Effect of Source Strength and Attenuation on Dual Photon Absorptiometry

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A systematic error in dual photon absorptiometry (DPA) measurements of bone mineral density (BMD) related to source strength has been previously described and attributed to an erroneous algorithm for deadtime correction. Since detected counts (or photon flux) is a product of source strength and attenuation, the effect of various source activities and attenuation depths on BMD calculations were evaluated using a phantom. Ten DPA scans were acquired at two source strengths, 0.3 and 1.0 Ci, and at each of two water depths, 16.4 and 24.5 cm. These activities and depths are within the range encountered clinically. Scans were acquired and processed using a commercially available lumbar spine scanner and software, and were reanalyzed with two upgraded versions of software. Mean BMD obtained with the initial software varied by 2 to 14% with changes in both source strength and attenuating depth. Software revisions reduced but did not entirely eliminate these differences. The remaining 6% discrepancy is of sufficient magnitude to influence both patient management and research investigations.

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Dual photon absorptiometry (DPA) is in widespread clinical and investigational use to quantify bone mineral and to detect osteopenia. Numerous cross-sectional and longitudinal studies using DPA have been performed to define bone density in normal and diseased populations, to monitor progression of bone disease, and to evaluate effectiveness of therapy. These applications of DPA are critically dependent on the accuracy and precision of the measurement. Although much of the existing data suggest that DPA is accurate and reasonably precise (*1–11*), the majority of these studies have been performed under limited conditions not fully representative of the range of clinical and research settings in which DPA is used.

A systematic error in DPA measurements related to the decay of the radioactive source has recently been reported (*12–15*). As a result, sources of lower radioactivity yield bone mineral density (BMD) results which are significantly higher than those obtained with sources of greater activity. The origin of this problem has been attributed to an error in the software algorithm for deadtime correction of photon flux which exceeds the count rate capability of the instrument (*16,17*). Since the photon flux reaching the detector depends upon both source strength and the amount of attenuating media in the beam path, it seemed likely that variations in either could affect bone mineral measurements and that these effects could be interactive.

To investigate this possibility, the effects of different depths of attenuating media on BMD determinations with relatively hot and cold sources (hereafter referred to as hot and cold) were studied.

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METHODS

DPA studies were performed on a phantom which consisted of an aluminum tube with a 5-cm diameter and 3-mm wall thickness which was fixed in a lucite box. Water was added to the box to attain the desired depth of attenuating media. Source activities typical of a new Gadolinium source, 1 Ci, and of a source after 1 yr of use, 0.3 Ci, were used. Measurements were made with simulated soft-tissue depths of 16.4 and 24.5 centimeters of water. These values are within the range of lower abdominal AP diameters measured in 105 women who were within 15% of ideal body weight. Ten studies were acquired with each combination of source strength (hot and cold) and water depth (shallow and deep).

Measurements were made with a Lunar Radiation Corporation DP-3A Scanner (Madison, WI). Using calibration values derived from the measurement of a standard block having three cylinders of known bone mineral equivalent, attenuated counts are converted to grams of bone mineral content (BMC). Results are expressed in relation to the corresponding area as BMD in g/cm^2. Although the aluminum tube was used to simulate bone attenuation of photons, the attenuated counts measured on the phantom are automatically converted to the familiar BMC and transformed to BMD. Therefore, the results on the phantom will hereafter be referred to as BMC or BMD.

Acquisition, analysis of data, and quality control functions were performed through the use of manufacturer provided software. All scans were acquired and processed using typical parameters for analysis of spine bone mineral (8 mm detector collimation, 3 mm source collimation, 2.5 mm/sec scan speed, and 4.5 mm stepping increment).

All data were acquired and processed using software release 7G and were subsequently reanalyzed with software versions 8B and then 8C. Software 7G was the software version in most common use when the deadtime correction problem was detected. Software 8B was released by the manufacturer to improve the deadtime correction and to eliminate the effect of source strength on DPA measurements. Software 8C was developed (but has not been officially released) to improve the assessment of the soft-tissue component of beam attenuation.

Statistical Methods

The mean BMD, BMC, and area for the four groups were compared by using multiple t-tests that account for the inequality of variances within each group. The Bonferroni adjustment was employed (*18*) so that the overall experimental error rate would remain at 0.05.

A Bartlett's test for homogeneity of variances was performed to test for differences between groups (*19*). Multiple comparisons were carried out using the F statistic and the Bonferroni adjustment to give more detailed information about the variances in the four groups.

Group differences in mean BMD between software versions were compared by the method of Satterthwaite (*20*) which constructs a contrast among the group means and uses a t-test for unequal variances and approximate number of degrees of freedom.

RESULTS

Effect of Source Strength

Results obtained with 7G software are presented in Table 1, and Figure 1. A significant effect of source strength on BMD was documented at both depths of attenuating media. At the lower depth, the mean BMD of 0.727 g/cm^2 with the cold (0.3 Ci) source was 2.4% higher than the mean BMD of 0.710 g/cm^2 obtained with the hot (1.0 Ci) source ($p \le 0.0001$). At the greater depth, the effect of source strength was more pronounced. Mean BMD with the cold source, 0.813 g/cm^2, was 13.6% higher than mean BMD with the hot source, 0.715 g/cm^2, ($p \le 0.0001$).

The variability of measurements at each depth did not increase significantly with the change in source strength.

Effect of Attenuating Depth

The effect of different depths of water on BMD was dependent on source strength. Bone density did not differ with changes in water depth when using the hot source. When the colder source was used, however, the apparent BMD increased by 10.5% as the depth of the water was increased from 16.4 to 24.5 cm ($p \le 0.0001$).

The variability of repeated measurements increased significantly with the increase in water depth at both source strengths (Fig. 1). With the hot source, the standard deviation (s.d.) at the greater depth was almost

TABLE 1
The Effect of Attenuating Depth and Source Activity on Dual Photon Absorptiometry Results Measured with 7G Software

Source activity	DPA variable	Water depth: 16.5 cm	Water depth: 24.4 cm	Difference due to water depth	[%]
1.0 Ci	BMD (g/cm^2)	0.710 ± 0.004*	0.715 ± 0.014	0.005	[0.8]
	BMC (g/cm)	34.41 ± 0.18	34.78 ± 0.76	0.37	[1.1]
	Area (cm^2)	48.47 ± 0.18	48.62 ± 0.19	0.15	[0.3]
0.3 Ci	BMD (g/cm^2)	0.727 ± 0.005	0.813 ± 0.028	0.086	[10.5]†
	BMC (g/cm)	35.27 ± 0.30	39.74 ± 1.58	4.47	[12.7]†
	Area (cm^2)	48.50 ± 0.17	48.90 ± 0.29	0.40	[0.8]‡
Difference due to source Activity [%]	BMD (g/cm^2)	0.017 [2.4]†	0.098 [13.6]†		
	BMC (g/cm)	0.86 [2.5]†	4.96 [14.3]†		
	Area (cm^2)	0.03 [0.1]	0.28 [0.6]		

* Values are the mean ± 1 s.d. for 10 measurements (n = 10) with each combination of source activity and water depth.
† $p \le 0.0001$.
‡ $p \le 0.002$.

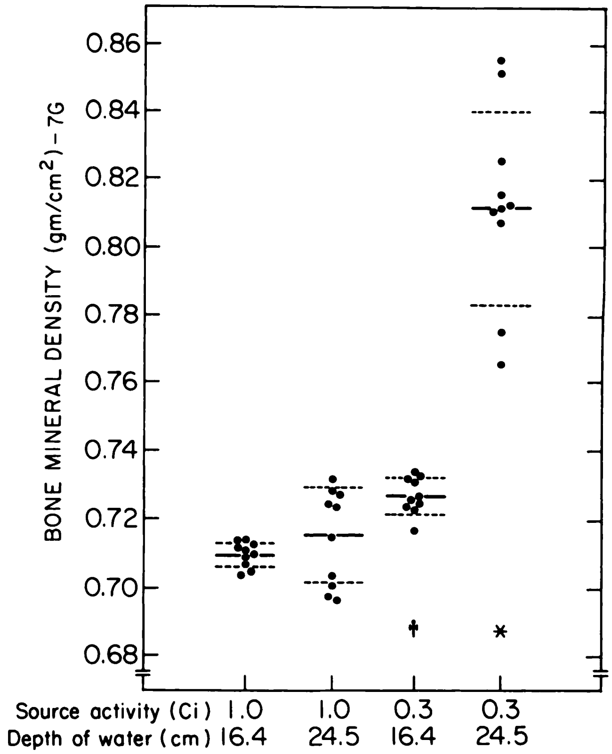

FIGURE 1
The effect of depth of water and source activity on dual photon absorptiometry results measured with 7G software. *Mean BMD is significantly higher than each of the other three groups ($p \leq 0.0001$). †Mean BMD is significantly higher than the hot shallow group ($p \leq 0.0001$).

fourfold larger than the s.d. of measurements made at the lesser depth ($p \leq 0.0004$). When using the cold sources, the s.d. increased more than fivefold with the increase in depth ($p \leq 0.0001$).

Effect of Software Revisions

The results of reanalyzing scans with software 8B are shown in Table 2, and Figure 2. 8B processing eliminated the effect of source strength on BMD when the measurements were made at the shallow water depth. At the greater depth, however, source strength continued to have a highly significant effect on BMD measurements ($p \leq 0.0001$).

The results of 8C reprocessing are presented in Table 3 and Figure 3. As with 8B software, changing the water depth did not significantly influence BMD when a hot source was in use. The mean BMD obtained with a cold source at the greater depth remained significantly higher than the means of each of the other three groups ($p \leq 0.0001$). However, these differences are significantly less with 8C than those obtained with 7G and 8B softwares (Table 4). At the extremes of the experimental conditions (cold-deep versus hot-shallow) the mean BMDs differed by 0.103 g/cm² (12.9%) for 7G and 0.039 g/cm² (5.1%) for 8C. The improvement with 8C software is significant ($p \leq 0.001$). Reprocessing with 8B and 8C did not influence the variability of repeated measurements in any of the groups.

Effect on BMC and Area

Analysis of BMD into its two components, BMC and area, reveal that the BMD differences found between groups are predominantly attributable to differences in BMC (Tables 1–3). There are significant differences in area measurements only in the cold-deep groups when using 7G and 8B softwares. These differences are small relative to the differences found in BMC. Unlike BMD and BMC, the variances of the area within the groups are homogeneous.

TABLE 2
The Effect of Attenuating Depth and Source Activity on Dual Photon Absorptiometry Results Measured with 8B Software

Source activity	DPA variable	Water depth 16.5 cm	Water depth 24.4 cm	Difference due to water depth	[%]
1.0 Ci	BMD (g/cm²)	0.718 ± 0.004*	0.723 ± 0.014	0.005	[0.7]
	BMC (g/cm)	34.81 ± 0.19	35.18 ± 0.75	0.37	[1.1]
	Area (cm²)	48.49 ± 0.19	48.65 ± 0.17	0.16	[0.3]
0.3 Ci	BMD (g/cm²)	0.714 ± 0.005	0.798 ± 0.027	0.084	[11.7]†
	BMC (g/cm)	34.65 ± 0.29	39.06 ± 1.54	4.40	[12.3]†
	Area (cm²)	48.52 ± 0.15	48.96 ± 0.29	0.44	[0.9]‡
Difference due to	BMD (g/cm²)	0.004 [0.5]	0.075 [10.3]†		
source	BMC (g/cm)	0.15 [0.4]	3.88 [11.0]†		
Activity [%]	Area (cm²)	0.03 [0.06]	0.31 [0.6]§		

* Values are the mean ± 1 s.d. for ten measurements (n = 10) with each combination of source activity and water depth.
† $p \leq 0.0001$.
‡ $p \leq 0.001$.
§ $p \leq 0.009$.

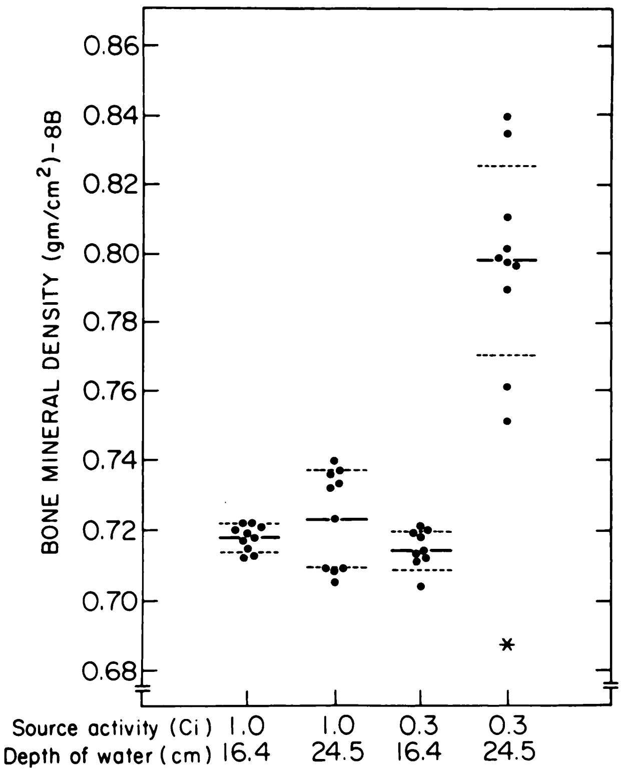

FIGURE 2
The effect of depth of water and source activity on dual photon absorptiometry results measured with 8B software. *Mean BMD is significantly higher than each of the other three groups ($p \leq 0.0001$).

DISCUSSION

Highly significant discrepancies in DPA measurements of BMD were found to be related to differences in source strength and simulated soft-tissue thickness. Revisions of software designed to improve the accuracy of BMD measurements reduced but did not eliminate these discrepancies. The results of this study suggest that all software evaluated here will overestimate BMD in subjects with thicker abdominal depths when a source of relatively low activity is used. The effect of source strength on BMD is consistent with previous reports of this problem (*12–17*). The effect of varying depths of soft-tissue equivalent on BMD measurements has not been previously reported.

The clinical relevance of these findings is underscored by the fact that all measurements were taken well within the range of source strengths and patient thicknesses encountered clinically. Although the absorption coefficient of water is higher than that of fat, the 8.1-cm difference in water depths evaluated in this study is equivalent to 8.8 cm of abdominal fat as seen by the 44 keV photon and 9.9 cm of fat as seen by the 100 keV photon (*21*). The maximum abdominal AP diameter measured in 105 nonobese women was 28 cm which could theoretically represent 12.5 cm of additional abdominal fat compared to the lowest depth studied (16.4 cm). Thus, the 8.1 cm of water used in this study (equivalent to 9.9 cm of fat) is representative of the range of abdominal fatness expected in nonobese women. The effect on DPA of greater photon attenuation with abdominal obesity may be even greater than that demonstrated here.

The usual method of assessing reproducibility of DPA involves repeated scans of a phantom immersed in a fixed depth of water or lucite (*1,5,10,13,14*). The deterioration of DPA precision with decreasing photon flux suggests that the use of a single source strength and/or a single depth of simulated soft tissue may yield misleadingly low estimates of precision error. In this study, an aluminum tube phantom was used purposefully to reduce the variability attributable to detection problems which are associated with the irregular ge-

TABLE 3
The Effect of Attenuating Depth and Source Activity on Dual Photon Absorptiometry Results Measured with 8C Software

Source activity	DPA variable	Water depth 16.5 cm	Water depth 24.4 cm	Difference due to water depth	[%]
1.0 Ci	BMD (g/cm²)	0.722 ± 0.005*	0.724 ± 0.012	0.002	[0.3]
	BMC (g/cm)	35.02 ± 0.27	35.23 ± 0.62	0.20	[0.6]
	Area (cm²)	48.54 ± 0.15	48.66 ± 0.14	0.12	[0.2]
0.3 Ci	BMD (g/cm²)	0.714 ± 0.007	0.761 ± 0.020	0.047	[6.1]†
	BMC (g/cm)	34.69 ± 0.42	37.10 ± 1.08	2.41	[6.9]†
	Area (cm²)	48.56 ± 0.20	48.74 ± 0.24	0.18	[0.4]
Difference due to	BMD (g/cm²)	0.008 [1.0]	0.037 [5.1]†		
source	BMC (g/cm)	0.34 [1.0]	1.87 [5.3]‡		
Activity [%]	Area (cm²)	0.02 [0.04]	0.08 [0.2]		

* Values are the mean ± 1 s.d. for 10 measurements (n = 10) with each combination of source activity and water depth.
† $p \leq 0.0001$.
‡ $p \leq 0.0002$.

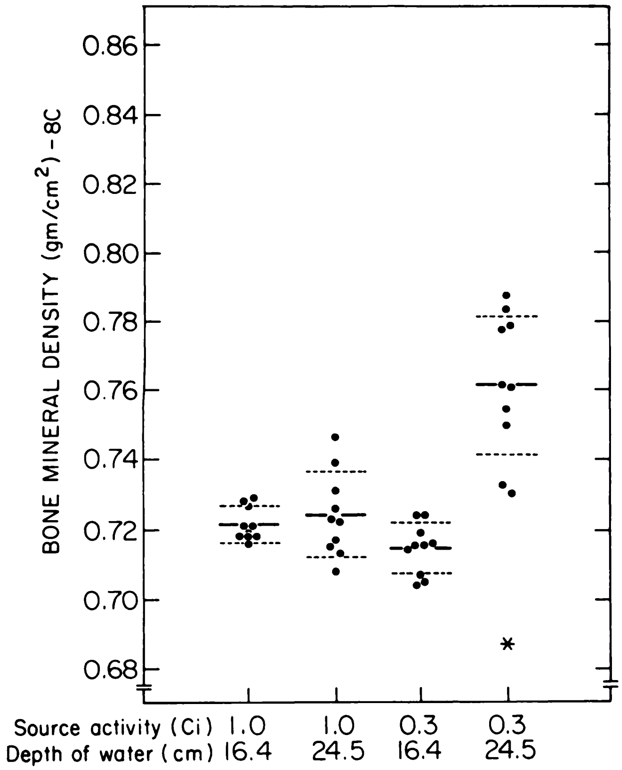

FIGURE 3
The effect of depth of water and source activity on dual photon absorptiometry results measured with 8C software. *Mean BMD is significantly higher than each of the other three groups ($p \leq 0.0001$).

ometry of lumbar vertebrae. In vivo measurements may, therefore, be even less precise than those documented here with an aluminum phantom.

It has been suggested that BMD data can be corrected for the differences in count rates by using equations derived from longitudinal measurements of a phantom immersed in a fixed depth of soft-tissue equivalent (*13*, *14*). The interaction of count rate and depth of attenuating media on BMD measurements demonstrated by this study suggest that these correction factors will not be applicable to patients with soft tissue thicknesses which differ from that used to measure the phantom. If applied to all subjects, these correction factors could introduce new error by systematically under and over correcting BMD in thicker and thinner subjects, respectively.

The etiology of the errors in BMD resulting from differences in source strength and soft-tissue thickness cannot be determined from this study. The changes in the apparent BMD observed with 7G software suggest that BMD is artifactually increased as photon flux reaching the detector decreases. Whether the effect of source strength and soft-tissue depth on BMD is operative throughout a source life (i.e., a linear effect) or is only operative below a certain level of photon flux (i.e., a threshold effect) is not clear. This study examined only four of the many possible combinations of source activities and simulated patient thicknesses. Further studies evaluating other combinations of source activity and patient thickness as well as variations in soft tissue composition are necessary.

Recently, DPA using an x-ray tube as a photon source has been introduced. To the extent that this approach provides an abundant and stable source of photons, the variability due to source strength will have been eliminated. Whether the specific algorithm used to correct for variations in soft-tissue thickness at a given photon flux in x-ray-based DPA is sufficient to correct for the effect on variations in thickness encountered clinically cannot be predicted. Software developed for the x-ray tube method should be evaluated.

In conclusion, systematic errors have been identified

TABLE 4
The Effect of 7G, 8B, and 8C Software on Group Differences in Mean Bone Mineral Density (BMD)

	BMD differences between groups (g/cm²) [%]				
	Software 7G	p (7G–8C)	Software 8C	p (8C–8B)	Software 8B
COLD DEEP – HOT SHALLOW	0.103 [12.9]	p = 0.001	0.039 [5.1]	p = 0.01	0.080 [10.0]
COLD DEEP – HOT DEEP	0.098 [12.1]	p = 0.001	0.037 [4.9]	p = 0.01	0.075 [9.4]
COLD DEEP – COLD SHALLOW	0.086 [10.6]	p = 0.01	0.047 [6.2]	p = 0.01	0.084 [10.5]

p Value for the effect of software on differences between mean BMD of group and each of the other groups.

in BMD determinations which are associated with differences in both source activity and soft tissue thickness. These errors are of sufficient magnitude to adversely affect precision and introduce significant bias in cross-sectional and longitudinal DPA studies whenever unequal distribution of source strength and soft-tissue thickness exist or whenever these parameters change over time. In addition, the clinical utility of DPA as a diagnostic tool to detect osteopenia in individual patients may be adversely affected by these problems, particularly in thicker patients measured at low source activities. Software modifications designed to correct these errors require rigorous evaluation before use and, in our study, improved but did not eliminate the problems. Appropriate correction of these errors will require further definition of the relationships between photon flux and BMD. In the interim, investigators and clinicians employing DPA should assess their studies for the influence of these potential sources of bias and carefully monitor longitudinal reproducibility in a wide range of clinically relevant conditions.

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