phantom so as to its height above the X-ray table was the half of the phantom thickness.

For purpose of standardization, the same X-ray unit with the inherent filtration of 2 mm aluminium has been used throughout this work. SAKURA Q type medical X-ray film was used with KYOKKO MS intensifying screen and Bucky diaphragm. The focus-to-film distance was kept to 100 cm. The film was processed soon after the exposure with high speed automatic equipment. For non-simultaneous exposure technique, it was found necessary to use the same cassette with an intensifying screen to obtain good consistency and reproducibility of film density.

The X-ray beam was adjusted to the size of 10 by 30 cm on the film to reduce the scattered rays. Unevenness of film density on this narrow field, especially on the transverse section, was improved by attaching a polyacrylate filter (Fig. 1a) to the exit side of X-ray tube (Fig. 1b). The filter was designed after trial and error. The similar type of filter has been reported by Meema et al.[5]. The film density patterns on the transverse section with and without the filter are compared in Fig. 2. The unevenness of basic film density within the region of 3 to 4 cm distance from the center was less than ±0.01, which was small enough in practice. A film density on longitudinal section was also uniform within the region of 6 to 7 cm distance from the center. As the width of one aluminium step is 12 mm on the film, 5 steps around the centered one were considered acceptable as calibration standard.

2. Evaluation of optimum exposure technique

The tube voltage was kept to 90 kV, and the tube current (mA) and exposure time (sec) were controlled to obtain good contrast.

A practical characteristic curve of the X-ray film has been prepared by radiographing phantoms of various thickness. The curve was nearly straight between the density of 2.1 (D_{MAX}) and 0.8(D_{MIN}) (Fig. 3), and this region was considered as the optimum range for densitometry. When the film density on the image of steps falls in this range, linear calibration curves with maximum contrast (slope) could be obtained. This is shown schematically in Fig. 4. Slight perturbation would occur due to the film characteristic. Over- and under ex-

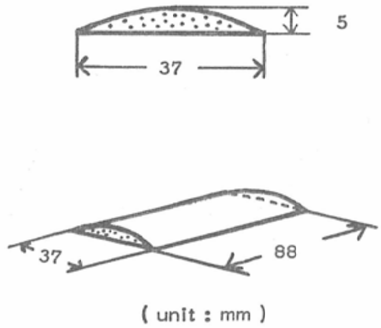


Fig. 1. a) Polyacrylate filter designed to correct the unevenness of the film density.

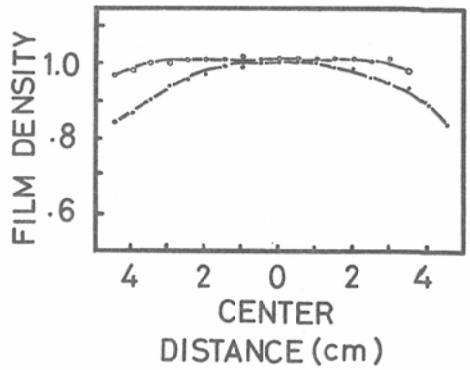
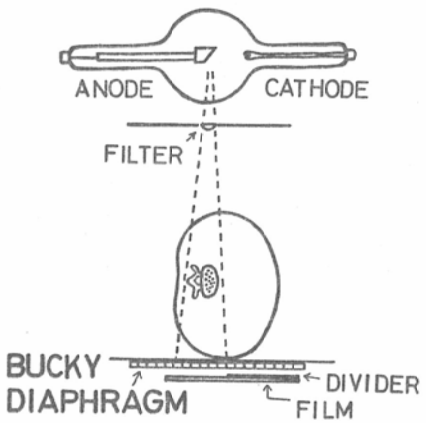


Fig. 2. Basic film density patterns on the transverse section with (open circles) and without (closed circles) the polyacrylate filter. The film density at the center was normalized to 1.00.



b) Diagram of positioning apparatus and lumbar vertebrae. The polyacrylate filter was attached to the exit side of X-ray tube. Focus-to-film distance is 100 cm.

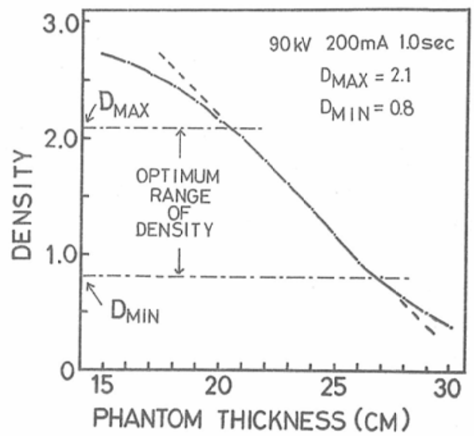


Fig. 3. Absorption standard curve. Straight line part was considered as the optimum range of density.

posures cause the decrease in contrast as shown with the curve A and Curve B, respectively. The tube exposure should be controlled so as to avoid these over- and under- exposures.

The acceptable range of phantom thickness for an exposure technique has been derived on the basis of the characteristic curve. The procedures are shown illustratively in Fig. 5. An aluminium step was divided into two groups for practical use, 1 to 10 mm and 8 to 18 m. The contrast by an aluminium step was represented by the value of 0.045 per step. Ranges of basic film density were calculated from the value of D_{MAX}, D_{MIN} and the contrast of aluminium steps. For the 1-10 mm group, maximum basic film density is $D_{MAX}+0(=2.1)$, and the minimum basic film density is $D_{MIN}+0.45(=1.25)$. For the 8-18 mm group, the minimum basic film density is $D_{MIN}+0.8(=1.6)$. The minimum phantom thickness for this group is estimated by subtracting 1.8 cm, which nearly corresponds to the 8 mm aluminium, from the phantom thickness providing the basic film density of D_{MAX}. The acceptable range of phantom thickness can be evaluated by reading the value on the abscissa for the

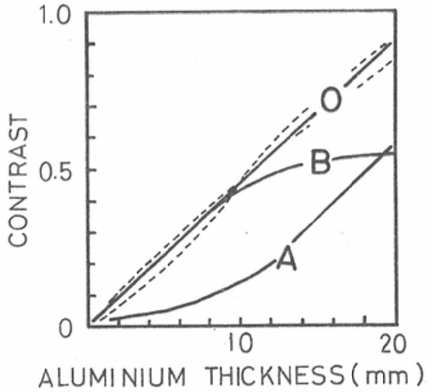


Fig. 4. Schematic diagram showing the relation between the contrast and aluminium thickness. Curve O is obtained in case the film density on the whole steps falls in the "optimum range of density". Curve A shows the over exposure for thin aluminiums, and Curve B the under exposure for thick aluminiums.

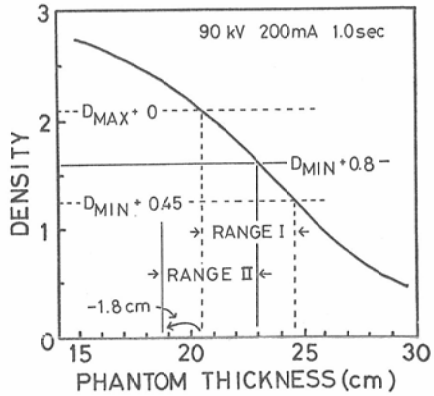


Fig. 5. The evaluation of acceptable range of phantom thickness. RANGE I is for thin aluminiums (1 to 10 mm) and RANGE II is for thick aluminiums (8 to 18 mm).

intersecting points of the characteristic curve with the described maximum and minimum basic film density.

For example, the exposure of 200 mA-1.0 sec is adequate for the phantoms of 21.5 to 24.5 cm thickness (RANGE I) for calibrating thin aluminium, namely the bone of low mineral content, and 18.5 to 22.5 cm thickness (RANGE II) for calibrating thick aluminium, namely the bone of high mineral content (Fig. 5). If it is required to cover the whole range of aluminium thickness (1 to 20 mm) in the optimum range, the acceptable range of phantom thickness becames 21.5 to 22.5 cm, which is too narrow to control the tube exposure in the daily examination.

The similar procedures have been applied for the exposure of 400 mA-0.3, 0.4, 0.5, 0.6, and 0.8 sec, and the derived acceptable ranges of phantom thickness were summarized in Fig. 6 together with the results for 200 mA exposures.

Patients have been classified into three groups according to the soft tissue thickness and the expected bone mineral content (Fig. 7). On the basis of the results in Fig. 6, the standardized exposure technique was determined for each group (Table 1).

3. Densitometry and data analysis

Patient was radiographed in succession dividing equally the film with the center on the third lumbar vertebra (L3) (Fig. 8). The radiograph of a standard is shown in Fig. 9. For the measurement of the bone of low mineral content, the step of 5 mm was centered while the step of 13 mm was centered for the measurement of the bone of high mineral content.

The site of densitometry on a radiograph of a patient is shown in Fig. 10: four points around the center of vertebral body image, and the two portions of intervertebral canals L2 and L3, and L3 and L4. The film density on intervertebral canals were measured to estimate the thickness of soft tissue surrounding the vertebral body by comparing with a series of basic film density on phantoms like shown in Fig. 3.

Theoretical treatment was made in this study to reduce the effect of intensity fluctuation. The principle is to obtain the contrast from the difference between the basic film density and the film density on each

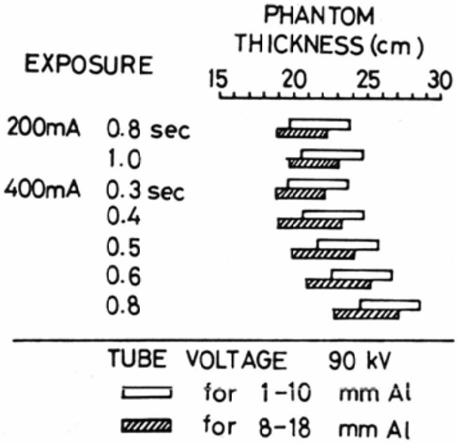


Fig. 6. Summarized illustrations of the acceptable range of phantom thickness for some exposure techniques.

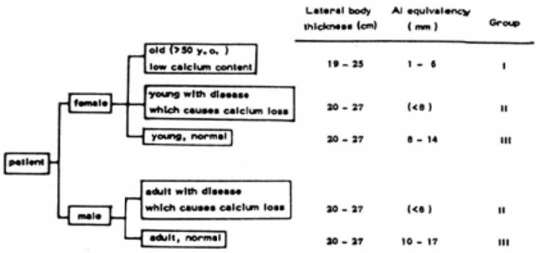


Fig. 7. Classification of patients for the radiographic densitometry of lumbar vertebrae. Patients were classified into three groups according to the lateral body thickness and expected aluminium equivalency.

Table 1 Optimum tube exposure for the groups of patients

Group I	200 mA	0.8 sec
	200 mA	1.0 sec
Group II	400 mA	0.3 sec
	400 mA	0.6 sec
Group III	400 mA	0.4 sec
	400 mA	0.8 sec

Tube voltage 90 kV

aluminium step, and to use the relationship between the contrast, instead of the film density, and aluminium thickness as a calibration curve. The following designations will be used:

- P: index for phantoms
- s : index for lean soft and adipose tissues
- A: index for aluminium
- B: index for bone mineral
- D: film density
- I_0: intensity of incidnet X-rays
- μ : mass absorption coefficient, cm^2/g
- ρ : density, g/cm^3
- S : intensity of scattered X-rays arrived to the film
- ℓ : thickness of the absorber in the path of X-ray
- G: film contrast on the characteristic curve of X-ray film.

Film contrast at the film density produced by aluminium or bone mineral is indicated with prime sign while that at the film density produced by phantom of soft tissue is shown without prime sign (concerning the definition of film contrast, see Meredith and Massey[6], for example).

Assuming the law of exponential attenuation of X-rays, the following relations between the film density

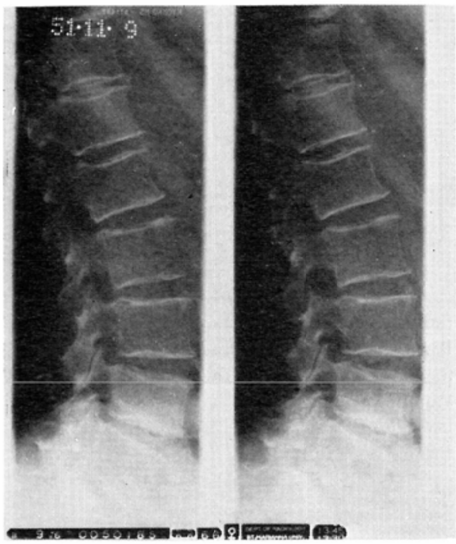


Fig. 8. Radiograph of a patient exposured on lateral projection in succession on the field of 10 by 30 cm.

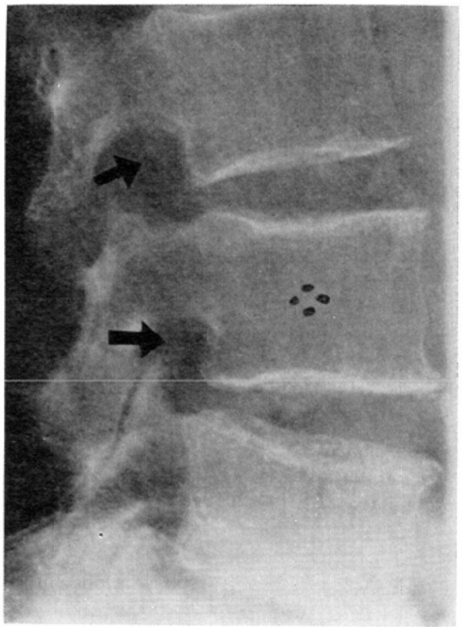


Fig. 10. The sites of densitometric measurement on the image of vertebral body L3 and the intervertebral canals between L2 and L3, and L3 and L4. The film density on the canals was used to estimate the soft tissue thickness by comapring with the standard curve.

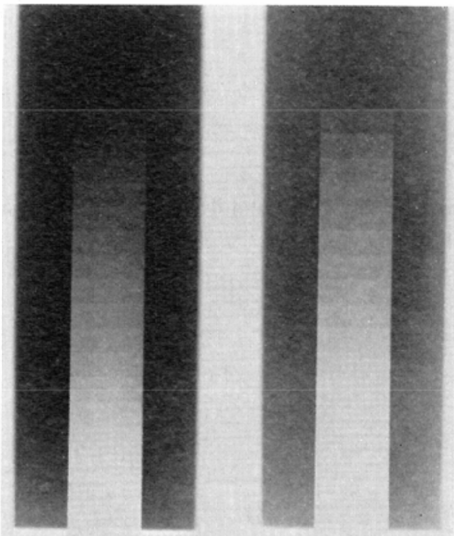


Fig. 9. Radiograph of an aluminium step wedge in phantom.

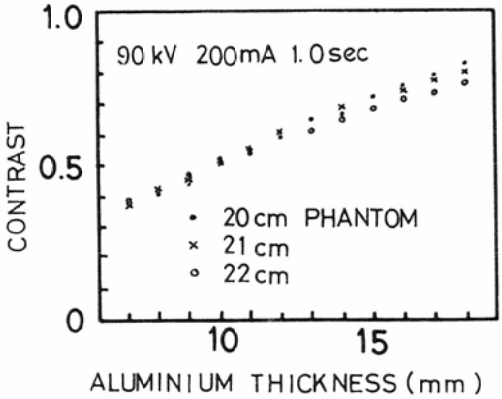


Fig. 11. A typical calibration curve relating contrast to aluminium thickness.

and the X-ray intensity arrived to the film could be expressed as follows:

$$D_P = G\{\ln(I_0 \cdot \exp(-\mu_P \rho_P \ell)) + S_P\}$$
$$= G(\ln I_0 - \mu_P \rho_P \ell + S_P) \quad \cdots\cdots (1)$$
$$D_S = G(\ln I_0 - \mu_S \rho_S \ell + S_S) \quad \cdots\cdots (2)$$

$$D_A = G'\{\ln I_0 - \mu_P\rho_P(\ell-\ell_A) - \mu_A\rho_A\ell_A + S_P\} \quad (3)$$

$$D_B = G'\{\ln I_0 - \mu_S\rho_S(\ell-\ell_B) - \mu_B\rho_B\ell_B + S_S\} \quad (4)$$

The contrasts, e.g. the differences between equations (1) and (3), and equations (2) and (4), are

$$D_P - D_A = (G-G')\cdot(\ln I_0 - \mu_P\rho_P\ell + S_P) + G'(\mu_A\rho_A - \mu_P\rho_P)\cdot\ell_A \quad (5)$$

and

$$D_S - D_B = (G-G')\cdot(\ln I_0 - \mu_S\rho_S\ell + S_S) + G'(\mu_B\rho_B - \mu_S\rho_S)\cdot\ell_B \quad (6),$$

respectively.

As the difference of film contrast, $G-G'$, is much smaller than G or G', the effect of fluctuation of the intensity of incident X-rays, I_0, could be reduced as indicated in the first terms of these equations. When both D_P and D_A, or both D_S and D_B, fall in the optimum range (Fig. 3), the first terms of equations (5) and (6) would be negligible, that is the effect of the fluctuation of I_0would be negligible.

A calibration curve obtained by the optimum exposure technique has maximum slope and is little affected by the phantom thickness. An example is shown in Fig. 11. One calibration curve was selected for a patient according to the thickness of soft tissue, and the selection is unsensitive to the possible uncertainty of the estimation of soft tissue thickness because of the adjacency of curves to each other. This kind of calibration curve has much better reproducibility than the relation between film density and aluminium thickness. It is a favorable feature as calibration curves.

Results and discussion

At the begin and end of the examination which took one to two hours, phantom was radiographed and the consistency of film density was tested. Variation of film density was not more than +0.02, +0.01 in most of the cases, and was small enough for this work.

Aluminium equivalency of bone mineral content of autopsied lumbar vertebrae were determined by this method: one (Case I) was a 82-year-old female died of pneumonia and another one (Case II) was a 24-year-old female died of profuse bleeding. No significant trends with phantom thickness or exposure technique have been found in the evaluated aluminium equivalency (Table 2). The aluminium equivalency of L3 was 2.4 mm for Case I and 3.4 mm for Case II. Observation of the section of vertebral body indicated strongly porotic structure for Case I as expected from the aluminium equivalency. For Case II, the section of the vertebral body showed

Table 2 Aluminium equivalency of bone mineral content of autopsied vertebra L3

Phantom thickness (cm)	Case I* exposure time**	Case II* exposure time**	
	0.4 sec	1.0 sec	0.8 sec
20	2.3	3.5	3.7
21	2.3	3.3	3.0
22	2.7	3.5	3.4
23	2.4	3.2	3.5
24	2.4	3.5	3.6
25	2.5	3.4	—
mean	$2.4_3 \pm 0.1_5$	$3.4_0 \pm 0.1_3$	$3.4_4 \pm 0.2_7$

* Removed vertebrae were immersed in water phantom.

** Tube voltage was 90 kV and current was 200 mA.

Table 3　Aluminium equivalency of vertebral bone mineral content of subjects

No.	Sex	Age	Aluminium equivalency (mm)
1	M	19	14.2
2	M	27	10.8
3	F	24	9.5
4	F	41	12.8
5	F	46	8.0
6	F	51	5.0
7	F	56	5.3
8	F	60	7.3
9	F	60	3.7
10	F	61	3.3
11	F	62	5.2
12	F	63	4.0
13	F	63	2.6
14	F	64	2.4
15	F	65	5.9
16	F	66	2.6
17	F	66	5.7
18	F	66	5.7
19	F	67	3.9
20	F	68	3.7
21	F	69	6.0
22	F	73	6.3
23	F	73	2.7
24	F	74	9.0
25	F	76	5.7
26	F	77	3.3
27	F	85	1.5

more compact structure than expected from the densitometrical data.

The reproducibility in the current stage of this method has been tested by replicate measurement of the vertebrae L3 and L4 of Case II. Radiographing has been performed eleven times within two weeks. The standard deviations (1σ) were 0.1_4 for L3 and 0.2_3 for L4, and the coefficients of variation were 4% for L3 and 6% for L4.

The reproducibility of the radiographical measurement of vertebral bone mineral content in vivo has been reported by Vose[3] to be 5%, which was derived as the maximum difference among the values of the three tests which were performed at three-day intervals. The reproducibility of photon absorptiometric measurement has been reported as 3% in phantom experiment and 3 to 8% in patient measurement by Roos and Sköldborn[4] based on the measurement series consisted at least 10 measurements. Although the absolute values of bone mineral contents were not described in these literatures, the reproducibility of our method is comparable with those of their techniques.

This method has been applied for more than 60 persons and in Table 3 there are some results obtained in the early stage of this work. Mean aluminium equivalency for normals was about 12 mm. Examined abnormals had the complaints of pains of lumbar vertebrae and all of them were diagnosed as osteoporosis.

Conclusion

Several improvements have been made in this study for the radiographic determination of aluminium equivalency of vertebral bone mineral content.

1. Patients and a series of absorption standards were radiographed not simultaneously. Patients were radiographed on lateral projection. It was necessary to use the same cassette with an intensifying screen in radiographing patients and standards.

2. Basic film density uniform enough for this work was obtained on the field of 10 by 30 cm by using a special plastic filter attached to the exit side of the X-ray tube.

3. Relation between the basic film density and the phantom thickness was used to estimate the thickness of soft tissue surrounding the vertebrae by comparing the film density on the image of intervertebral canals with standard.

4. General procedure is shown to evaluate the optimum exposure technique for various situations of phantom thickness and aluminium thickness. This procedure requires only simple experimental data as the basis of calculations. Patients were classified into three groups and the standardized exposure technique has been utilized.

5. The relationship between the contrast and aluminium thickness was used as a calibration curve. This relation has some advantages: (1) reduce the effect of the fluctuation of the X-ray intensity, (2) better reproducibility than the relation between the film density and aluminium thickness, and (3) slightly affected by the phantom thickness when the exposure is optimum.

6. Reproducibility of this method (1σ) is 4 to 6% for the bone mineral content of 3 to 4 mm aluminium equivalency.

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