

IN VIVO MEASUREMENT OF BONE STRUCTURAL PARAMETERS: ACCURACY AND PRECISION OF A DENSITOMETRIC TECHNIQUE

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INTRODUCTION

We implemented a three-scan single-energy densitometric method to determine the accuracy and precision of measuring the cross-sectional structural parameters of the long bones of the lower leg in vivo.

METHODS

The in vivo setup consists of a foot fixture attached to an indexable rotating plate and an acrylic cylinder, aligned along the length of the table, that fits over the leg in the area to be scanned (Figure 1). The cylinder, with machined parallel flat surfaces, is fitted with an inner urethane bladder that is filled with saline to give a constant soft tissue baseline X-ray attenuation value in non-bone regions (Figure 1). All scans were taken with a Hologic QDR-1000/W bone densitometer using the spine scan mode (point spacing: 0.951 mm, line spacing: 1.003 mm).

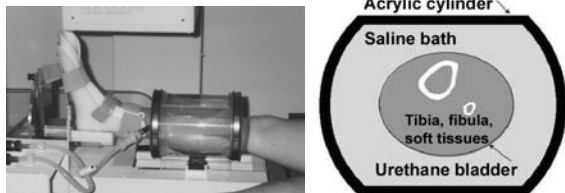


Figure 1: In vivo set up and cross-section.

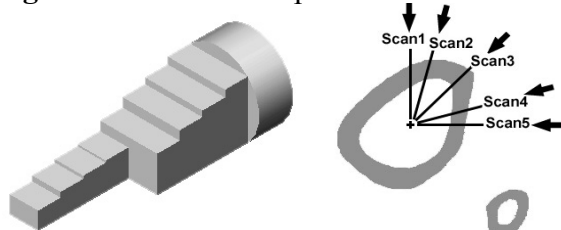


Figure 2: Aluminum phantom; lower leg scan orientations.

Accuracy: Accuracy was determined using an aluminum phantom (Figure 2), dimensioned to match a normal range in tibia and fibula cross-sectional area (A) and principal moments of inertia (I_{max} , I_{min}). The stepped end of the phantom was encased in a saline filled urethane tube; the other end held in a precision indexer.

The phantom, inserted into the cylinder in the manner of a leg, with the urethane bladder filled to eliminate air voids, was scanned in 15° increments of axial rotation spanning 90° (7 scans total). The principal axis of the phantom was initially set at 60° to the horizontal projection plane. A step phantom, machined from the same aluminum billet, was scanned in the same thickness of saline (plus acrylic) and used to convert X-ray attenuations to equivalent aluminum thickness values after subtracting a soft tissue (saline) baseline offset.

Cross-sectional structural parameters (A , I_{max} , I_{min} , and $J = I_{max} + I_{min}$, and principal angle) were computed for each section using three scans spanning included angles of 60° and 90° , respectively (Cleek and Whalen, 2002). Separate analyses using high and low DXA energies were performed.

Precision: In vivo precision of tibial structural parameters was computed from same day repeated measures of the tibial mid-diaphysis of fifteen female subjects aged 25 and older. The study was approved by NASA and Stanford University IRBs. Lead makers, marking start and stop scan

positions, were taped to the mid-diaphysis of the lower leg for registration of the scans during post processing. Five scans were taken. Between each scan, the leg was internally rotated to give scan sets which spanned included angles of 60° and 90°, in which the tibia and fibula did not overlap in the projected image (Figure 2). This entire procedure, with the subject getting off the table and markers removed, was repeated twice for a total of three independent measurements of structural parameters.

A set of dense bovine cortical bone steps was scanned and used to convert attenuations to equivalent cortical bone thickness. A simple thresholding program was used to detect bone edges. Structural parameters were computed as before from three scans spanning 60° and 90° and high and low energies, respectively (four combinations). Measurement averages for a 5 cm section centered at the mid-diaphysis were computed for each scan set at both included angles and at each energy level. Precision from triplicate measurements was calculated according to Gluer, et al. (1995).

RESULTS AND DISCUSSION

Accuracy: Estimated principal moments were within 4.1% and principal angles were within 1.2° for both energies and included angles (Table 1). Low standard deviations

in error indicate little line to line variability. This is the "best case" in vivo accuracy to be expected with the current setup.

Precision: The low energy yielded slightly better precision than the high energy and the results for included angles of 60° and 90° were comparable at the low energy (Table 2). Better performance of the lower energy may be due to its larger dynamic range that can compensate for a decrease in signal to noise due to the large soft tissue thickness surrounding the bone in the in vivo setup. Our precision values from repeated measures incorporates errors in marker placement, initial foot position, and scan-to-scan misalignment. As a result, the measured precision is considered to be a "worse case", conservative estimate for the current setup.

In conclusion, we have validated a three-scan densitometric method for measuring structural parameters in long bones for use in future in vivo studies. The measured in vivo accuracy and precision establishes the confidence limits for measuring differences or changes in these parameters.

REFERENCES

- Cleek, T.M., Whalen, R.T. (2002) *J. Biomechanics*, **35**, 511-516.
 Gluer, C.C. et al. (1995) *Osteop. Int.*, **5**, 262-270.

Table 1: Errors (mean ± SD) in calculated section properties and principal angle for phantom.

Included angle, energy	Area (%)	I _{max} (%)	I _{min} (%)	J (%)	Pri angle (deg)
90°, hi energy	-4.80 ± 2.14	-4.07 ± 1.87	1.07 ± 2.13	-2.26 ± 0.99	0.33 ± 0.94
90°, lo energy	-5.03 ± 1.92	-3.65 ± 0.74	-2.91 ± 1.61	-3.43 ± 0.65	1.17 ± 1.44
60°, hi energy	-4.61 ± 1.88	-3.37 ± 3.40	1.07 ± 2.86	-1.72 ± 2.86	-0.76 ± 3.54
60°, lo energy	-5.34 ± 2.02	-2.85 ± 4.98	-3.38 ± 2.06	-3.12 ± 3.06	0.89 ± 1.99

Table 2: Calculated precision of structural parameters from triplicate measurements.

Included angle, energy	Area (cm ²)	I _{max} (cm ⁴)	I _{min} (cm ⁴)	J (cm ⁴)	Pri angle (deg)
90°, hi energy	0.046	0.083	0.033	0.084	7.040
90°, lo energy	0.025	0.053	0.022	0.051	3.098
60°, hi energy	0.017	0.086	0.068	0.108	13.823
60°, lo energy	0.013	0.071	0.019	0.077	6.164