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ORIGINAL ARTICLE

Can the WHO definition of osteoporosis be applied to multi-site axial transmission quantitative ultrasound?

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Abstract Osteoporosis is a highly prevalent but preventable disease and, as such, it is important that there are appropriate diagnostic criteria to identify those at risk of low trauma fracture. In 1994 the World Health Organization (WHO) introduced definitions of osteoporosis and osteopenia using T-scores, which identified 30% of all Caucasian post-menopausal women as having osteoporosis. However, the use of the WHO T-score thresholds of −2.5 for osteoporosis and −1.0 for osteopenia may be inappropriate at skeletal sites other than the spine, hip and forearm or when other modalities, such as quantitative ultrasound (QUS) are used. The aim of this study was to evaluate the age-dependence of T-scores for speed of sound (SOS) measurements at the radius, tibia, phalanx and metatarsal by use of the Sunlight Omnisense, to evaluate the prevalence of osteoporosis and osteopenia at these sites by use of the WHO criteria, and calculate appropriate equivalent T-score thresholds. The study population consisted of 278 healthy pre-menopausal women, 194 healthy post-menopausal women and 115 women with atraumatic vertebral fractures. All women had SOS measurements at the radius, tibia, phalanx and metatarsal and bone mineral density (BMD) measurements at the lumbar spine and hip. A group of healthy pre-menopausal women aged 20–40 years from the pre-menopausal group were used to estimate the population mean and SD for each of the SOS and BMD measurement sites. Healthy post-menopausal women were classified into normal, osteopenic or osteoporotic, based upon the standard WHO definition of osteoporosis and expressed as a percentage. We investigated the age-related decline in T-scores from 20–79 by stratifying the healthy subjects into 10-year age groups and calculating the mean T-score for each of these groups. Finally, we estimated appropriate T-score thresholds, using five different approaches. The prevalence of osteoporosis in the post-menopausal women aged 50 years and over ranged from 1.4 to 12.7% for SOS and 1.3 to 5.2% for BMD. The age-related decline in T-scores ranged from −0.92 to −1.80 for SOS measurements in the 60 to 69-year age group and −0.60 to −1.19 for BMD measurements in the same age group. The WHO definition was not suitable for use with SOS measurements, and revised T-score thresholds for the diagnosis of osteoporosis of −2.6, −3.0, −3.0 and −2.2 and for osteopenia of −1.4, −1.6, −2.3, and −1.4, for the radius, tibia, phalanx and metatarsal, respectively, were recommended.

Keywords Axial transmission quantitative ultrasound · Bone density · Prevalence of osteoporosis · WHO criteria

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Introduction

Osteoporosis is a highly prevalent, but preventable disease and as such, it is important that there are appropriate diagnostic criteria to identify those at risk of a low trauma fracture. In 1994 the World Health Organization (WHO) introduced a new epidemiological definition of osteoporosis and osteopenia, based on measurements of bone mineral density (BMD) expressed in SD units called T-scores. Osteoporosis and osteopenia were defined by T-score thresholds of equal to or more than 2.5 or 1.0 SD, respectively, below the healthy young

adult mean at the spine hip or radius. The lower threshold identified 30% of all Caucasian post-menopausal women as having osteoporosis. Of these, more than half will have sustained a prior osteoporotic fracture. However, not all women diagnosed as having osteoporosis by this cut-off value will suffer a fracture, and not all women with a low trauma fracture will be diagnosed as osteoporotic by this cut-off value. In addition, particular individuals will be categorized differently, depending upon the measurements site and technique, the equipment and the reference population used [1, 2, 3, 4, 5, 6, 7, 8, 9]. The WHO definition is now widely used by clinicians to diagnose osteoporosis and by investigators and governmental agencies for the registration of new drugs [10]. However, the use of a T-score threshold of −2.5 may be inappropriate for the diagnosis of osteoporosis that uses BMD at skeletal sites other than the spine, hip or radius, or for use with other modalities such as quantitative ultrasound (QUS) or quantitative computed tomography (QCT).

The aim of this study was to evaluate the age-dependence of T-scores for radius, tibia, phalanx and metatarsal speed of sound (SOS) measured by use of the Omnisense (Sunlight, Tel-Aviv, Israel), to evaluate the prevalence of osteoporosis and osteopenia at these sites by use of the WHO definition, and to calculate the appropriate equivalent T-score thresholds for these SOS measurement sites to obtain optimum assessment with T-scores derived from spine and hip BMD. The evaluation of appropriate equivalent T-score thresholds are important for the accurate diagnosis of osteoporosis by multi-site axial transmission ultrasound measurements, as the standard WHO definition may not be suitable for use with these measurements and different T-score thresholds may be required, depending on the measurement site.

Materials and methods

The Omnisense

The Omnisense is the first quantitative ultrasound system with the ability to perform SOS measurements in bone at multiple skeletal sites. To accomplish this it uses a number of hand-held probes designed for specific sites. The probes contain an array of transducers, some acting as transmitters and others as receivers, that measure the path of the sound wave taking the shortest propagation time between the transmitting and receiving transducers. The time taken for the signal to travel between such transducers is used to infer the SOS in bone [11]. The manufacturers also claim that the Omnisense corrects for overlying soft tissue, giving the true SOS measurement in bone [12].

Subjects

The study population consisted of three groups: (1) healthy pre-menopausal women ($n=278$); (2) healthy post-menopausal women ($n=194$); (3) patients with vertebral fractures ($n=115$). The exclusion criteria for the healthy pre-menopausal and post-menopausal controls included: menopause before the age of 45; amenorrhea for greater than 6 months; a history of drugs or diseases known to affect bone metabolism; a history of low trauma fracture [13]. The patients were recruited from a number of sources: (1) patients referred for spine and hip BMD measurement at Guy's Hospital by their general practitioner (GP); (2) hospital personnel; (3) volunteers from the general population and; (4) twin volunteers attending the Twin Research Unit at St Thomas' Hospital. For each monozygotic pair of twins, only one randomly selected twin was included in the study population. However, for dizygotic pairs both twins were included, due to the much lower correlation between twin pair measurement values. The study was approved by the Guy's and St Thomas' Hospitals research ethics committees.

Subject measurement

SOS measurements were performed at the non-dominant, third, proximal phalanx, medial aspect of the 1/3 radius, the antero-medial aspect of the midshaft tibia and the lateral aspect of the fifth metatarsal, with the Sunlight Omnisense™. The Omnisense uses a total of three different probes to perform measurements at these four sites. One probe measures both the radius and tibia, whilst the phalanx and metatarsal are measured by individual probes. Fewer subjects had measurements of the phalanx and metatarsal because these probes were not available at the start of the study. Two Omnisense devices were used, one based at Guy's Hospital and one at St Thomas' Hospital. The short-term precision (RMS CV%) for the Omnisense was measured by duplicate scans in 37 subjects, mean age 42 years (± 13.2 years). The RMSSD (CV%) was 22.8 m/s (0.55%) for the radius, 17.7 m/s (0.45%) for the tibia, 44.8 m/s (1.11%) for the phalanx and 27.8 m/s (0.76%) for the metatarsal. When we standardized them by expressing them in T-score units, these results became 0.21, 0.16, 0.28 and 0.13 for the radius, tibia, phalanx and metatarsal, respectively [14]. In addition to the SOS measurements, all subjects also underwent BMD measurements of the lumbar spine and proximal femur by one of four Hologic DXA densitometers (Hologic, Bedford, Mass., USA).

The two Omnisense devices and four QDR densitometers were cross-calibrated via in vitro and in vivo cross calibration. The in vitro cross-calibration was performed by use of ten repeated phantom scans with repositioning between scans. The in vivo cross-calibration involved 25 subjects who underwent BMD measurements of the spine and hip on four Hologic QDR densitometers and SOS measurements of the radius, tibia, phalanx and metatarsal on the two Sunlight Omnisense devices. We corrected the data, where appropriate, using the slope and intercept from linear regression analysis.

Statistical analysis

A group of healthy pre-menopausal women aged 20–40 years ($n=135$) was used to estimate the young, normal population mean and SD for each of the SOS and BMD measurement sites, and T-scores were calculated from these data. These subjects were a subgroup of the healthy pre-menopausal women. Healthy post-menopausal women were classified into three groups according to their T-scores, based on the WHO criteria: normal, $T \geq -1.0$; osteopenic $-1.0 > T > -2.5$; osteoporotic $T \leq -2.5$. The numbers of healthy post-menopausal women aged over 50 years in each WHO category were expressed as percentages. To examine the age-related decline in T-scores, we divided the population into 10-year age groups, from 20–79 years, and calculated the mean T-score for each of these groups. To evaluate the optimum diagnostic threshold for identifying a high-risk group for each of the SOS measurement sites, we compared five different approaches, as described by Frost et al. [8] and Weiss et al. [15].

Approach 1

Linear regression was performed between the age-related decline in each of the SOS measurement sites T-scores and the age-related decline in lumbar spine, femoral neck and total hip T-scores, forcing the line through the origin. We multiplied the slope of the regression line by −2.5 to estimate the equivalent T-score threshold for each SOS variable for osteoporosis and by −1.0 for osteopenia.

Approach 2

We estimated a threshold for SOS by taking the equivalent T-score threshold that would identify the same percentage of healthy women as osteoporotic and osteopenic as diagnosed by lumbar spine, femoral neck or total hip BMD.

Approach 3

This approach was similar to that used by Weiss et al. [15]. The prevalence of osteoporosis and osteopenia was calculated for the age group 60–69 years. The equivalent T-score required to identify the same percentage of patients as osteoporotic and osteopenic as that identified by lumbar spine, femoral neck or total hip BMD was calculated.

Approach 4

This is a similar to approach 3, but this time the SOS and BMD measurements were age-adjusted, from the slope and intercept from linear regression, to be 65 years of age. This added the benefit of providing increased numbers of subjects for the comparison. The prevalence of osteoporosis and osteopenia was calculated and equivalent T-score thresholds for each SOS measurement site calculated as for approach 3.

Approach 5

The percentage of women with vertebral fractures with a lumbar spine, femoral neck or total hip BMD T-score ≤ -2.5 and between ≤ -1.0 and -2.5 was calculated. The equivalent T-score for SOS at each measurement site was calculated by estimation of the T-score required to detect the same percentage of women with vertebral fractures as identified by BMD. This is identical to the method used by Hans et al., in the EPIDOS study, to calculate equivalent T-scores for QUS data in hip fracture patients [7].

Results

Table 1 shows the patients' characteristics. A young, normal, group was defined from the subjects in the pre-menopausal group aged 20–40 years. The post-menopausal group subjects are significantly shorter and have a greater BMI than the pre-menopausal group. The mean SOS and BMD measurements for the post-menopausal group are all significantly reduced when compared with those for the pre-menopausal group. The vertebral fracture patients were significantly older, lighter, and shorter than the post-menopausal group. They also had a significantly younger menopause age and greater years since menopause. All mean SOS and BMD measurements were significantly reduced in the vertebral fracture group when compared with those for the post-menopausal group, although, this is partly explained by the age difference between the two groups. Not all women were able to be measured at all four sites by axial transmission ultrasound. The failure rates were 3% at the radius and tibia and 9% at the metatarsal. However, all scans at the phalanx were successful. Failure to obtain measurements was related to obesity in the patients or, in the case of the lower limb, occasionally the presence of edema.

Table 2 and Figs. 1 and 2 demonstrate the age-related decline in T-scores for all SOS and BMD measurement sites. Radius SOS increases from 20 to

Table 1 Patients' characteristics (*YSM* years since menopause)

Characteristic	Young, normal (20–40 years) Mean (SD)	Pre-menopausal Mean (SD)	Post-menopausal Mean (SD)	Vertebral fracture Mean (SD)
Number	135	278	194	115
Age (years)	31.73 (5.96)	37.77 (9.31)	59.91 (7.27)	71.77 (8.05)†
BMI (kg/m^2)	24.23 (4.76)	24.60 (4.58)	25.37 (3.74)*	25.40 (4.67)
Weight (kg)	66.73 (14.12)	66.04 (13.07)	66.67 (11.97)	60.68 (13.59)†
Height (cm)	164.64 (6.87)	163.76 (6.51)	161.20 (9.64)*	158.96 (8.14)†
Age at menopause (years)	–	–	50.24 (3.28)	46.40 (6.36)†
YSM	–	–	9.65 (7.18)	25.45 (10.18)†
SOS				
Radius (m/s)	4105 (111)	4115 (103)	4020 (118)**	3974 (145)†
Tibia (m/s)	3917 (110)	3904 (112)	3822 (142)**	3751 (157)†
Phalanx (m/s)	4053 (160)	4053 (156)	3856 (194)**	3680 (196)†
Metatarsal (m/s)	3748 (222)	3779 (207)	3580 (190)**	3409 (252)†
BMD				
Lumbar spine (g/cm^2)	1.029 (0.123)	1.039 (0.126)	0.930 (0.142)**	0.752 (0.140)†
Femoral neck (g/cm^2)	0.851 (0.122)	0.846 (0.119)	0.757 (0.114)**	0.586 (0.118)†
Total hip (g/cm^2)	0.920 (0.120)	0.926 (0.129)	0.877 (0.122)**	0.663 (0.139)†

*$P = < 0.05$, **$P = < 0.01$ when compared with the pre-menopausal group, †$P = < 0.01$ when compared with the post-menopausal group

Table 2 Age-related decline in T-scores for SOS and BMD measurement sites

Site	*n*	20–29 years (SEM)	*n*	30–39 years (SEM)	*n*	40–49 years (SEM)	*n*	50–59 years (SEM)	*n*	60–69 years (SEM)	*n*	70–79 years (SEM)
SOS												
Radius	49	−0.37 (0.11)	78	0.24 (0.12)	114	0.05 (0.08)	139	−0.21 (0.09)	71	−1.00 (0.12)	19	−1.42 (0.24)
Tibia	47	0.07 (0.13)	77	0.00 (0.12)	113	−0.33 (0.09)	137	−0.41 (0.10)	75	−1.15 (0.14)	21	−1.21 (0.34)
Phalanx	30	−0.34 (0.15)	46	0.12 (0.14)	67	0.17 (0.13)	93	−0.52 (0.12)	52	−1.80 (0.12)	13	−2.09 (0.24)
Metatarsal	29	−0.07 (0.18)	39	0.07 (0.17)	59	0.24 (0.10)	86	−0.36 (0.10)	49	−0.92 (0.12)	9	−1.27 (0.35)
BMD												
Lumbar spine	47	0.02 (0.16)	74	0.02 (0.12)	113	0.12 (0.10)	140	−0.34 (0.09)	72	−1.19 (0.14)	20	−1.26 (0.25)
Femoral neck	47	0.32 (0.16)	74	−0.13 (0.10)	113	−0.13 (0.08)	140	−0.32 (0.08)	72	−1.09 (0.10)	20	−1.43 (0.19)
Total hip	47	0.26 (0.15)	74	−0.08 (0.11)	113	0.06 (0.10)	140	−0.04 (0.09)	72	−0.60 (0.12)	20	−1.06 (0.18)

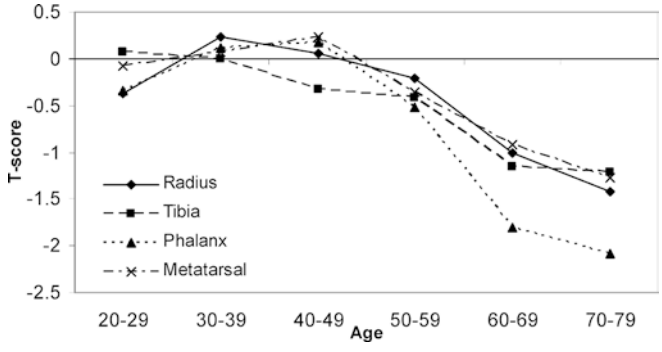

Fig. 1 Age-related decline in T-scores for SOS measurements at the radius, tibia, phalanx and metatarsal. Age range is in years

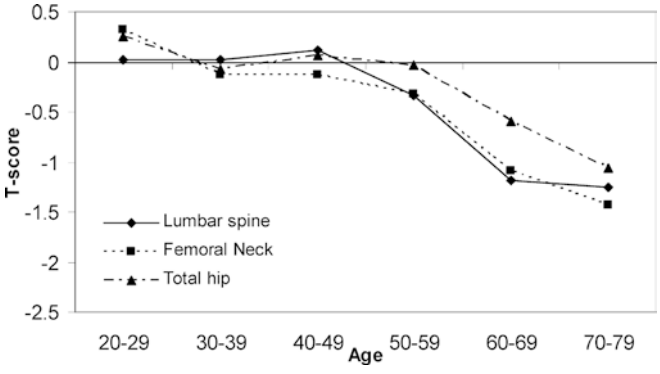

Fig. 2 Age-related decline in T-scores of BMD measurements of the lumbar spine, femoral neck and total hip. Age range is in years

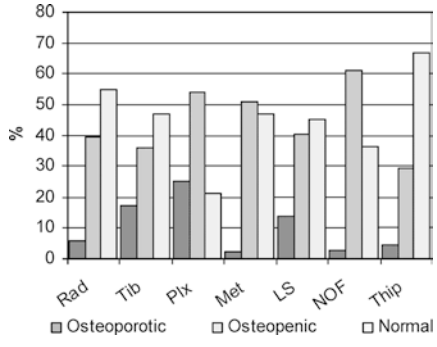

Fig. 3 The prevalence of osteopenia and osteoporosis in normal post-menopausal women aged 60–69 years (*Rad* radius, *Tib* tibia, *Plx* phalanx and *Met* metatarsal, *LS* lumbar spine, *NOF* neck of femur, *Thip* total hip)

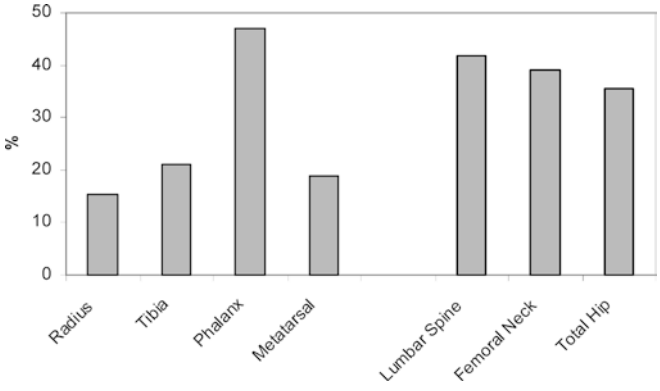

Fig. 4 Prevalence of vertebral fracture patients with T ≤ -2.5

29 and peaks in the 30 to 39-year age group, declining from this point on and reaching a T-score of −1.42 in the 70 to 79-year age group. The tibia peaks in the 20 to 29-year age group and declines from this point on. The phalanx increases from the 20 to 29-year age group, peaks in the 40 to 49-year age group, then declines. The metatarsal follows a similar pattern to the phalanx, peaking in the 40 to 49-year age group, then declining. Lumbar spine BMD peaks in the 40 to 49-year age group, then declines from this point; however, the femoral neck and total hip peak in the 20 to 29-year age group, declining thereafter.

Figure 3 shows the prevalence of osteopenia and osteoporosis as defined by the WHO criteria in the post-menopausal study population aged 60 to 69 years. The prevalence of osteoporosis diagnosed by BMD ranges from 2.8 to 13.9%, whilst the prevalence of osteoporosis diagnosed by SOS ranges from 2.0 to 25.0%.

The prevalence of vertebral fracture patients with a T-score ≤ -2.5 is shown in Fig. 4. The prevalence of vertebral fracture patients with T ≤ -2.5 was 15%, 21%, 47% and 19% at the radius, tibia, phalanx and metatarsal, respectively, while the prevalence of osteoporosis in vertebral fracture patients as diagnosed by

Table 3 T-score thresholds yielded by approaches 1 to 5

Approach	Lumbar spine	Femoral neck	Total hip
Radius			
1	−2.4	−2.2	−3.2
2	−2.4	−2.9	−2.9
3	−1.9	−2.8	−2.6
4	−1.9	−2.9	−2.9
5	−1.5	−1.5	−1.6
Tibia			
1	−2.4	−2.3	−3.2
2	−2.9	−3.8	−3.6
3	−2.4	−3.2	−3.0
4	−2.5	−3.7	−3.7
5	−1.8	−1.8	−1.9
Phalanx			
1	−4.0	−3.6	−5.2
2	−2.9	−3.3	−3.2
3	−2.5	−3.1	−3.5
4	−2.6	−3.3	−3.3
5	−2.6	−2.7	−2.8
Metatarsal			
1	−2.3	−2.1	−3.1
2	−2.2	−2.6	−2.3
3	−1.6	−2.2	−2.2
4	−1.7	−2.3	−2.3
5	−1.8	−1.8	−1.9

Table 4 T-score thresholds for osteopenia from approaches 1 to 5

Approach	Lumbar spine	Femoral neck	Total hip
Radius			
1	−0.9	−0.9	−0.6
2	−0.9	−0.9	−1.4
3	−0.9	−0.8	−1.4
4	−0.8	−0.7	−1.3
5	−0.1	1.0	−0.1
Tibia			
1	−1.0	−1.0	−0.7
2	−0.9	−0.9	−1.6
3	−1.0	−0.6	−1.6
4	−1.0	−0.8	−1.8
5	−0.2	0.2	−0.3
Phalanx			
1	−0.6	−0.6	−0.4
2	−1.6	−1.6	−2.1
3	−1.8	−1.6	−2.3
4	−1.6	−1.4	−2.3
5	−0.7	−0.7	−1.2
Metatarsal			
1	−1.1	−1.1	−0.7
2	−0.9	−0.8	−1.2
3	−1.0	−0.9	−1.4
4	−1.0	−0.9	−1.4
5	−0.3	−0.2	−0.7

BMD was 42%, 39% and 36% for lumbar spine, femoral neck and total hip BMD, respectively.

Table 3 shows the T-score thresholds for SOS measurements at the radius, tibia, phalanx and metatarsal, calculated via the five different approaches and based on lumbar spine, femoral neck and total hip BMD. The T-score cut-off values for the SOS measurements vary considerably, depending upon the BMD site used for the calculation, the method of calculation and the SOS measurement site used.

Table 4 shows the T-score thresholds for osteopenia. Again, these vary, depending upon SOS measurement site, the BMD site and method of calculation.

Discussion

This study examined the application of the WHO criteria for the diagnosis of osteoporosis and osteopenia for SOS measurements at the radius, tibia, phalanx and metatarsal using the Omnisense and found these to be inappropriate. The Omnisense presently has pre-market approval (PMA) from the Federal Drug Administration (FDA) in the USA, and, therefore, appropriate criteria for the diagnosis of osteopenia and osteoporosis are important as the system may be increasingly used in a clinical setting. The WHO criteria, which were proposed for the interpretation of BMD results [1] are generally not suitable for use with many QUS devices. In addition, with QUS devices such as the Omnisense, which performs measurements at multiple sites, a single T-score cut-off may not be suitable, with a site-matched criterion for each skeletal site being more appropriate.

The age-related decline in T-scores differed between the various SOS measurement sites and BMD, with the mean T-scores for the 60 to 69-year age group ranging from −0.92 to −1.80 for SOS and −0.60 to −1.19 for BMD. This is consistent with other studies, which have found differing age-related declines for various skeletal sites by the use of several measurement modalities. Faulkner et al. found the mean normative T-score at the age of 60 to range from −0.7 for calcaneal QUS to −2.5 for lumbar spine QCT [6]. Frost et al. also found differing rates of age-related decline, with the mean T-score at the age of 65 years ranging from −1.0 for calcaneal broadband ultrasound attenuation (BUA) to almost −2.0 for femoral neck BMD [8]. Weiss et al., using the Sunlight Omnisense, found the radius and phalanx to cross the T = −2.5 level at around the age of 75 years, whilst the tibia and metatarsal decreased to only approximately −2.0, even by the age of 85 years [15]. The T-scores reported by Weiss et al. are somewhat more negative than those found in the same age group in this study. Both this study and the results reported by Weiss et al. [15] found a trend of greater age-related decline in T-scores at the radius and phalanx than at the tibia and metatarsal. One reason for this might be that the tibia and metatarsal are both weight bearing sites, while the radius and phalanx are not. It has been well documented that exercise and occupational activity has a positive influence on bone loss [16, 17, 18, 19], and it is, therefore, conceivable that the bone loss in the lower limb will be arrested as a result of its weight bearing status. In

addition, the lower T-score age-related decline at the metatarsal is partially as a result of the larger, young, normal population SD at this site (Table 1). The large population SD at this site is probably due to measurement errors, as this site is the most difficult for one to perform accurate measurements on. There is potentially an impact of site-specific inaccuracies on all the calculations of T-scores. The phalanx and metatarsal have larger SDs than do the radius and tibia, and larger precision errors as well. It is, therefore, probable that the T-score calculations at these sites contain the largest inaccuracies, and there may be a bearing of this on the T-score differences observed between the different sites.

The differing rate of T-score age-related decline between the SOS measurement sites is a problem for the diagnosis of osteoporosis that uses the WHO definition. The latter was based upon 30% of post-menopausal Caucasian women being diagnosed as osteoporotic at the forearm, hip or spine [1]. However, this is dependent upon the site, modality, and reference population used to calculate the T-scores. It is common for there to be a discordance between measurement sites in the diagnosis of osteoporosis [9, 20, 21, 22, 23]. In this study peak bone mass was obtained at varying ages, dependent upon skeletal site. We used the age group 20–40 years as the young normal population for the calculation of T-scores for all measurement sites to maintain consistency. However, the radius, phalanx and metatarsal continue to gain bone, peaking at around 40 years of age. The inclusion of subjects in their twenties may, therefore, reduce the young normal population mean and thus lead to an underestimation of osteoporosis. Gürlek et al. reported large differences in the prevalence of osteoporosis in a Turkish population diagnosed using a local Turkish reference data compared with using a US reference database [21]. The prevalence of osteoporosis as defined by the WHO criteria in the present study ranged from 1.4 to 12.7% for SOS and 1.3 to 5.2% for BMD of the post-menopausal population aged 50 years and over. These differences demonstrate that the WHO cut-off score of $T \leq -2.5$ would not be suitable for all the ultrasound sites measured in this study.

The prevalence of osteoporosis as diagnosed by the BMD measurement sites in this study is somewhat lower than the 30% of post-menopausal Caucasian women aged 50 years and over as described in the WHO report [1]. One reason for this discrepancy is that the post-menopausal population in this study contained greater numbers of women in their fifties than in their seventies, therefore creating a bias, as the older women would be more likely to suffer from osteoporosis. To correct for this bias, we used the prevalence in just the 60 to 69-year-old age group, ranging from 3 to 13% for the BMD sites, which is still less than that reported in the WHO report [1]. Melton, in 1995, reported the prevalence of osteoporosis to range from 3.7 to 7.6% in 50 to 59-year-old Caucasian women at the spine, hip or forearm, compared to 32 to 50% in those aged 80 years and above [24]. Looker et al. reported the prevalence of osteoporosis in US Caucasian women aged 50 years and over to be 18% at the femoral neck and 16% at the total hip [25], whilst Ballard et al. reported the prevalence of osteoporosis to be 24% in white Caucasian women in their seventh decade [26]. When the prevalence of osteoporosis was calculated for the age group 60–69 years in this study for SOS, it was 6% at the radius, 17% at the tibia, 25% at the phalanx, 2% at the metatarsal, and for BMD, 13% at the lumbar spine, 3% at the femoral neck and 4% at the total hip. Weiss et al. reported a prevalence of osteoporosis as defined by the WHO criteria of 36% at the radius using the Omnisense in a 60 to 69-year age group [15]. This is somewhat higher than that found in this study, where the prevalence for the radius was 6% in the 60 to 69-year age group. Other authors have reported the prevalence of osteoporosis in their study populations to range from 0.9 to 33%, depending upon the site measured, modality used and population studied [8, 20, 27].

Finally, when the prevalence of osteoporosis in post-menopausal women with vertebral fractures was calculated in this study, it was 15% at the radius, 21% at the tibia, 47% at the phalanx, 17% at the metatarsal, 42% at the lumbar spine, 39% at the femoral neck and 36% at the total hip. Ish-Shalom et al. performed a similar study in 67 subjects with vertebral fractures, and the prevalence of $T \leq -2.5$ was 59% at the radius, 33% at the tibia, 56% at the phalanx, 60% at the lumbar spine and 46% at the femoral neck [9]. When these two studies are compared the prevalence of osteoporosis is fairly comparable for most sites, with the Israeli data providing a slightly greater prevalence of individuals with $T \leq -2.5$ than the UK study.

The thresholds calculated for the diagnosis of osteoporosis by SOS measurements at multiple sites yielded varying T-scores based upon the approach used. The T-score cut-off value calculated by the use of approach 1 tended to provide the most negative estimates, whilst the cut-off values calculated via approach 3 yielded the least negative. Approach 2 was the most similar to that used by the WHO working party to define a T-score threshold [1] and it yielded T-score cut-off values which fell between those obtained from approaches 1 and 3. All these methods have been used in previous publications [7, 8, 9, 14, 28]. However, the preferred method chosen in this study upon which to base the T-score cut-offs was approach 3, using the 60 to 69-year age group and the T-score equivalent that provides the same prevalence of osteoporosis as the WHO criteria at the total hip. This approach was chosen because it was least affected by the biases within the data. The resulting T-scores for the diagnosis of osteoporosis for the recommended SOS variables were −2.6 for the radius, −3.0 for the tibia, −3.0 for the phalanx and −2.2 for the metatarsal. This demonstrates that a single T-score threshold for the diagnosis of osteoporosis is not suitable for use with the Omnisense and a site matched T-score cut-off is more appropriate. When compared with previous studies that use the Omnisense, these values are quite different.

Ish-Shalom et al. reported that a T-score cut-off of T ≤ -2.5, as defined by the WHO criteria, would be a suitable threshold for the diagnosis of osteoporosis using SOS measurements at the radius, tibia and phalanx [9]. Weiss et al. based their T-score thresholds on the prevalence of osteoporosis defined as T ≤ -2.5 diagnosed by SOS at the radius in Caucasian post-menopausal women aged 60–69 years. The T-score cut-off values for other sites were based on the prevalence at this site and were −1.89 for the tibia, −2.59 for the phalanx, and −1.75 for the metatarsal [15]. However, they did not have any BMD data to verify the use of a T-score cut-off of ≤ -2.5 at the radius, and, therefore, the other T-score cut-off based upon this assumption may be inaccurate. The T-score cut-off values in this study are different from those of other studies, due to the different populations examined.

T-score thresholds for the diagnosis of osteopenia were calculated, and approach 3 was again used as the basis for recommendation. The recommended T-score thresholds for the diagnosis of osteopenia are −1.4, −1.6, −2.3 and −1.4 for the radius, tibia, phalanx and metatarsal, respectively.

There are limited data to date with which the Omnisense can be evaluated. However, on the basis of data from other devices the National Osteoporosis Society (NOS) in the UK currently recommends that if a patient has a low QUS measurement they should be referred for further investigation by axial BMD and that QUS cannot, currently, be used to diagnose osteoporosis [29]. The Omnisense is still new technology in comparison with calcaneal QUS, for which there is strong evidence for its ability to predict fracture in large prospective studies. It is, therefore, important that the performance of the Omnisense be evaluated in prospective studies and in comparison with conventional QUS devices.

There are a number of potential limitations with our study. Firstly, the numbers of individuals in the reference data are relatively small. Secondly, the reference population is a selected one, as it contains predominantly individuals who volunteered for research. It is, therefore, possible that mainly fit, health-conscious individuals would volunteer and the sample would not be representative of the normal population, especially for the older subjects. However, studies of volunteer populations have not shown any differences from general population data in our hands [30, 31]. In addition, the strict exclusion criteria also resulted in only the fit, healthy individuals being included within the reference population and made it difficult for us to recruit elderly women, which resulted in the low numbers of subjects in their late sixties and seventies. A large range of T-score thresholds was obtained by use of the different approaches in this study, based on the rates of osteoporosis via the BMD data. Other methods may provide yet more different thresholds, and other approaches such as lifetime risk of fracture, based on Z-score threshold or relative risk, were not investigated [32, 33, 34].

In conclusion, the WHO criteria for the diagnosis of osteoporosis cannot be applied to SOS measurements that use the Omnisense. Further, a single T-score threshold is not suitable for use with multi-site SOS measurements. From our data the recommended T-score cut-off values for use with the Omnisense for the diagnosis of osteoporosis would be −2.6, −3.0, −3.0 and −2.2 for the radius, phalanx, tibia and metatarsal, respectively, and −1.4, -1.6, -2.3 and −1.4, respectively, for the diagnosis of osteopenia.

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