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Bone Densitometry of the Forearm: Comparison of Single-Photon and Dual-Energy X-Ray Absorptiometry

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Forearm bone mineral densitometry was performed initially by single-photon absorptiometry (SPA), but is now achievable by dual-energy X-ray absorptiometry (DXA) as well, with a good correlation between both measurements. However, it is still unknown whether: (1) short-term precision of DXA is superior to SPA and (2) identical regions of interest (ROI) are mandatory to correlate SPA with DXA. The aim of this study was to answer these questions using a commercial system for DXA (DXA-FAS) and to test an in-house system using spine DXA and a soft-tissue compensator (DXA-STC). In ten subjects, four measurements on the same day showed significantly lower ($p < 0.05$) coefficients of variation (CV) for bone mineral density (BMD) by DXA-FAS (proximal site: 0.74%; ultradistal site: 1.20%) than by SPA (1.26% and 2.25%). However, the CV for bone mineral content (BMC) were similar for DXA-FAS (0.73% and 1.58%) and SPA (0.79% and 1.34%). The significant difference ($p < 0.05$) for surface calculation by DXA-FAS (1.24% and 0.93%) compared with SPA (2.36% and 1.28%) explains all the advantages of DXA-FAS for short-term precision. The measurements taken on the same day on the ulna and the radius or on the radius alone by SPA, DXA-FAS, and DXA-STC on 108 subjects aged 18–80 years were highly correlated [r ranging from 0.925 to 0.995 ($p < 0.0001$) and standard error of the estimate from 3.15% to 8.89%]. The need for a manual adjustment of the ROI was found to be mandatory for BMC but not BMD assessment. The use of DXA-STC is a fast method for forearm bone densitometry and its correlation with SPA is very high. However, its short-term precision for BMC (3.00% and 1.54%), BMD (2.15% and 1.12%), and surfaces (1.99% and 1.12%) is significantly higher ($p < 0.05$) than that of DXA-FAS. We conclude that short-term precision of DXA is better than that of SPA only for BMD and surface measurement but not for BMC. ROI should be adjusted manually for the assessment of BMC but not for that of BMD. (*Bone 18:575–579; 1996*)

Key Words: Single-photon absorptiometry; Dual-energy X-ray absorptiometry; Forearm densitometry; Bone mineral density; Bone mineral content; Osteoporosis.

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Introduction

Single-photon absorptiometry (SPA) is the oldest reliable method of bone densitometry and has been extensively used for bone mass measurement of appendicular skeleton since 1963, when it was first described by Cameron and Sorenson.[2] The development of new methods of axial bone densitometry [dual-photon absorphometry (DPA) and dual-energy X-ray absorptiometry (DXA)] progressively raised the question about the usefulness of appendicular bone densitometry, particularly because of the relatively poor correlation between bone mineral density (BMD) of the forearm and that of the spine.[25,28] Nevertheless, several studies reported the value of forearm densitometry for the assessment of risk fracture,[7,8,15,22,23,27] either for spine[21,26] or for hip and other bones.[1,5,6,10,11] There is agreement that osteoporosis can be diagnosed by densitometry at various sites of the skeleton, and SPA is one of the methods recommended by a Consensus Conference on Osteoporosis.[4] The measurement of the ultradistal regions of the radius and the cubitus, which contain a higher proportion of trabecular bone, improves the correlation between forearm and spine densities.[19,20] Additionally, the ultradistal site shows a greater loss of bone during the first postmenopausal decade than other sites of the forearm.[24]

Dual-energy X-ray absorptiometry (DXA) was first developed for spine and hip measurements. Its main advantages over DPA consist in better precision, a shorter examination time, a reduced radiation dose, and no need for photon source replacement.[12,29] Recently, DXA software for the forearm was developed, allowing the same equipment to be used for multisite densitometry. Several studies have pointed out a very high correlation between SPA and DXA for forearm densitometry.[13,14,17,18,30] Although the accuracy of DXA has been demonstrated,[9] its better precision than that of SPA remains controversial.[13,14,17,18]

Moreover, DXA equipment does not measure the same regions of interest (ROI) as SPA, and it is not known whether this is relevant.[18]

This study aimed to compare in the same groups of patients the precision and correlation of forearm bone mass measurement with or without the same ROI, by SPA or DXA using either commercial software or in-house equipment (commercial spine software and a soft-tissue compensator).

Materials and Methods

Equipment

Single-photon absorptiometry was performed using a Nuclear Data 1100 bone mineral analyzer (Nuclear Data, Schaumburg,

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IL) loaded with a source of iodine 125 with an energy of 27 keV. The patient plunged his forearm into a water-filled bag and maintained it in an intermediate position with the help of a handle.

The measurement started at an interosseous space between ulna and radius of 8 mm; six proximal scans 4 mm apart (SPA Prox) and four distal scans 2 mm apart (SPA UD) were obtained. After a proximal translation of 4 cm, six additional scans 2 mm apart were obtained (SPA Mid).

The mean values of bone mineral content (BMC) and bone mineral density (BMD) were calculated for each region. BMC is expressed as arbitrary units of absorption (UA) after correction for fat absorption. BMD is expressed as grams of bone divided by the projected area of the measured bone (g/cm^2) after the conversion of units of absorption in grams of bone. The projected area (Area) equals the length of the scanned bone, measured in millimeters, multiplied by a factor depending on the number and the distance between each scan. SPA examination time was 8–10 min. Daily calibration was achieved by measuring a standard phantom. The coefficient of variation in vitro over a 2-year period was 0.78%.

Dual-energy X-ray absorptiometry was performed with a Hologic QDR 1000 bone densitometer (Hologic, Waltham, MA) with an X-ray source of switched-pulsed energy of 70 and 140 keV.

Two methods were used for bone densitometry of the forearm:

1. Commercial forearm software (DXA-FAS) (Forearm Version 5.26, Hologic, Waltham, MA) was supplied by the manufacturer. The patient's forearm was positioned against a foam block in a prone position with the hand flat. The transverse scanning speed was 30 mm/sec and the longitudinal increment was 1 mm. Pixels measured 0.5 × 1 mm. The examination time ranged between 6 and 8 min.
2. Standard spine software and an in-house soft-tissue compensator (DXA-STC) were used as described by Casez et al.,[3] consisting of a nylon bag filled with an organic powder and limited on the upper and lateral sides by a plastic box. The patient's forearm was slipped into the bag. X-ray absorption of the powder was similar to that of the patient's soft tissues. This device compensated for the heterogeneity of soft-tissues thickness around the ulna and radius and afffored an optimal baseline calculation. The transverse scanning speed was 60 mm/sec and the longitudinal increment between two contiguous scans was 1 mm, cutting pixels of 1 × 1 mm. Low-threshold software was used for the analysis (Ultra High, Version 4.10, Hologic, Waltham, MA) allowing better edge detection of bone of very low density. The time required for the examination was about 4 min.

For both DXA systems, BMC is expressed in grams, and BMD in grams per square centimeter, and the projected area of the scanned bone in square centimeters. Quality control was achieved daily using a lumbar spine anthropomorphic phantom made of hydroxyapatite-equivalent plastic material embedded in an epoxy matrix. Over a 1-year period, the coefficient of variation in vitro was 0.41%.

Scan Analyses: Determination of ROI

SPA. In the analysis process of SPA scans, the ROI were determined by the measurement protocol.

DXA. Commercial version: For DXA-FAS scans, the ROI were chosen by the manufacturer. The height of the global ROI equals the third of the length of the forearm measured from the ulnar styloid process to the olecranon, plus 10 mm. The top of the ROI was placed on the tip of the ulnar styloid process. Then, three sub-ROI were automatically determined: (a) the midshaft region (DXA Mid)—that is, the most proximal 20 mm; (b) the ultradistal region (DXA UD)—that is, the most distal 15 mm to the terminal end plate of the radius; and (c) the proximal region (DXA Prox)—that is, the whole intermediate region. After a first analysis according to manufacturer, all scans were reanalyzed manually (DXA-FASm) with ROI determined to match exactly the ROI of SPA. It implied the determination of the 8 mm interosseous starting point between radius and ulna by visual means on the computer screen.

For DXA-STC scans, the ROI were defined only manually, to match those of SPA, as described for DXA-FASm scans.

Precision

Short-term precision of SPA, DXA-FAS, and DXA-STC was assessed in vivo for ten volunteers (six normal and four osteoporotic persons). Each volunteer had, on the same day, four bone density measurements of the forearm at proximal and ultradistal sites with each of the three methods. The forearm was repositioned between each measurement.

Subjects

Bone densitometry of the nondominant forearm (except in the case of previous fracture) was performed in 108 persons: There were 85 women and 23 men, ages 18 to 82 years [mean age ± Standard deviation SD = 53.8 ± 15.1 years]. The subjects were volunteers recruited among the hospital community and patients from the Mineral Metabolism Unit. The sample was composed by 55 normal and 53 osteoporotic persons defined by a previous vertebral or femoral fracture. The characteristics of the 108 persons were (mean ± SD, range): BMI: 24.3 ± 0.4 kg/m^2, 16.7–36.1; SPA BMD-UD: 0.300 ± 0.082 g/cm^2, 0.150–0.520; and SPA BMD-Prox: 0.409 ± 0.097 g/cm^2, 0.220–0.670.

For each subject, forearm densitometry by the different methods was performed on the same day. Among the 108 persons, a first group of 48 subjects had densitometry of the forearm at ultradistal and proximal sites with SPA and DXA-STC. A second group of 31 subjects had densitometry at the same sites with SPA, DXA-STC, and DXA-FAS. A third group of 29 subjects were measured at ultradistal, proximal, and midshaft sites with SPA, DXA-STC, and DXA-FAS.

The protocol study was approved by the Ethical Committee of the University Hospital. All subjects gave their written informed consent.

Statistical Analysis

Precision study. Precision error was calculated as the percentage (coefficient of variation = SD ÷ mean) as well as the absolute value for each densitometer, for the values of BMC, Area, and BMD at the UD and Prox sites. Comparison between the different systems was made by a one-way analysis of variance, $p < 0.05$ was considered significant.

Correlation study. Linear regression analysis was done between SPA and DXA. As one aim of this study was to correlate SPA used for a long time in longitudinal studies and DXA newly in use, SPA was considered to be the independent variable and DXA the dependent variable. Equations of the curve (a and b

values), Pearson correlation coefficient and standard error of the estimate (SEE) (expressed as a percentage) were calculated for each regression. A F-test was performed for each regression, and $p < 0.05$ was considered significant.

Results

Short-term reproducibility is displayed in **Table 1** and includes results for BMC, projected areas of scanned bones, and BMD measured at ultradistal and proximal sites. Results are expressed as a percentage (coefficient of variation) as well as absolute values.

The CV for BMC measurements with SPA or DXA-FAS were not significantly different at any site (UD: SPA = 1.34 and DXA-FAS = 1.58; Prox: SPA = 0.79 and DXA-FAS = 0.73). On the other hand, the study on surfaces revealed a significant difference ($p < 0.05$) between the CV of SPA and that of DXA-FAS for the ultradistal site (SPA = 2.36; DXA-FAS = 1.24) but only a nonsignificant trend at the proximal site (SPA = 1.28; DXA-FAS = 0.93). For BMD determinations, the CV were significantly higher for SPA (UD = 2.25; Prox = 1.26) than for DXA-FAS (UD = 1.20; Prox = 0.74), whatever the site measured.

The CV of the DXA analyses with ROI determined manually (DXA-FASm) were similar to those of DXA-FAS for BMC, Area, and BMD. The CV of DXA-FASm revealed a significant difference with SPA for Area-UD, BMD-UD, and BMD-Prox measurements. The CV of DXA-STC were higher ($p < 0.05$) than those of SPA for BMC at the ultradistal (DXA-STC = 3.00; SPA = 1.34) and proximal sites (DXA-STC = 1.54; SPA = 0.79), but they were similar for Area and BMD. Except for the measurement of Area-Prox, the CV of DXA-STC always were higher than those of DXA-FAS.

Linear regression analyses between SPA and DXA for densitometry of the forearm (ulna and radius) are shown in **Table 2.** For the measurement of BMC, the comparisons were made only between methods with ROI covering the same areas. Pearson correlation coefficients ranged from 0.925 to 0.995 and were highly significant ($p < 0.0001$). The SEE of the linear regression always was under 9%. For BMD measurement, r values remained highly significant, ranging from 0.933 to 0.975. Again, the SEE was under 9%.

The correlations between SPA and DXA-STC were slightly but not significantly better than those between SPA and DXA-FAS. Interestingly, the correction of the ROI of DXA-FAS did not enhance the correlation with SPA, nor did it reduce the value of the SEE. The best correlation was achieved between SPA and DXA-STC for measurement of BMC at proximal site **(Figure 1).**

Table 3 gives the analyses of the linear regression between SPA and DXA-FAS for the assessment of BMD of the radius alone. As for the correlation between SPA and DXA-FAS for ulna and radius, r values were highly significant ($p < 0.0001$), ranging from 0.925 to 0.957. The SEE always was under 8%.

Table 2. Linear regression analyses between SPA (independent variable) and DXA (dependent variable) for bone densitometry of the forearm

	DXA	Site	n	a	b	r^a	SEE (%)
BMC	FASm	UD	60	0.129	0.025	0.971	7.16
		Prox	60	0.302	0.068	0.985	4.50
		Mid	29	0.027	0.039	0.925	8.12
	STC	UD	108	−0.001	0.027	0.985	6.16
		Prox	108	0.071	0.074	0.995	3.15
		Mid	29	0.016	0.040	0.973	4.68
BMD	FAS	UD	60	0.057	0.902	0.941	8.08
		Prox	60	0.070	0.999	0.957	5.76
		Mid	29	−0.017	1.012	0.933	7.18
	FASm	UD	60	0.051	0.915	0.942	8.46
		Prox	60	0.068	0.868	0.964	5.13
		Mid	29	0.042	0.884	0.948	5.64
	STC	UD	108	0.003	1.038	0.952	8.89
		Prox	108	0.016	1.019	0.975	5.08
		Mid	29	0	0.995	0.950	5.91

n = number of subjects; a = intercept of the regression line; b = slope of the regression line; r = Pearson correlation coefficient; SEE = standard error of the estimate; Site = ultradistal (UD), proximal (Prox), and midshaft (Mid); DXA-FAS = dual-energy X-ray absorptiometry with commercial software; DXA-FASm = dual-energy X-ray absorptiometry with modified ROI; DXA-STC = dual energy X-ray absorptiometry with soft-tissue compensator.
[a] $p < 0.0001$.

Discussion

Studies on short-term precision of forearm densitometry by DXA have arrived at controversial results. Larcos and Wahner[13] found a mean CV of 1.7% in normal volunteers and 1.5% in osteoporotic patients for BMD measurements. These results were not different from the CV of SPA. Weinstein et al.,[30] studying three normal subjects, determined a mean CV for BMD of 1.2% compared with 1.6% to 2.0% for SPA. Other studies of normal vol-

Table 1. Short-term reproducibility of bone densitometry of the forearm at different sites by SPA and DXA

CV (Absolute value)	SPA	DXA-FAS	DXA-FASm	DXA-STC
BMC-UD	1.34 ± 0.17 (0.543 ± 0.065)	1.58 ± 0.20 (0.036 ± 0.005)	1.42 ± 0.15 (0.016 ± 0.001)	3.00 ± 0.29 (0.034 ± 0.005)[b]
BMC-Prox	0.79 ± 0.30 (0.281 ± 0.063)	0.73 ± 0.15 (0.040 ± 0.007)	0.68 ± 0.14 (0.021 ± 0.004)	1.54 ± 0.14 (0.048 ± 0.005)[b]
Area-UD	2.36 ± 0.26 (0.953 ± 0.108)	1.24 ± 0.24 (0.076 ± 0.015)[a]	1.45 ± 0.24 (0.047 ± 0.008)[a]	1.99 ± 0.26 (0.065 ± 0.007)[c]
Area-Prox	1.28 ± 0.19 (0.373 ± 0.055)	0.93 ± 0.10 (0.107 ± 0.009)	0.84 ± 0.10 (0.056 ± 0.006)	1.12 ± 0.17 (0.075 ± 0.011)
BMD-UD	2.25 ± 0.44 (0.021 ± 0.002)	1.20 ± 0.17 (0.004 ± 0.001)[a]	1.32 ± 0.15 (0.004 ± 0.001)[a]	2.15 ± 0.31 (0.007 ± 0.001)[c]
BMD-Prox	1.26 ± 0.17 (0.017 ± 0.002)	0.74 ± 0.09 (0.004 ± 0.000)[a]	0.86 ± 0.13 (0.004 ± 0.000)[a]	1.12 ± 0.12 (0.005 ± 0.001)[c]

n = 10 subjects with four measurements by the three methods on the same day. CV = coefficient of variation (mean ± SEM) (%); absolute value = precision error (mean ± SEM) in units of measurement; SPA = single photon absorptiometry; DXA-FAS = dual-energy X-ray absorptiometry with commercial software; DXA-FASm = dual-energy X-ray absorptiometry with modified ROI; DXA-STC = dual-energy X-ray absorptiometry with soft-tissue compensator; BMC = bone mineral content (UA for SPA and g for DXA); Area = projected area of scanned bone (mm for SPA and cm^2 for DXA); BMD = bone mineral density (g/cm^2 for SPA and DXA); UD = ultradistal site; Prox = proximal site.
[a] $p < 0.05$ compared with SPA.
[b] $p < 0.05$ compared with SPA and DXA-FAS.
[c] $p < 0.05$ compared with DXA-FAS.

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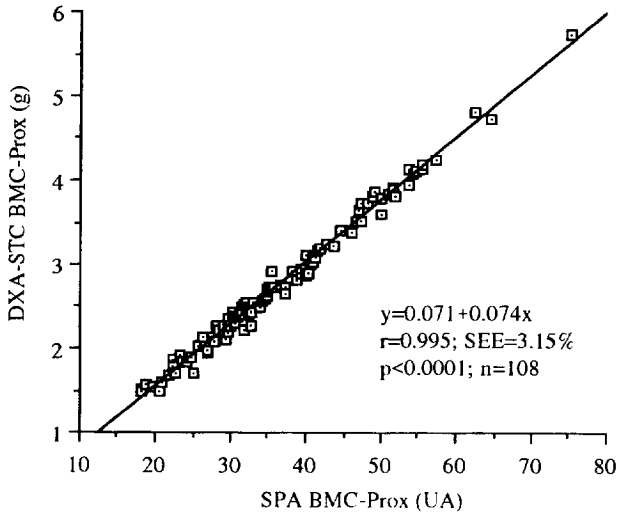

Figure 1. Linear regression straight between SPA and DXA with soft-tissue compensator for measurement of BMC of the forearm at proximal site. SPA is the independent variable and is expressed as arbitrary units of absorption (UA). DXA-STC is the dependent variable and is expressed as grams of bone (g).

Table 3. Linear regression analyses between SPA (independent variable) and DXA (dependent variable) for densitometry of the radius

	DXA	Site	*n*	*a*	*b*	r^a	SEE (%)
BMD	FAS	UD	60	0.069	0.954	0.951	7.50
		Prox	60	0.060	1.104	0.957	5.74
		Mid	29	−0.029	1.114	0.925	7.59

n = number of subjects; *a* = intercept of the regression line; *b* = slope of the regression line; *r* = Pearson correlation coefficient; SEE = standard error of the estimate; Site = ultradistal (UD), proximal (Prox), and midshaft (Mid); DXA-FAS = dual-energy X-ray absorptiometry with commercial software.
[a] $p < 0.0001$.

unteers[14,17,18] reported mean CV ranging from 0.6% to 1.6% for DXA without any difference compared with mean CV for SPA. These disappointing results questioned the advantages of DXA over SPA and emphasized the need for a study including normal volunteers and osteoporotic patients with serial measurements of each patient by DXA and SPA.[16]

Our study on precision was conducted on ten subjects who had measurements of the forearm by both SPA and DXA on the same day. Short-term precision of SPA for BMC was in accordance with that found by Nilas et al.[19] On the other hand, the CV for BMD measurements by SPA were higher than those found by others.[6,24,28,30] This might be due to their use of normal volunteers only for the evaluation of precision, whereas osteoporotic patients were also measured in the present study. The use of osteoporotic patients not only results mathematically in a higher CV because of their lower BMC and BMD values (if the SD are constant), but also induces a higher precision error in area calculation.

Our study clearly demonstrates the better short-term precision of DXA-FAS over SPA for BMD, whereas the CV for BMC are similar for both methods. Thus, all of the advantages for DXA-FAS with regard to short-term precision occur in a more precise estimation of area. This is demonstrated by the significantly lower CV of area calculation by DXA-FAS than by SPA. This might be explained by the use of an ^{125}I source, which results in smaller counting statistics compared with an X-ray source. Increasing the counting statistics with an X-ray source probably improves the area calculation. Moreover, our SPA equipment was developed several years ago, and this might have resulted in higher precision error on area calculation.

Whatever the equipment used, the CV is smaller for proximal than for ultradistal measurements. The higher bone mass of the proximal site probably accounts for this. Whereas the precision of SPA depends on the site (ultradistal vs. proximal) and type (BMC vs. BMD) of measurements, the precision of DXA is similar for BMC and BMD and depends only on the site of measurement.

Coefficients of variation of BMC with SPA are identical to those of BMD with DXA-FAS. In this way, the use of BMC in longitudinal studies conducted with SPA is recommended. Furthermore, several recently published studies used SPA with values of forearm densitometry expressed in terms of BMC.[19,21,23] On the other hand, the use of BMD values is recommended for longitudinal studies conducted with DXA-FAS.

The correlation between SPA and DXA-FAS is good, and the regression analysis shows a linear relationship even for very low bone mineral values. This is true for the measurement of ulna and radius as well as for radius alone. These results are in accordance with other studies.[13,14,17,18,30] Nevertheless, the equipment used for SPA in these studies differed in the way the regions of interest were determined. Some studies were conducted with ROI identical for SPA and DXA,[17,30] whereas others were done with densitometers using different ROI.[14,18] However, the benefit of correcting the ROI to see whether it might increase the correlation between SPA and DXA has never been evaluated.

Even when the correction was achieved by visual means on the computer screen, our data demonstrated that modification of the ROI did not diminish the short-term precision of DXA-FAS. For BMD measurements, correction of the ROI did not significantly modify the correlation between SPA and DXA-FAS. The value of adjusting the ROI was not systematically tested for BMC measurements because it was meaningless to compare absolute values of BMC measured at different sites. The need for such an adjustment to match the ROI was evident, and is easily illustrated by the following example: For BMC measurements at the proximal site, the correlation between SPA and DXA-FAS achieved $r = 0.909$ and SEE = 15.83%. Adjustment of the ROI for DXA-FAS greatly improved the correlation, with $r = 0.985$ and SEE = 4.50%.

Forearm densitometry is also achievable by DXA with the use of standard spine software and a soft-tissue compensator system. Compared with the DXA system proposed by the manufacturer, DXA-STC has a slightly shorter time of examination (4 vs. 6 min) and is a less-irradiating system. The short-term precision of DXA-STC equals that of SPA for BMD but is higher for BMC. Moreover, the CV of DXA-STC are significantly higher than those of DXA-FAS. This is due in part to the larger pixel size, resulting in twice as few measurements, and probably the use by, DXA-FAS of an algorithm for bone-edge detection that does not require soft-tissue equivalence over the scanned area. Whatever the site and type of measurement, the correlation between SPA and DXA-STC is very good, and the SEE is slightly smaller using DXA-STC rather than DXA-FAS. Thus, the soft-tissue compensator appears to be an alternative to the forearm software system proposed by the manufacturer. It might be recommended for large transversal population studies when the need for a short examination time and minimal irradiation is mandatory. On the

other hand, the use of DXA-FAS is superior for longitudinal studies because of its better short-term precision.

Conclusion

In conclusion, because of the high correlation between SPA and DXA-FAS and the good short-term precision of DXA-FAS, the changeover from one system to another during a longitudinal population study might be acceptable. However, if values of forearm densitometry are expressed in BMC data, adjustment of the ROI is mandatory. However, this is not essential for BMD data. Moreover, the SEE values should be taken into account when converting data obtained with one system to another system, because the differences expected might be as high as 9%. This is acceptable for population studies and can be achieved by using equations of regression. On the contrary, this cannot be recommended for a single patient, because the differences of BMC or BMD data from one system to another might be much higher than the expected biological variation. Thus, the changeover from one system to another for a single patient should only be done with caution, and this will probably necessitate simultaneously taking several measurements of the same patient with the two systems.

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