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Relationship between patient exposure and measurement precision in dual-photon absorptiometry of the spine

J A Sorenson†
LUNAR Radiation Corporation, Madison, WI, USA

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Abstract. Computer simulations and experimental studies were performed to investigate the relationship between patient exposure and measurement precision in dual-photon absorptiometry (DPA). Systems employing ^{153}Gd, K-edge filtered x-rays and dual-kV x-rays were analysed. The results indicate that, except for added exposure due to beam-profile overlap between scan lines, currently available systems are capable of operating at or near the limits of statistical precision per unit of patient exposure. They further indicate that there are no major advantages in exposure requirements for x-ray systems as compared to ^{153}Gd systems.

1. Introduction

Patient exposure is small in dual-photon absorptiometry (DPA) in comparison to other radiological examinations. Nevertheless, it is a consideration when repeated measurements are made to detect small changes in bone mineral density (BMD) and in studies on younger subjects. Over the years, a wide range of exposure or dose values have been reported for ^{153}Gd systems (1–18 mrad, see table 1). The discrepancies between reported values are relatively large and are not explained by adjustment source activity. More likely, they are the result of differences in scanning techniques, e.g. to the amount of beam-profile overlap between scan lines, possibly to radioactive source contaminants.

Table 1. Summary of reported-radiation exposure and precision for DPA of the spine with ^{153}Gd

Reference	Source activity (Ci)	Entrance exposure or dose	Precision (%)	
			Phantoms	Patients
U W Bone Lab (1973)	0.2	1 mR	—[a]	—[a]
Wilson and Madsen (1976)	1.5	2 mrad	1.7	0.7–3.8
Krolner *et al* (1980)	1.0	10 mrad	1.6–2.3	1.4–2.6
Tothill *et al* (1983)	0.3	14 mrad	1.2–2.4	1.0–3.0
Wahner *et al* (1984)	1.5	18 mrad	1.8	2–3
Beck (1986)	1.0	5.3 mrad	—[a]	—[a]
Riis and Christiansen (1988)	1.0	—[a]	—[a]	4–5
Slemenda and Johnston (1988)	—[a]	—[a]	—[a]	1.4

[a] Not specified.

† Current address and address for reprint requests: University of Wisconsin, Magnetic Resonance Imaging Center, Waisman Center S-117, 1500 Highland Avenue, Madison, WI 53705, USA.

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Data are becoming available on newer x-ray based systems suggesting that they may operate at lower exposure levels than ^{153}Gd systems (Sorenson *et al* 1988, Wahner *et al* 1988); however, the degree of improvement is not yet clear, especially in view of the wide variability of reported exposure/dose values for ^{153}Gd systems.

Precision is critical in DPA because it limits the detectability of small changes in BMD. Precision for measurement of spinal BMD with ^{153}Gd systems has been reported in the range of 1.2–2.4% on phantoms, and anywhere from 0.7-5% on patients (table 1). Early reports suggest that precision errors with x-ray systems are smaller (Wahner *et al* 1988), in the range of 0.5% for phantoms and 1% for patients.

Patient exposure and measurement precision are inter-related. Statistical precision refers to precision error resulting solely from random variations in counting rates. Unlike other causes of precision error, such as instrument drift, edge finding, or patient positioning, statistical precision error is unavoidable and uncorrectable. Thus, it establishes a minimum precision error that can be achieved for a given scanning system design, and can serve as a 'target' for clinical measurement precision.

The purpose of this study was to investigate the relationship between statistical precision error and patient exposure for measurement of spinal BMD. Computer simulations were used to predict these relationships, and experimental studies on phantoms were used to verify them. Realistic spine phantoms were used to eliminate biological variables in experimental studies. Since precision ultimately is limited by counting statistics, which are directly related to patient exposure, these relationships define the ultimate limits of patient exposure and precision error for clinical measurements.

2. Methods

Computer simulations were used to estimate patient entrance exposures and detected photon fluences for DPA scans using ^{153}Gd, and for x-ray based systems using constant kV with K-edge beam filters, as well as for systems employing dual kV. The emission spectrum for ^{153}Gd was taken from the *Table of Radioactive Isotopes* (Brown and Firestone 1986), corrected for self-absorption in a 1 mm thick Gd_2O_3 source pellet and for attenuation by a 0.0635 mm thick (0.025 in) source capsule. X-ray spectra were taken from the *Catalog of Spectral Data for Diagnostic X-rays* (Birch *et al* 1979), modified for attenuation by various beam filters. Constant potential spectra were used in all cases. Characteristics of the ^{153}Gd and x-ray spectra are summarized in table 2.

In the computer simulations, transmitted photon fluences were calculated in 1 keV intervals. A detection efficiency of 100% and perfect discrimination of high- versus low-energy photons were assumed. For the K-edge filter techniques, the spectrum was

Table 2. Spectral characteristics of systems analysed in this study

System	Spectrum
^{153}Gd	40.9 keV (0.135[a]), 41.5 keV (0.256), 47.0 keV (0.090), 48.5 keV (0.028), 69.7 keV (0.008), 97.4 keV (0.164), 103.2 keV (0.124)
X-rays: K-edge filtered	80 kV, 2 mm Al + 0.033 g cm^{-2} Ce filter
X-rays: switched kV	70 kV, 4 mm Al filter
	140 kV, 4 mm Al + 3.1 mm Cu filter

[a] Photons/disintegration.

divided just above the K-shell absorption edge. For ^{153}Gd, low-energy counts were integrated from 40–50 keV and high-energy counts from 90–105 keV. For the dual-kV simulations, the full spectrum was integrated for each kV. It was further assumed that no scattered radiation was detected, since scatter levels are small ($\leqslant$10%) for beam dimensions used in DPA (<1 cm^2) (Motz and Dick 1975). It was also assumed that measurement noise was due to quantum statistics. Additional details of the simulation model may be found in Sorenson *et al* (1989).

Measurements of entrance (table-top) exposure were made on a ^{153}Gd system (LUNAR DP3, 4.5 mm line spacing, 5 mm s^{-1} scan speed, 3 mm diameter source collimator, source–collimator length 72 mm, source–table-top distance 85 mm) and on a K-edge filtered x-ray system (LUNAR DPX, 76 kV, 0.35 g cm^{-2} Ce filter, 0.75 mA tube current, 1.2 mm line spacing, 80 mm s^{-1} scan speed, 1.7 mm diameter source collimator, source–collimator length 80 mm, source-table-top distance 93 mm), using both thermoluminescent dosimeters (TLD) and an ionization chamber. Multiple scans (typically 25) were performed and exposures integrated to achieve exposure levels that were significantly above background levels. These experimental results were then compared with data from the computer simulations.

Statistical precision was estimated for different detected photon counting rates from the basic equations for computing BMD. The equation for computing BMD at a single point is

$$\mathrm{BMD} = \mathrm{CF}[(R \ln N_{\mathrm{hb}} - \ln N_{\mathrm{lb}}) - (R \ln N_{\mathrm{hs}} - \ln N_{\mathrm{ls}})] \tag{1}$$

where N_{hb} and N_{lb} are the high- and low-energy counts measured through bone, N_{hs} and N_{ls} are the counts measured through soft tissue adjacent to bone, $R(=\mu_{\mathrm{ls}}/\mu_{\mathrm{hs}})$ is the ratio of the low- to high-energy attenuation coefficients of soft tissue, and CF is the calibration factor for converting the bracketed quantity into units of BMD (g cm^{-2}).

In practice, BMD are measured at many points through bone and adjacent soft tissue, n_{b} and n_{s} respectively. Under these conditions, it can be shown that the statistical precision error in the *average* BMD in a scan measurement is given by

$$\sigma = \mathrm{CF}\left\{(1/n_{\mathrm{s}})^2 \sum_i [(R^2/N_{\mathrm{hs},i}) + (1/N_{\mathrm{ls},i})] + (1/n_{\mathrm{b}})^2 \sum_j [(R^2/N_{\mathrm{hb},j}) + (1/N_{\mathrm{lb},j})]\right\}^{1/2} \tag{2}$$

where $N_{\mathrm{hs},i}$ and $N_{\mathrm{ls},i}$ are counts measured at n_{s} individual soft-tissue measurement points, and $N_{\mathrm{hb},j}$ and $N_{\mathrm{lb},j}$ are counts measured at n_{b} individual bone measurements points (units of σ are g cm^{-2}). This result follows from the propagation of statistical errors in individual counting measurements according to

$$\sigma^2 = \sum_k (\partial \mathrm{BMD}/\partial N_k)^2 \sigma_k^2 \tag{3}$$

where the N_k are individual counting measurements and $\sigma_k^2 = N_k$.

To test the validity of equation (2) for predicting statistical precision error, nine sets of 10 scans each of a realistic spine phantom were performed using a K-edge filtered x-ray scanner (LUNAR DPX). The phantom consisted of three defatted human vertebral bodies (L2–L4) encapsulated in 10 cm thick acrylic. The average BMD of the vertebral bodies was 1.0 g cm^{-2}. To avoid positioning errors, the phantom was not moved between scans. Counts were varied between different sets of scans by adjusting x-ray tube current and/or the amount of soft-tissue-equivalent material overlying the phantom. A similar experiment was performed at two different count levels using a ^{153}Gd DPA scanner (LUNAR DP3) and two different source activities. The precision obtained in these experiments was compared to statistical precision predicted from equation (2).

3. Results

3.1. Patient exposure

Table 3 summarizes patient entrance exposures predicted from computer simulations for DPA scanners using ^{153}Gd and x-ray sources. Also listed are values measured on two LUNAR scanners and reported values for a dual-kV scanner.

Table 3. Predicted and measured entrance exposures.

	Entrance exposure (mR)	
System	Predicted	Measured
^{153}Gd (1 Ci)	0.6	0.9 1.3[b]
X-rays: K-edge filtered	1.1	0.9
X-rays: switched kV	3.5[a]	3.4[b]

[a] For same scanning geometry and statistical precision in measured BMD as K-edge filtered system (Sorenson *et al* 1989).
[b] Wahner *et al* (1988). ^{153}Gd values normalized to same scan speed and line spacing as our simulations and measurements.

The effects of beam-profile overlap were taken into account in computing the predicted exposure values for ^{153}Gd. For the geometry of the DP3 system, described above, only about one-third of the photons incident on the patient are within the useful beam. Thus, the predicted exposure for ^{153}Gd given in table 3 is three times greater than its theoretical minimum. For both of the x-ray systems analyzed, virtually all of the incident photons are within the useful beam; thus, the predicted exposure is also the theoretical minimum.

There was good agreement between the predicted and measured or reported exposure values for the x-ray systems. Somewehat larger discrepancies were noted for the ^{153}Gd system, possibly due to discrepancies in the assumed amount of beam filtration and beam geometry parameters, which can have significant effects on actual exposure levels.

Nevertheless, both the computed and measured values for the ^{153}Gd DPA system were smaller than most previously reported values (table 1). Some of this discrepancy may have been due to differences in beam geometry and scan parameters. Also, some ^{153}Gd sources produced in the past contained small but significant quantities of high-energy contaminants, principally isotopes of europium and terbium. These high-energy contaminants produce relatively low but constant levels of background radiation during the entire 15–30 min scan, which could have been a significant contributor to total exposure for earlier systems.

3.2. Statistical precision

Figure 1 shows the results of experiments conducted on a K-edge filtered x-ray scanner (LUNAR DPX), comparing statistical precision computed from equation (2) against

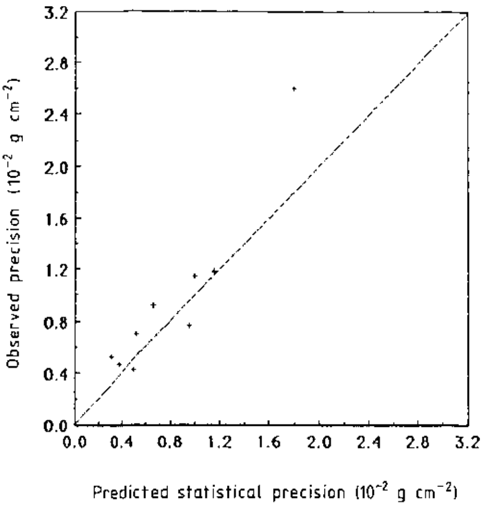

Figure 1. Observed precision (SD) for nine sets of 10 measurements each of an L2–L4 spine phantom with a K-edge filtered x-ray scanner at different counting levels plotted against statistical precision predicted from photon counting statistics.

observed precision error (SD) for nine sets of 10 scans each of a realistic spine phantom. There was good agreement between observed and predicted precision for precision errors as small as 0.004 g cm^{-2} (0.4% on this phantom, which had an average BMD of 1.0 g cm^{-2}). The only major discrepancy occurred for very low count rates, corresponding to an equivalent patient thickness of 30 cm, which provided such low counting rates that edge finding was difficult.

Equation (2) was also used to predict statistical precision errors for scans of spine phantoms on a ^{153}Gd scanner (LUNAR DP3). The observed precision error in a set of 35 scans was 1.1%, against a predicted statistical precision of 1.0%. For a 'slow scan' (3 mm line spacing, 2.5 mm s^{-1} scan speed) on a somewhat thinner phantom, the observed precision error in a series of 25 scans was 0.55%, against 0.5% predicted from equation (2).

These results indicate that both x-ray and ^{153}Gd scanners are capable of operating at or near the limits of statistical precision on realistic spine phantoms. They are also in agreement with the results of Tothill *et al* (1983) who achieved precision on spine phantoms with a ^{153}Gd scanner at levels predicted from photon statistics.

Table 4 summarizes predicted statistical precision versus patient thickness and spinal BMD for a ^{153}Gd scanner. Virtually identical trends in precision error were obtained in similar calculations for the two x-ray systems. Note that statistical precision

Table 4. Statistical precision, in g cm^{-2} (or %) versus patient thickness and BMD.[a]

Patient thickness (cm)	BMD (g cm^{-2}) 0.6	1.0	1.4
15	0.004 (0.7%)	0.006 (0.6%)	0.007 (0.5%)
20	0.009 (1.5%)	0.010 (1.0%)	0.011 (0.8%)
25	0.016 (2.7%)	0.018 (1.8%)	0.020 (1.4%)

[a] Values for 15 min scans (4.5 mm line spacing, 5 mm s^{-1} scan speed) using a 0.5 Ci ^{153}Gd source with 13 mm detector collimator.

error expressed as a percentage of BMD decreases significantly with increasing BMD. For example, for a 20 cm thick patient, the predicted precision error is 1.5% for a spine with average BMD of 0.6 g cm^{-2} whereas it is only 0.8% in a spine with average BMD of 1.4 g cm^{-2}.

Note also that statistical precision errors increase by about a factor of two for each 5 cm increase in patient thickness. Similar results were obtained from the simulations for x-ray systems. Thus, measurements made on thick phantoms or on patients with low BMD will have poorer *percentage* precision than measurements made on thin phantoms or patients with high BMD. Results obtained under these extreme conditions might not accurately reflect what is achievable on 'average' patients.

4. Discussion

Based on the simulation studies and experiments reported here, as well as studies reported by others in the literature, the following conclusions are offered.

(1) The minimum exposure for a K-edge filtered x-ray system for measurement of 1 g cm^{-2} bone mineral in a 20 cm thick patient with 0.5% precision is about 1 mR. For dual-kV systems, the minimum exposure requirement is about 3 mR for the same precision (Wahner *et al* 1988).

(2) In theory, ^{153}Gd systems should require less exposure than either of the x-ray systems, because of the somewhat more favourable distribution of photon energies for this source (Sorenson *et al* 1989). In practice, ^{153}Gd systems are intermediate to the K-edge filtered and dual-kV x-ray systems, due to their larger source dimensions, which result in significant beam-profile overlap between scan lines. For example, extrapolating from the simulation results (which include the effects of beam-profile overlap) presented in table 4, statistical precision of 0.5% for measurement of 1 g cm^{-2} BMD in a 20 cm thick patient would require a 2 Ci ^{153}Gd source. According to table 3, this would require a minimum entrance exposure of about 2 mR.

(3) Precision at or near the limit of photon statistics can be achieved on phantoms with both ^{153}Gd and x-ray sources. Precision at near-minimum levels has been achieved in clinical practice by some investigators (Slemenda and Johnston 1988).

(4) Precision ultimately is limited by photon statistics, which in turn are directly related to patient exposure. Reports of precision errors with exposures smaller than theoretical minimum limits should be interpreted with caution.

Precision errors cannot be reduced to indefinitely small values, particularly with ^{153}Gd systems, due to the need for long scan times (patient motion) and the effects of limited spatial resolution (edge finding). Intrapatient variability in soft-tissue composition also contributes errors that are beyond those that can be controlled by photon counting statistics, which can be comparable in magnitude to the statistical limits of 0.5% of modern x-ray scanners (Sorenson 1990). Nevertheless, with careful attention to measurement techniques, such as patient positioning and selection of bone edges, stable detectors and electronics, and with feature improvements in hardware (e.g. automatic gain stabilizers) and software (e.g. for more reliable edge finding) it should be possible to achieve clinical precision at the 0.5–1% level that has been achieved on phantoms.

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Note added in proof. The SI conversion factors for units used in this paper are 1 Ci = 3.7×10^{10} Bq; 1 rad = 10^{-2} Gy; 1 R = 2.58×10^{-4} C kg^{-1}.

Résumé

Relation entre l'exposition du patient et la precision de la mesure en absorptiometrie bi photonique de la moelle.

L'auteur a réalisé des simulations sur ordinateur et des études expérimentales afin d'étudier la relation entre l'exposition du patient et la précision de la mesure en absorptiométrie bi photonique (DPA), les systèmes utilisant le Gd-153, les rayons X filtrés par la raie K et les rayons X à double haute tension ont été analysés. Les résultats montrent que, en dehors des expositions cumulées dues au recouvrement des faisceaux entre les profils analysés, les systèmes couramment utilisés sont capables d'opérer aux, ou près, des limites de précision statistiques par unité d'exposition de patient. Ils indiquent en outre qu'il n'y a pas d'avantages majeurs vis-à-vis de l'exposition pour les systèmes à rayons X comparés aux systèmes à Gd-153.

Zusammenfassung

Beziehung zwischen der Strahlenexposition des Patienten und der Meßgenauigkeit bei der Zwei-Photonenabsorptiometrie der Wirbelsäule

Computersimulationen und experimentelle Untersuchungen wurden durchgeführt, um die Beziehung zwischen Patientenexposition und Meßgenauigkeit bei der Zwei-Photonenabsorptiometrie (DPA) zu untersuchen. Systeme mit Gd-153, K-Kanten gefilterten Röntgenstrahlen und Röntgenstrahlen zweier kV-Werte wurden analysiert. Die Ergebnisse zeigen, daß, außer, für zusätzliche Exposition durch Überlappungen der Straphlprofile zwischen den Abtastlinien, die zur Zeit erhältlichen Systeme, an oder nahe den Grenzen statistischer Genauigkeit der Patientenexposition betrieben werden. Des weiteren zeigt sich, daß es keine großen Vorteile bzgl. der notwendigen Exposition bei Röntgensystemen gegenüber Gd-153 Systemen gibt.

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