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Effect of Titanium Prosthesis on Computed Tomography Measurements of Bone Mineral Density

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요 약 : 본 연구에서는 骨內의 티타늄, 보철물, malalignment, 측정범위, 그리고 보철물 distal flare 등이 전산화단층 (CT) 촬영으로 골밀도를 측정할때에 미치는 영향을 조사하였다. 8구의 남성 사체로부터 대퇴골과 경골을 각각 8개씩 얻었으며 경골의 상부에 위치해있는 해면골 부분에서 15개의 평행사변형 시편을 만들었다. 평행사변형 시편과 대퇴골을 CT 스캔받침대의 중앙에 바로 놓았을때와 조금 떨어져 놓았을때 그리고 티타늄 보철물을 骨內에 넣었을 경우와 그렇지 않았을 경우 모두에 대해서 각각 스캔하였다. 이때 얻어진 CT 영상자료는 측정범위를 10cm와 30cm로 해서 재구성 하였다. 그리고 골밀도는 영상분석 소프트웨어를 사용하여 측정하였다. 그결과 시편을 CT 스캔받침의 중앙에 놓았을경우에는 그렇지 않았을경우에 비해 골밀도 평균값의 상대차이가 피질골과 해면골 모두에 대해서 1% 미만이었다. 그러나 보철물의 malalignment와 distal flare는 골밀도의 측정값에 상당히 영향을 미쳤다. 骨內에 티타늄 보철물의 존재여부는 시편을 CT 스캔받침대의 중앙에 놓았을 경우에는 피질골 뿐만아니라 해면골 골밀도 측정값에 영향을 미치지 않았다. 그러나 骨內에 티타늄 보철물의 존재가 malalignment 효과와 합쳐졌을때에는 골밀도 측정값에 많은 차이를 드러내었다.

Abstract : This study investigated the effects of a titanium prosthesis, malalignment, field of view, and distal flare of titanium prosthesis on computed tomography (CT) measurements of bone mineral density. Eight femora and eight tibiae from fresh male cadavers were used. Fifteen pieces of cancellous bone from the proximal tibiae were milled into rectangular parallelepipeds. Parallelepipeds and femora were scanned with and without titanium prosthesis when centered in the gantry of the CT scanner and malaligned, respectively. Image data were then reconstructed with field of view of 10 and 30 cm. Bone mineral density (BMD) values were obtained from CT images using C-MED software. The effects of titanium prosthesis, malalignment, and field of view were investigated. When bone was centered in the gantry of the CT scanner, the mean relative difference of BMD measurements caused by a titanium prosthesis was less than 1% for both cortical and cancellous bone. Field of view had a negligible effect on BMD measurements as well. Malalignment and distal flare of prosthesis, however, caused a significant difference in BMD measurements ($p<0.0001$). The titanium prosthesis did not interfere with BMD measurements of cortical and cancellous bone when bone was centered in the gantry of the CT scanner. However, the effect of malalignment combining the existence of a titanium prosthesis on BMD measurements was significant.

Key words : Computed tomography, Bone mineral density, Cortical bone, Cancellous bone, Titanium prosthesis.

INTRODUCTION

One of the major uses of quantitative computed tomography (QCT) has been the measurements of bone mineral density (BMD) at various skeletal sites. Techniques for BMD measurements have been developed to predict fracture risk in osteoporosis patients, particularly in the vertebral body and the proximal region of the femur [1,2]. In addition, the evaluation of bone loss adjacent to metallic prostheses in patients with total joint replacements (TJR) may allow better prediction of prosthesis loosening. Successful application of QCT in BMD measurements depends on its accuracy. QCT has been shown to accurately measure bone mineral density of patients without TJR [3,4]. However, the presence of a metal prosthesis in bone limited the application of CT-based image analysis to patients undergoing total joint replacement [5]. Metal-associated artifacts in CT images usually result from the severe attenuation of the metal to x-ray beam [6]. Titanium is a popular material in cementless arthroplasties. Prior studies have shown that the application of a titanium prosthesis in TJR reduced the

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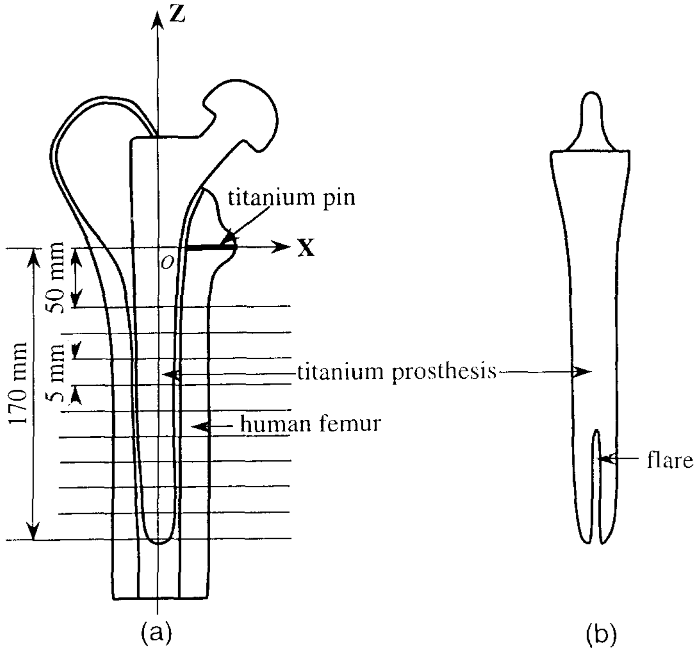


Fig. 1. (a) Reference axis system of a human femur implanted with a titanium prosthesis. (b) Lateral-medial view of a titanium prosthesis with a distal flare

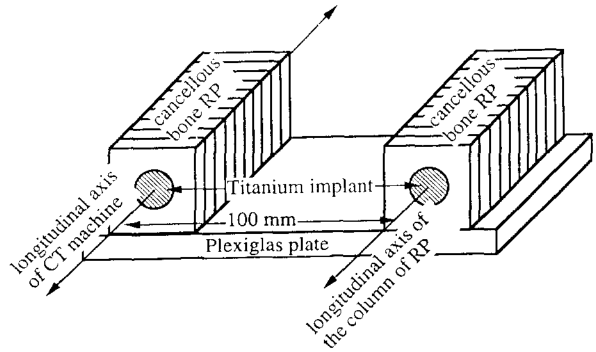


Fig. 2. Reference axis system of the column of cancellous bone RP

metal-associated artifacts, allowing for precise geometric measurement of cortical bone dimensions [7,8]. However, little information is known concerning the effect of a titanium prosthesis on BMD measurement of human cortical and cancellous bone using QCT.

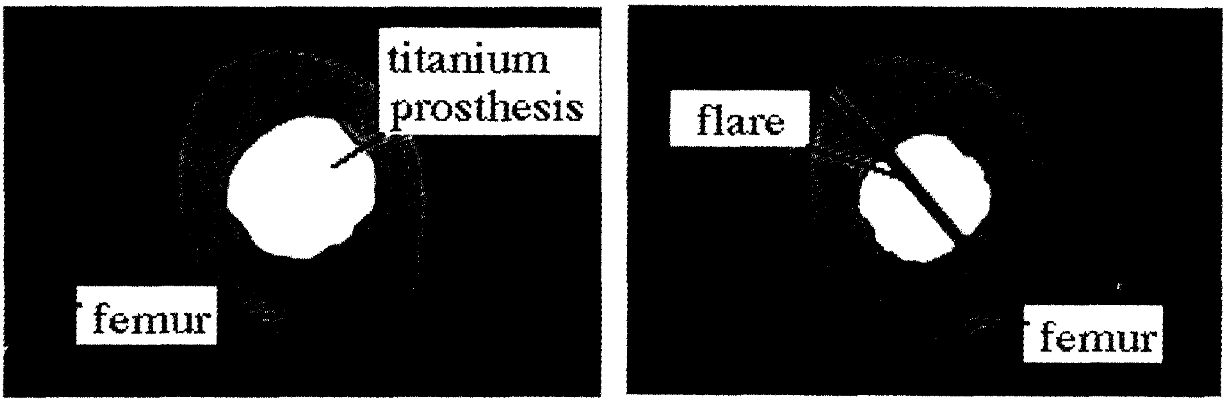
The objective of this study was to examine the effects of a titanium prosthesis, malalignment, field of view, and shape of the prosthesis on BMD measurements by QCT.

MATERIALS AND METHODS

Eight femora and eight tibiae from fresh male cadavers (mean age : 74±14) with radiographically documented normal anatomy and density were selected for this study. The femora were used to investigate the effects of a titanium prosthesis, malalignment, and field of view on BMD measurements of cortical bone. Cancellous bone specimens obtained from the proximal tibiae were also used to investigate these same effects on BMD measurements of cancellous bone.

A Intermedics Natural[R] Cementless Titanium prosthesis (Intermedics Orthopedics, Inc., Austin, TX) was inserted into each femur according to the procedure recommended by the manufacturer. The prosthesis has a distal flare (Fig. 1) to improve its fit to the canal of the femur and to match its stiffness to that of cortical bone. A hole was drilled through the tip of the lesser trochanter perpendicular to the longitudinal axis of each femur. A titanium pin 0.6 mm in diameter was inserted into each hole as CT position markers. Fifteen cancellous bone specimens from proximal tibiae were machined under water irrigation into rectangular parallelepipeds (RP), 25 mm (width) ×25 mm (length) × 3 mm (thickness). At the center of each RP, a hole 14.1 mm in diameter was drilled through. The RP were mounted onto a Plexiglas[R] plate and arranged in a single column (Fig. 2). A rod (14 mm in diameter) cut from the distal end of a titanium prosthesis was inserted through the holes of the RP.

Each femur was placed in a water-filled Plexiglas[R] box and scanned with a GE 9800 scanner (General Electric, Pace PlusTM, Milwaukee, WI). The CT was operated at 120 kVp, 120 mA, with a scan time of 2 seconds. This setting was selected to match clinical examination. CT slices (1.5 mm in thickness) were taken at 5 mm intervals starting from 50 mm to 170 mm below the tip of the lesser trochanter of each femur (Fig. 1). Twenty-four cuts were taken from each femur. Cancellous bone RP specimens with the prosthesis were also similarly CT scanned. CT slices (1.5 mm in thickness) were taken perpendicular to the longitudinal axis of the column at the middle of the thickness of each RP. A calibration phantom was placed under the Plexiglas[R] box during scanning. Each femur and RP was scanned with and without a titanium prosthesis in two different alignment conditions, respectively : (1) each femur and RP was centered in the gantry of the CT scanner; and (2) the longitudinal axes of the column of RP and each femur were parallel with the axis of the gantry but at a distance of 10 cm (malalignment). CT images were then



(a) (b)

Fig. 3. (a) CT images of a midshaft femur with a titanium prosthesis. (b) CT image of a midshaft femur with a titanium prosthesis having a flare. Note the scattering from the flare

Table 1. Effect of a titanium prosthesis on BMD measurements

Field of view	Human cortical bone		Human cancellous bone	
	10cm	30cm	10cm	30cm
Relative error, % Mean±S.D.	0.63±0.87	0.69±1.53	0.81±1.22	0.80±0.30

*Femora and the column of bone RP were centered in the gantry of the CT scanner.

reconstructed from raw data using bone reconstruction kernels on a 512×512 matrix with a field of view (FOV) of 10 and 30 cm, respectively.

To test the reproducibility of BMD measurements, a femur and the column of cancellous bone RP implanted with a titanium prosthesis were scanned at the same setting three times on three different days. The coefficient of variation was calculated using statistics software (StatView, Abacus Concepts Inc., Berkeley, CA).

The CT images of the human femora and RP were transferred in a compressed format to a Sun SPARC station 10 (Sun Microsystems, Inc., Mountain View, CA) and analyzed by C-MED[R] software (Virtual Visions Software, Inc., Cupertino, CA). CT number was converted to BMD (mg/cm^3) using calibrated phantom. BMD of the entire area of femoral bone or RP was measured. An edge detection method based on half-maximal height CT number (HMH) was used to define the boundary of bone [9].

The effects of a titanium prosthesis (I), malalignment (M) and field of view (FOV) on BMD measurements were evaluated by making comparison with the control group (C) (without titanium prosthesis, 10 cm FOV, bone centered in the gantry of the CT scanner), respectively. Difference between BMD with all effects ($BMD_{I.M.FOV}$) and BMD of the control (BMD_C) was defined as relative error : $\varepsilon (\%) = 100 \times [(BMD_{I.M.FOV} - BMD_C)/BMD_C]$. Mean($\frac{\Sigma \varepsilon_i}{n}$) and standard deviation ($\sqrt{\frac{\Sigma(\varepsilon_i - \bar{\varepsilon})^2}{n-1}}$) of relative error of BMD measurements were also calculated. A paired t-test was performed between $BMD_{I.M.FOV}$ and BMD_C to determine the statistical significance of the errors caused by a titanium prosthesis, malalignment, and FOV using StatView software. A p-value of 5% ($p<0.05$) was used as the significance level.

RESULTS

Reproducibility of BMD measurements with a titanium prosthesis was 1.1% for cortical bone and 1.5% for cancellous bone. When femora or RP were centered in the gantry of the CT machine, the relative differences of BMD measurements caused by a titanium prosthesis were less than 1 % for both cortical and cancellous bone (Table 1). No significant difference was found between values with and without a titanium prosthesis ($p>0.1$).

There was no significant difference due to the malalignment when a titanium prosthesis was not implanted ($p>0.1$),

Table 2. Effect of malalignment on BMD measurements

Field of view		Human cortical bone		Human cancellous bone	
		10cm	30cm	10cm	30cm
Relative error, %	Without titanium	−0.48±0.59	−0.42±0.35	−86±0.81	−0.54±1.81
Mean±S.D.	With titanium	−6.24±2.41	−5.08±2.46	−6.08±1.56	−7.52±1.50

*The longitudinal axes of the column of bone RP and femora were parallel with the axis of the gantry of CT scanner but at a distance of 10cm

Table 3. Effect of field of view(FOV) on BMD measurements

		Cortical bone	Cancellous bone
Relative error, %	Without titanium	−0.02±0.87	−0.52±1.42
Mean±S.D.	With titanium	−0.08±0.19	−0.52±0.86

*Relative error of BMD measurements caused by increasing FOV from 10 to 30cm.
*Femora and the column of bone RP and were centered in the gantry of the CT scanner.

however, a significant difference was found when a titanium prosthesis was implanted ($p<0.0001$). Malalignment of 10 cm caused a decrease of BMD values by 6.24% (FOV=10cm) and 5.08% (FOV=30cm) for cortical bone, and 6.08 % (FOV=10cm) and 7.52% (FOV=30cm) for cancellous bone (Table 2).

Field of view demonstrated negligible effect on the BMD measurements for both cortical and cancellous bone when the femora or RP were centered in the gantry ($p>0.05$) (Table 3).

The distal flare of a titanium prosthesis caused the scattering of x-ray in CT images (Fig. 3b), resulting in significant error on BMD measurements (up to 31%), compared to prosthesis without flare. This error was reduced when the external diameter of that portion of the prosthesis containing the flare was decreased.

DISCUSSION

Titanium material is widely used for prostheses in total joint replacement. Its lower attenuation to x-ray was reported in prior studies [6]. However, the big difference of attenuation between bone and titanium may still cause artifacts in BMD measurements by QCT.

Results of this study demonstrated that when bone was centered in the gantry of the CT scanner (with alignment), use of a titanium prosthesis did not decrease the accuracy of the BMD measurements. When implanted within cortical bone, the difference of the BMD value caused by a titanium prosthesis was within the range of the reproducibility of BMD measurements of cortical bone (1.1%). Furthermore, when implanted within cancellous bone, the difference of the BMD value was still within the range of the reproducibility of BMD measurements of cancellous bone (1.5%). It was therefore demonstrated that when bone was centered in the gantry of the CT scanner, the existence of a titanium prosthesis within bone did not cause a significant difference to BMD measurement. Markel *et al.* reported an increase in BMD value by 5.3% when a titanium prosthesis was implanted into a canine bone specimen [10]. Their value was slightly larger than the present study, but not much larger than the reproducibility of the technique they applied (2.0 to 3.0%). It seems that the HMH method [9] used in this study led to a smaller error.

A 30 cm field of view is popularly used in clinical examination, whereas a 10 cm field of view is used more often in research. Since the pixel size of CT images is known to be an important factor in the accuracy of CT-based dimension measurement [11], field of view should have an effect on the accuracy of BMD measurements due to partial volume effect. The CT numbers of pixels located at the bone/soft tissue boundaries are the average intensity of the whole voxels including bone and soft tissue. The CT numbers of these voxels are lower than the actual CT numbers of bone, therefore, the smaller the pixels, the more accurate the BMD measurements. However, this study showed that field of view had negligible effect on the BMD measurements. The variation due to field of view was within the reproducibility of CT measurements. The difference may be due to the fact that a large region of interest (ROI) was selected in this study. The results of each measurement were the average of more than 500 pixels. Thus, the contribution of value of the pixels located at the boundary between bone and soft tissue to mean BMD value was negligible because a large portion of voxels were located inside bone boundary. When the ROI is smaller (e.g., for rat femur), the contribution of the pixels which located at the boundary could be more important. In this case the accuracy of BMD measurements using CT may be more dependent on the field of view.

Malalignment of femora of patients with the axis of the CT machine was often reported in clinical examination. In general, during CT scanning of a patient, the center line of patient's body is concordant with the axis of the CT machine, while both femora of the patient are malaligned with the axis of the CT machine. Without the existence of a metal prosthesis, malalignment of the objective does not cause a significant difference in the BMD value compared to that of alignment [12]. The attenuation of metal, including titanium, is much higher than that of bone. Markel *et al.* (1992) described a particular pattern of starburst streaking due to the system's geometry (orientation of titanium and bone) [10]. The existence of a titanium prosthesis combined with malalignment, revealed a significant difference in BMD values ($p<0.0001$). The 5.1% decrease in cortical BMD and 6.8% decrease in cancellous BMD were found in this study; hence, this difference should be taken into account during CT examination.

The effect of shape of a titanium prosthesis on the accuracy of the CT-based BMD measurement was not available in the literature. The present study showed that the round shape of a titanium prosthesis with a diameter ranging from 15 mm to 22 mm had no significant effect on the CT-based BMD measurements. The existence of a distal flare, however, caused obvious artifact on measurements. When compared to a circular shaped prosthesis, distal flare obviously caused the x-ray beam scattering in the CT images (Fig. 3b). The maximum error caused by the distal flare is 31%, which is not acceptable in clinical examination. This kind of scattering might result from the sudden change in geometry of the prosthesis and the non-symmetrical shape. Although the distal flare improves the fit of the prosthesis, achieving a better match of stiffness between the titanium prosthesis and femur bone, its effect on the CT image should be taken into account.

This study demonstrated that, (1) titanium implanted into cortical and cancellous bone had a negligible effect on the BMD measurements using QCT; (2) field of view had a negligible effect on a big ROI as well; and (3) malalignment caused a significant error in BMD measurements, when a titanium prosthesis was implanted in bone. Finally, the distal flare caused unacceptable error on BMD measurements. It is suggested that the effect of the shape of a prosthesis on BMD measurement should be considered when using QCT.

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