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REVIEW ARTICLE

Attempt at standardization of bone quantitative ultrasound in Japan

Takahiko Otani[1] · Masao Fukunaga[2] · Kosei Yho[3] · Takami Miki[4] · Kaoru Yamazaki[5] · Hideaki Kishimoto[6] · Mami Matsukawa[1] · Nobuyuki Endoh[7] · Hiroyuki Hachiya[8] · Hiroshi Kanai[9] · Saeko Fujiwara[10] · Yoshinori Nagai[11]

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Abstract Dual X-ray absorptiometry (DXA) is used to diagnose osteoporosis. On the other hand, quantitative ultrasound (QUS) is widely used to assess bone density as part of medical screening as it is relatively inexpensive and easy to perform. Current QUS devices do not share precise ultrasound-related parameters, such as frequency, waveform, beam pattern, transient response, definition of propagation time, definition of degree of attenuation, and precise measurement site, resulting in different measurements across models. The Japan Osteoporosis Society established a QUS Standardization Committee in 2007 to investigate standardization of speed of sound (SOS) and broadband ultrasonic attenuation (BUA) measurements to resolve this issue. The committee came up with a formula to convert SOS and BUA values yielded by each model available in Japan. This has made it possible to convert QUS measurements from different models into standardized values, greatly improving the effectiveness of QUS measurements.

Keywords Quantitative ultrasound (QUS) · Speed of sound (SOS) · Broadband ultrasonic attenuation (BUA) · Standardization of QUS

✉ Takahiko Otani
totani@oyoe.jp

1 Faculty of Science and Engineering, Doshisha University, Kyotanabe, Kyoto 610-0394, Japan

2 Kawasaki Medical School, Okayama, Japan

3 Aino Hospital, Osaka, Japan

4 Izumiotsu Municipal Hospital, Osaka, Japan

5 Department of Orthopedic Surgery, Iwata City Hospital, Shizuoka, Japan

6 Department of Orthopedic Surgery, Nojima Hospital, Tottori, Japan

7 Department of Electric, Electronics, and Information Engineering, Faculty of Engineering, Kanagawa University, Kanagawa, Japan

8 School of Engineering, Tokyo Institute of Technology, Tokyo, Japan

9 Graduate Schools of Engineering and Biomedical Engineering, Tohoku University, Miyagi, Japan

10 Health Management and Promotion Center, Hiroshima Atomic Bomb Casualty Council, Hiroshima, Japan

11 TM Clinical Support Co. Ltd., Tokyo, Japan

Introduction

Speed of sound (SOS) (m/s) and broadband ultrasonic attenuation (BUA) (dB/MHz), parameters of quantitative ultrasound (QUS) used to assess bone density (or bone mass), are highly correlated with bone density (mg/cm^3) [or bone mass (mg/cm^2)]. Therefore, QUS is widely used in medical screening in Japan as it is compact, light, inexpensive, and free of exposure to radiation.

Measurement of bone mass (or bone mineral content) (mg/cm^2) with dual X-ray absorptiometry (DXA) is currently used to judge increased fracture risk due to osteoporosis and other causes or to diagnose osteoporosis. Thus, there are few opportunities to use QUS in medical diagnosis.

Since the ultrasonic waves used in QUS devices are elastic waves, SOS and BUA measurements directly reflect the elastic properties of bone. Therefore, they are important parameters for assessing the elastic properties, i.e., the mechanical strength, of bone. Given that assessment of fracture risk, i.e., assessment of the mechanical strength of bone, is a critical component of diagnosis of osteoporosis, a method for evaluating bone using QUS parameters (SOS and BUA) holds promise. QUS devices are widely used for preventive medical screening in Japan, but QUS measurements are not used in cross-sectional studies, and they are not fully utilized in the diagnosis of osteoporosis. The main reasons for this are the fact that DXA measurements are considered the de facto diagnostic criteria for osteoporosis, and the fact that QUS devices have become ubiquitous without a clear definition of QUS parameters (SOS and BUA) and their reference ranges. The calcaneus is used as the measurement site with current QUS devices, but the precise measurement site, precise definition of SOS and BUA, and precise physical characteristics of the ultrasonic signals used differ from manufacturer to manufacturer. Thus, the measurements displayed will differ from manufacturer to manufacturer (or from model to model) even if the subject is the same. Nevertheless, the correlation coefficients of the measurements across these models are all high (good), suggesting that all of the models have been properly planned and manufactured.

Standardization of measurements of current QUS devices is an essential step toward establishing the potential of QUS devices for evaluating bone properties and expanding the scope of their application. Against this backdrop, the Japan Osteoporosis Society established a QUS Standardization Committee in 2007 to investigate standardization of QUS parameters (SOS and BUA). Some of the results of its investigation were reported in Osteoporosis Japan [1].

Issues associated with evaluation of bone density using QUS

The propagation speed of ultrasonic waves in a material and the attenuation coefficient (Np/m) are physical constants that indicate the elastic properties of the material. Such material physical constants are essential for studies of materials such as metals, polymers, and ceramics, and for quality control in the manufacturing process of industrial materials. Research on methods for determining the propagation speeds and attenuation coefficients of materials and the constants for each material began around the 1920s with advances in ultrasound technology. This field of research, which is currently referred to as ultrasonic material characterization, is an important field in condensed matter physics and material science. Many results were reported for the propagation speeds and attenuation coefficients of biological tissues in the J. Acoust. Soc. Am and other publications [2–7] from the 1950s to 1980s, and a wide range of research is still being conducted today.

Research began in the 1980s on bone characterization utilizing the fact that there is a strong correlation between bone density and the propagation speed and attenuation of ultrasonic waves at sites including cancellous bone [8], resulting in the practical application of an ultrasound-based method for diagnosing osteoporosis called quantitative ultrasound. Parameters measured by QUS devices currently available in Japan are SOS (m/s) and BUA (dB/MHz). SOS and BUA have been reported by many researchers to correlate well with bone density (or bone mass) [9–19], and SOS and BUA are considered to be widely accepted parameters for bone characterization. However, the site where QUS parameters are measured, i.e., the propagation path of the ultrasound beam, is connected to soft tissues, cortical bone, and cancellous bone in a complex configuration, and the ultrasonic beam reflects, refracts, scatters, and diffracts repeatedly as it is transmitted through the mediums. Thus, the SOS and BUA values of ultrasonic waves transmitted through the body are greatly affected by the frequency, beam pattern, and pulse waveform of the ultrasonic waves. Moreover, the ultrasonic beam is affected by the transducer material in the ultrasonic transmitter and receiver, their configuration and size, their mechanical resonance characteristics and electrical impedance characteristics, and other factors. Despite these issues with QUS devices that are inherent in in vivo ultrasound measurements, the devices were marketed without clearly indicating precise measurement sites, definitions of SOS and BUA, and characteristics of the ultrasonic waves used. All QUS devices currently on the market show a good correlation with bone density (mg/cm^3) or bone mass (mg/cm^2) as measured by X-ray methods[1], but there are deviations in measurements between models (between manufacturers), making it impossible to compare measurements between QUS devices at the present time.

Preliminary investigation for QUS standardization

QUS devices that had been approved as medical devices in Japan and were available as of establishment of the QUS Standardization Committee (October 2007) are shown in Table 1. The manufacturers (distributers), models, and measuring parameters are shown in Table 1. According to this table, the only QUS parameter that all models have in common is SOS. In the present study, we first investigated the standardization of SOS, which was then followed by an examination of BUA.

[1] In the case of X-ray methods, bone density (mg/cm^3) is measured by quantitative computed tomography (QCT), and bone mass (mg/cm^2) is determined by dual X-ray absorptiometry (DXA).

Table 1 QUS devices used in standardization study

Manufacturer or (distributor)	Device	Measuring parameters
Hitachi-Aloka Medical, Ltd.	AOS-100	SOS, TI, OSI, BUA
Furuno Electric Co., Ltd. (Canon Lifecare Solutions Inc.)	CM-200	SOS
GE Healthcare Japan, Co.	A-1000	SOS, BUA, Stiffness
DMS S.A. (Diagnostic Medical Systems S.A.)	UBIS5000	SOS, BUA, STI
Ishikawa Seisakusho, LTD. (NIHON KOHDEN CORPORATION)	Benus	SOS, Bone Area Ratio
(NIPPON SIGMAX Co., Ltd.)	Minelyzer	SOS, BUA, BQI

At the 1st meeting (October 13, 2007) of the QUS Standardization Committee, we took the opportunity to measure SOS values using five of the models shown in Table 1 that we were able to arrange, with 22 committee members in attendance serving as subjects. An in-house phantom (equipment number: S/N133) used for calibrating SOS values provided by Furuno Electric Co., Ltd. was also measured five times with each model. Figure 1 shows the SOS values for the 22 subjects in order of subject number. SOS values differed considerably from model to model, but the measurements for all models showed very similar tendencies, suggesting a high correlation coefficient for SOS values between models. The results of measurement of phantom S/N133 are shown in Table 2. Each model exhibited its own SOS value, with values ranging from 1548 to 1587 m/s. This indicated that each model was designed with its own unique standards, but the coefficient of variation values were all sufficiently low, suggesting technically very well-made devices that could be stably operated. However, the coefficient of variation is equal to standard deviation/mean value. In Table 3, mean SOS values for the phantom are shown in the left column, and mean SOS values for subjects are shown in the right column, in order of highest to lowest value. Judging from this table, the order of the mean values for the phantom and the order of the mean values for subjects do not agree. Therefore, Table 3 indicates that it is not appropriate to convert subject SOS values to standardized SOS values using phantom SOS values as reference values.

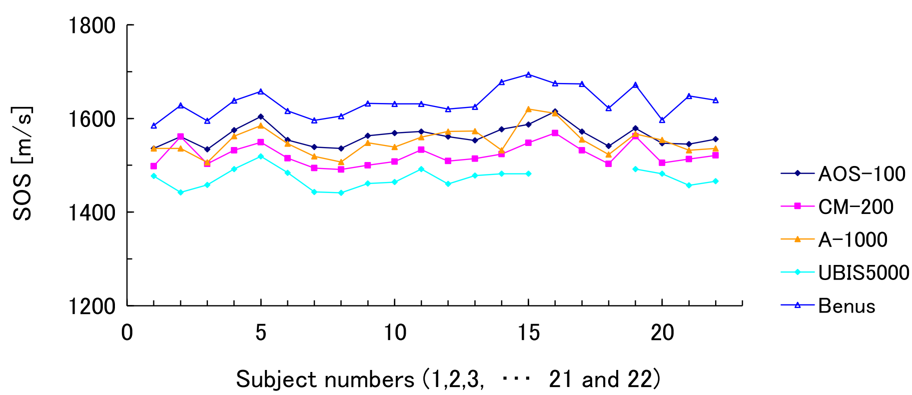

Fig. 1 Preliminary measurements for standardization (measurement results for 22 subjects; October 13, 2007; room temperature: 26 °C)

Table 2 Measurement results for phantom (October 31, 2007; room temperature: 26 °C; number of models: 5)

SOS	AOS-100	CM-200	A-1000	UBIS5000	Benus
Mean (m/s)	1549.4	1551.4	1565.0	1581.0	1568.2
Maximum (m/s)	1551	1552	1574	1587	1572
Minimum (m/s)	1548	1551	1562	1575	1566
Standard deviation (m/s)	1.517	0.548	5.050	5.339	2.387
CV (%)	0.098	0.035	0.323	0.338	0.152

Phantom: Furuno Electric (S/N 133)

CV coefficient of variation, standard deviation/mean value

CV (%) percent of the CV value

Table 3 Order of SOS mean values for phantom and subjects

Order of SOS mean values for phantom		Order of SOS mean values for subjects	
UBIS5000	1581.0 m/s	Benus	1634.5 m/s
Benus	1568.2 m/s	AOS–100	1562.5 m/s
A–1000	1565.0 m/s	A–1000	1550.9 m/s
CM–200	1551.4 m/s	CM–200	1522.0 m/s
AOS–100	1549.4 m/s	UBIS5000	1472.2 m/s

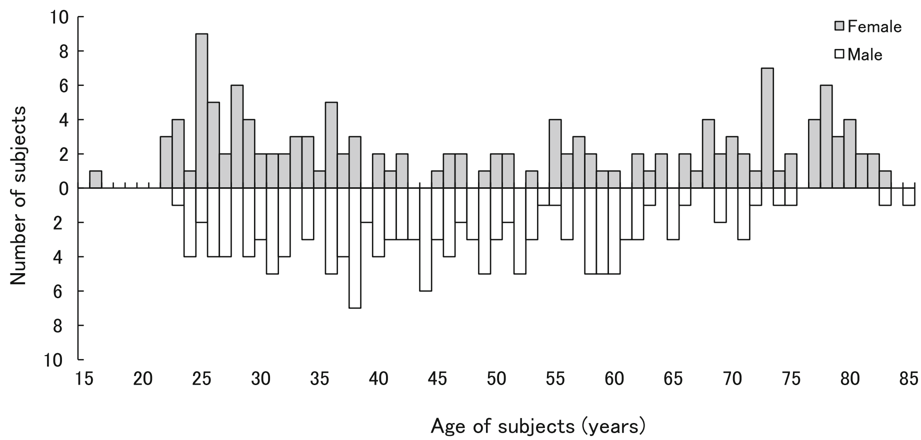

Fig. 2 Age distribution of subjects

Causes of differences in SOS values between models

Normally, the precise method for measuring SOS values and the procedure for deriving SOS values from transmitted ultrasonic waves (computational procedure and algorithm) are not generally made public for any of the products. Some possible reasons why SOS values differ from model to model despite measurement of the same phantom or the same subject are as follows:

a. Differences in the definition of SOS: The definition of SOS has not been standardized, with the following three definitions in use:
   - Calcaneus velocity
   - Heel velocity including soft tissue
   - Propagation velocity between transmitting and receiving transducers
b. Differences in measurement method of transmit time, i.e., signal processing method of transmitted waves: When measuring propagation time, the time will differ and the propagation velocity will change depending on whether the first apparent deviation from baseline, the first zero-crossing, or a fixed threshold is used as the first arrival point.
c. Differences in measurement site with each model: Individual differences in the calcaneus contour, size, and internal structure in each subject result in changes in the propagation path, which affect the measurement.
d. Ultrasonic characteristics of each model and differences in waveform processing method: Differences in the acoustic field characteristics, transient response, or resonance characteristics of the ultrasonic transmitter and receiver for each model result in differences in SOS values between devices.

Thus, there are many underlying factors for the “deviations” in SOS values between models, making it impossible to define a standard SOS at the present time. According to Table 2, however, the correlation coefficient between each model appears to be quite good; therefore, it was determined that it would be possible to statistically establish a standardized SOS.

In addition, slight changes (several percent) in QUS measurements can be seen from measurement to measurement even in cases where the same subject is measured with the same QUS device, but this is caused by changes in the propagation path of ultrasonic waves in response to local changes in the calcaneus contour and its internal structure, resulting in a QUS value that faithfully reflects the bone density and trabecular structure of cancellous

Table 4 Baseline characteristics

	Male			Female		
	Mean ± SD	Max.	Min.	Mean ± SD	Max.	Min.
Age (years)	45.9 ± 13.9	85	23	50.2 ± 20.6	83	16
Height (cm)	170.0 ± 6.5	186	151	155.2 ± 6.3	169	138
Body weight (kg)	67.5 ± 9.0	95	48	51.9 ± 7.3	73	34
BMI (kg/m^2)	23.3 ± 2.7	31.0	17.4	21.6 ± 2.9	30.7	15.7

BMI body mass index

$$\mathrm{BMI} = \frac{\text{Body weight (kg)}}{\text{Height (m)}^2}$$

Table 5 SOS correlation coefficients between models ($p < 0.0001$)

	AOS-100	CM-200	A-1000	UBIS5000	Benus	Minelyzer
AOS-100	1					
CM-200	0.82	1				
A-1000	0.87	0.88	1			
UBIS5000	0.83	0.85	0.84	1		
Benus	0.73	0.75	0.76	0.68	1	
Minelyzer	0.83	0.75	0.86	0.79	0.68	1

bone at the site of ultrasonic propagation. Changes in measurements in the same subject are information related to the internal structure of the subject's bone, and it is reasonable to regard the changes as information that serves as a clue for evaluating bone properties, rather than treating them as errors.

QUS standardization

Measurements for QUS standardization

With the cooperation of members participating in the 9th Annual Meeting of Japan Osteoporosis Society (November 14–16, 2007), QUS measurements were taken in 124 men and 75 women, and with the cooperation of participants in a public lecture (educational campaign by the Japan Osteoporosis Society aimed at the general population) (January 17, 2008) in Osaka by the Osteoporosis Network, QUS measurements were taken in 18 men and 64 women.

For QUS devices, all models approved as medical devices in Japan (six models in 2007) were arranged with the cooperation of the manufacturers and distributors. SOS values for all subjects (volunteers) were measured with all models (six models), and BUA measurements were also taken at the same time for the four models capable of measuring BUA.

The total number of subjects (volunteers) was 281, but the number of subjects in whom it was possible to measure SOS with all six models was 232 subjects (122 men, 110 women). The age distribution of the 281 subjects is shown in Fig. 2, and baseline characteristics are shown in Table 4. Pearson's correlation coefficient (r) was high in all six models, i.e., 0.68–0.88 (Table 5). The correlation coefficient between models was high, i.e.,>0.8 (0.82–0.88), for four of the six models. Based on the investigation by the QUS Standardization Committee, it was decided to use the mean SOS for each subject measured with the four models with a high correlation coefficient (AOS-100, CM-200, A-1000, UBIS5000) as the reference value (reference SOS). The reference SOS for each subject has been arranged in ascending order from lowest to highest to show it as a solid black line in Fig. 3, and the SOS values for each model corresponding to this value are also shown. There is a difference between the measured SOS values for each of the models and the reference SOS, but we can see from Fig. 3 that there is a good correlation (correlation coefficient) with the reference SOS.

Derivation of standardized SOS

The results of regression analysis of SOS measured with each model and the reference SOS (mean of four reference models) are shown in Fig. 4. With the reference SOS on the vertical axis and SOS measured with each model on the horizontal axis, the regression line and regression function are shown in the figure. It indicates that the correlation coefficient, r, is high, i.e., 0.87–0.96. Standard major axis regression analysis was used for regression analysis [20]. Measurements yielded by each model can

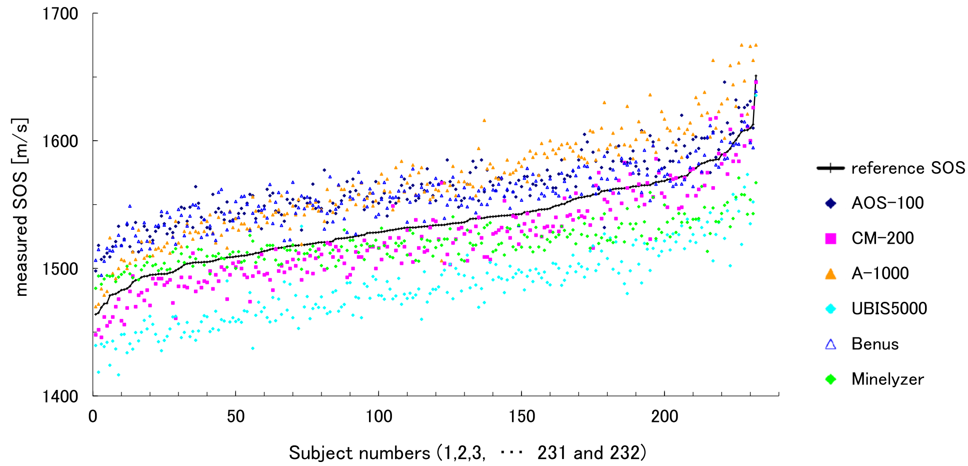

Fig. 3 Subject measurement results for SOS standardization. The mean SOS for four models with a high correlation coefficient has been arranged as a "reference SOS" in ascending order from lowest to highest, and the measured SOS values for each model are also shown

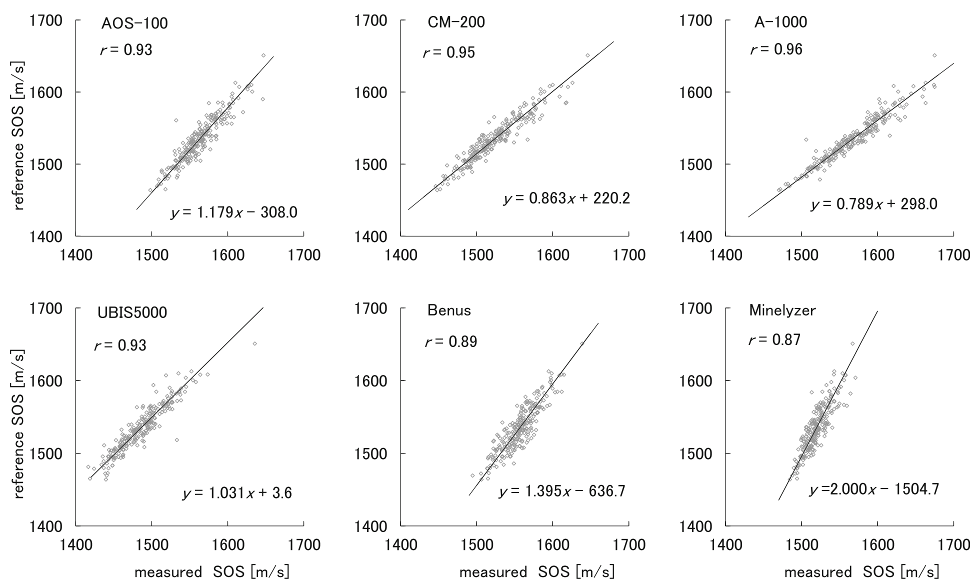

Fig. 4 Results of regression analysis of the reference SOS and the measured SOS values for each model ($p < 0.0001$) (regression analysis: standard major axis regression analysis)

be converted to a standardized SOS using this regression function. The formulas for converting the SOS measured by each model (x) to the standardized SOS (y) are summarized in Table 6. The results of regression analysis of this standardized SOS and reference SOS are shown in Fig. 5. The regression function satisfies $y = x$ for the most part for all of the models. The results after employing the same method in Fig. 3 are shown in Fig. 6, arranging the measured SOS after conversion and reference SOS in ascending order. We can see that good adjustment has been achieved with the standardization conversion formula (Table 6).

Table 6 Conversion formulas between standardized SOS and measured SOS for each QUS device

AOS-100	$y = 1.179x - 308.0$ (m/s)
CM-200	$y = 0.863x + 220.2$ (m/s)
A-1000	$y = 0.789x + 298.0$ (m/s)
UBIS5000	$y = 1.031x + 3.6$ (m/s)
Benus	$y = 1.395x - 636.7$ (m/s)
Minelyzer	$y = 2.000\ x - 1504.7$ (m/s)

y standardized SOS (s-SOS)

x measured SOS

Summary of standardized SOS

Standardization was attempted for six QUS models currently available in Japan (QUS devices approved as medical devices in Japan, 2007), from which was derived a formula for converting SOS to standardized SOS (s-SOS) (Table 6). The correlation coefficient, r, between s-SOS yielded by the conversion formula and the reference SOS (mean of four models) is sufficiently high, i.e., 0.87–0.96.

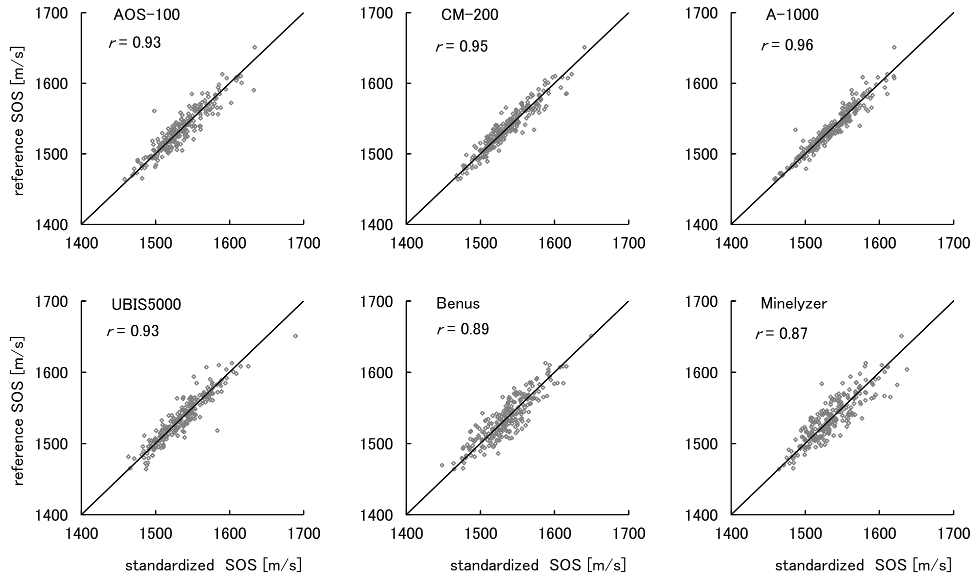

Fig. 5 Results of regression analysis of the reference SOS and the standardized SOS for each model ($p < 0.0001$) (regression analysis: standard major axis regression analysis)

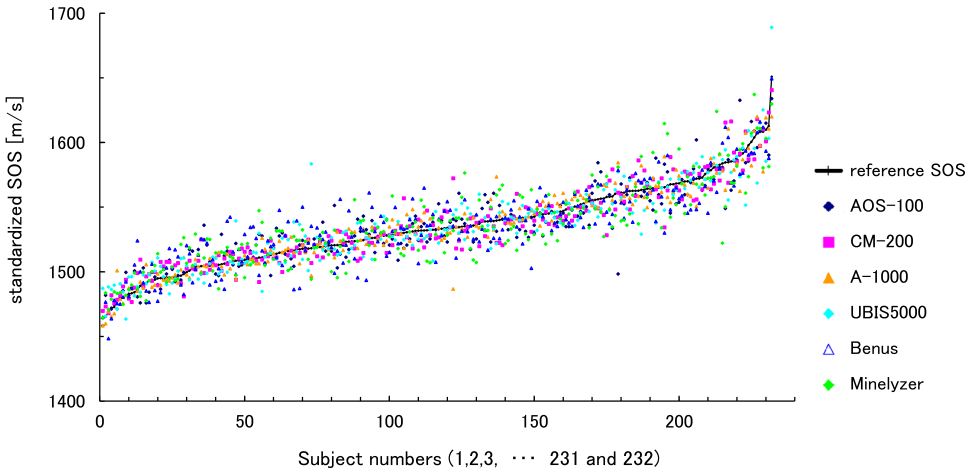

Fig. 6 Subject measurement results for standardized SOS. The mean SOS (reference SOS) has been arranged in ascending order from lowest to highest, and the standardized SOS for each model is also shown

This high correlation coefficient indicates that QUS devices are very well-made devices. The method for establishing this s-SOS described in this section is based on the method used to derive the standardized bone mineral density (s-BMD) proposed in the 1990s by the International Dual-photon X-ray Absorptiometry (DXA) Standardization Committee [21, 22].

Derivation of standardized BUA

In the case of attenuation of ultrasonic waves transmitted through the calcaneus, it is known that the degree of attenuation (dB) increases almost linearly relative to frequency (MHz) in the frequency range of 0.2–0.8 MHz. This rate of increase in the degree of attenuation relative to the frequency is referred to as broadband ultrasonic attenuation (BUA) (dB/MHz) and is used to evaluate bone density [8, 23, 24]. Like SOS, there is a considerable difference in BUA measurements from model to model as the measurement conditions differ for each model, but like SOS, the correlation coefficient between models is good, i.e., about 0.8.

Of the six QUS models available in Japan, four were capable of measuring BUA: AOS-100, A-1000, UBIS5000, and Minelyzer. BUA values of subjects were measured with each model when the above-mentioned SOS values were measured. Therefore, the subjects were the same as

Table 7 BUA correlation coefficients between models ($p < 0.0001$)

	AOS-100	A-1000	UBIS5000	Minelyzer
AOS-100	1			
A-1000	0.75	1		
UBIS5000	0.84	0.79	1	
Minelyzer	0.79	0.69	0.78	1

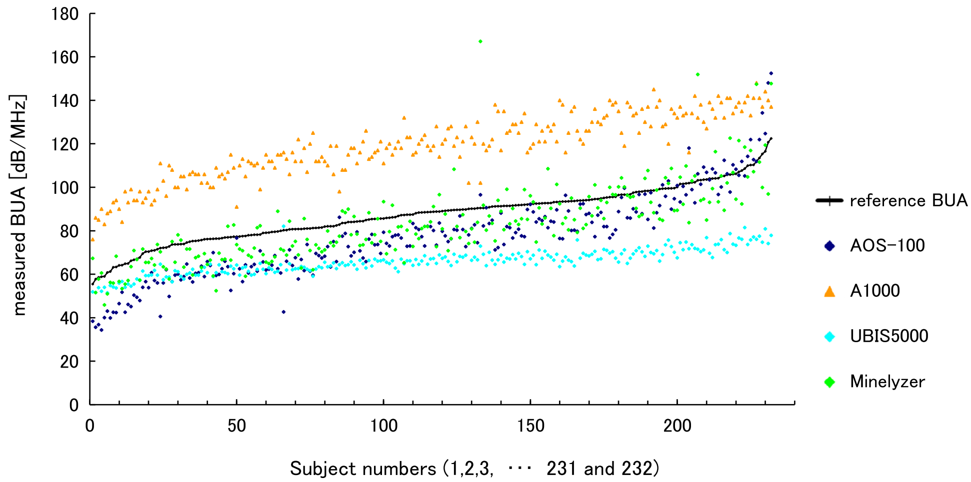

Fig. 7 Subject measurement results for BUA standardization. The mean BUA for three reference models has been arranged as a "reference BUA" in ascending order from lowest to highest, and the measured BUA for each model are also shown

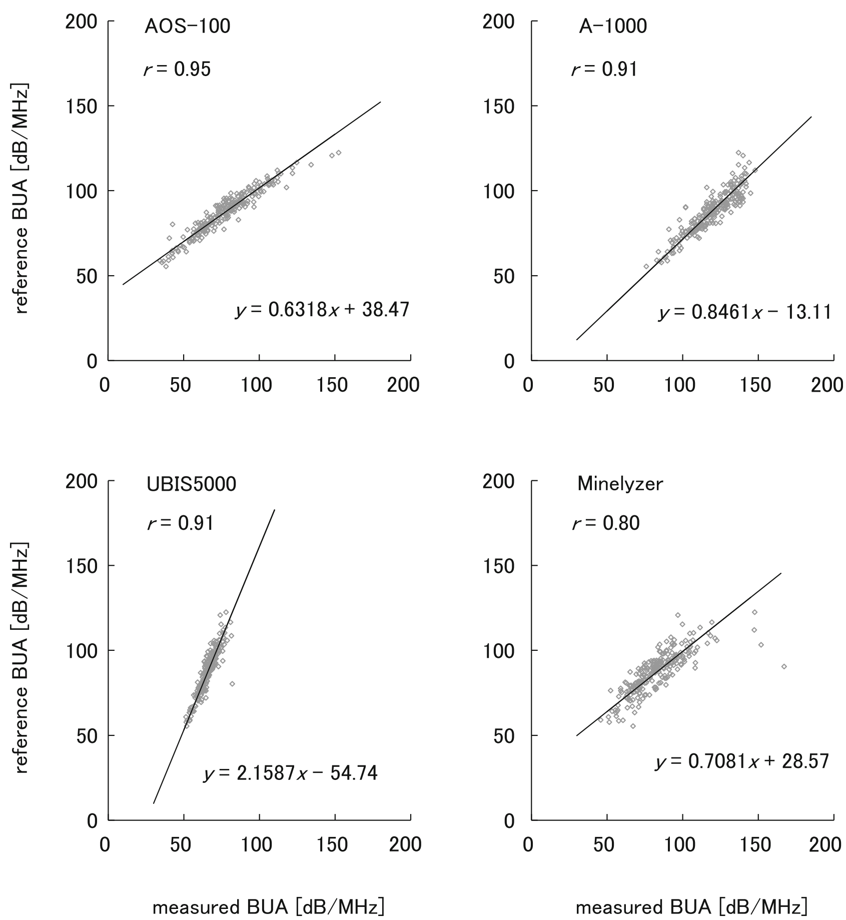

Fig. 8 Results of regression analysis of the reference BUA and the measured BUA values for each model ($p < 0.0001$) (regression analysis: standard major axis regression analysis)

those who went SOS measurement, with their age distribution shown in Fig. 2 and baseline characteristics in Table 4.

Correlation coefficients for six combinations of two of the four models calculated using the measured BUA are shown in Table 7. As shown in the table, correlation coefficients were distributed within the range of 0.69–0.84. Of the four models that were highly correlated in the standardization of SOS (AOS-100, CM-200, A-1000, UBIS5000), three models (AOS-100, A-1000, UBIS5000) were capable of measuring BUA. Since the correlation between the BUA values measured with these three models was also relatively good (Table 7), the mean of the BUA values measured with these three models was used as the

Table 8 Conversion formulas between standardized BUA and measured BUA for each QUS device

AOS-100	$y = 0.6318x + 38.47$ (dB/MHz)
A-1000	$y = 0.8461x - 13.11$ (dB/MHz)
UBIS5000	$y = 2.1587x - 54.74$ (dB/MHz)
Minelyzer	$y = 0.7081x + 28.57$ (dB/MHz)

y standardized BUA (s-BUA)

x measured BUA

reference value (reference BUA). This reference BUA is illustrated in Fig. 7 arranged from lowest to highest. The BUA values for each model corresponding to the reference BUA are also shown in Fig. 7. As was the case with SOS (Fig. 3), we can see that there is a good correlation between each model's BUA and the reference BUA. The results of regression analysis (standard major axis regression analysis) of the reference BUA and BUA measured with each model are shown in Fig. 8 and Table 8. Using the conversion formula shown in Table 8, BUA measured with each model can be converted to a standardized BUA (s-BUA). The results of regression analysis of s-BUA and reference BUA are shown in Fig. 9. The reference BUA has been arranged in ascending order from lowest to highest in Fig. 10, and the s-BUA for each model corresponding to this value are also shown. We can see that good adjustment has been achieved for the most part with the s-BUA conversion formula.

Summary of standardized BUA

After standardization of SOS, a conversion formula for standardization of BUA was derived using the same method as that for SOS standardization. The correlation coefficient between s-BUA obtained with the BUA standardization conversion formula and the reference BUA (mean BUA of three models) was 0.80–0.95, which was sufficiently high. We can see that the QUS devices are very well-made devices.

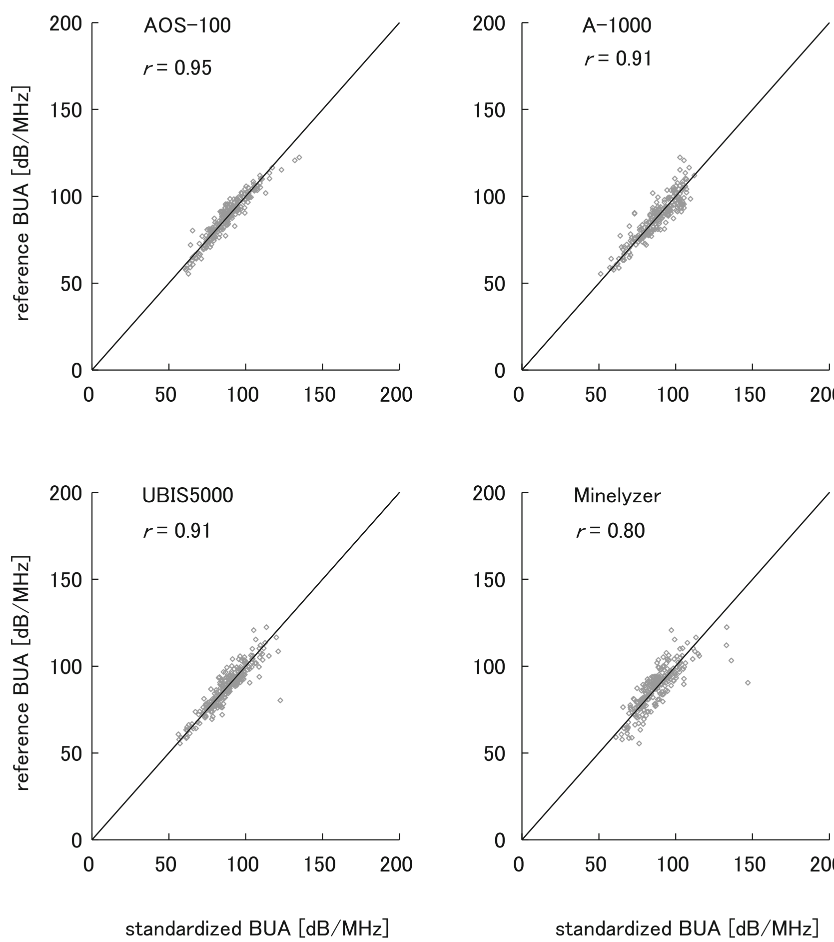

Fig. 9 Results of regression analysis of the reference BUA and the standardized BUA ($p < 0.0001$) (regression analysis: standard major axis regression analysis)

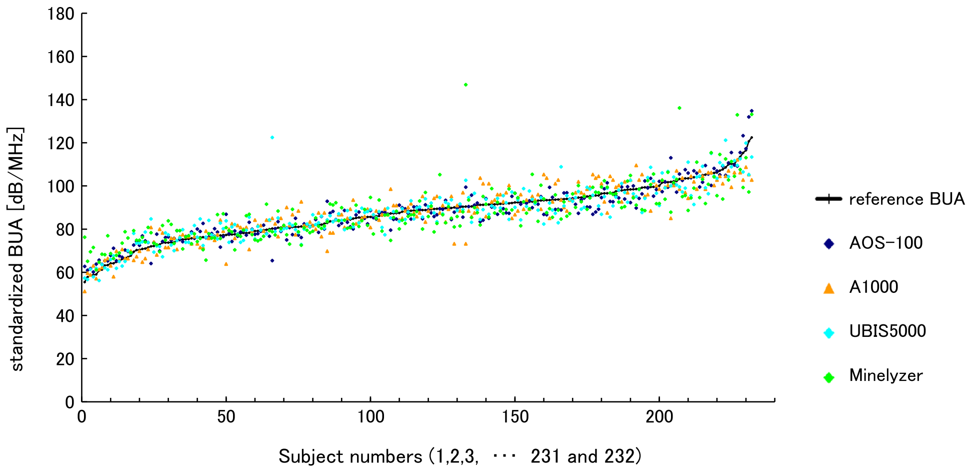

Fig. 10 Subject measurement results for standardized BUA. The mean BUA (reference BUA) has been arranged in ascending order from lowest to highest, and the standardized BUA for each model is also shown

Conclusion of QUS standardization

Standardization was attempted for six QUS models currently available in Japan (QUS devices approved as medical devices in Japan). This effort yielded a conversion formula for converting SOS and BUA measured with each model to s-SOS and s-BUA, respectively. In the case of SOS, the correlation coefficient between s-SOS yielded by the conversion formula and the reference SOS (mean of four reference models) was sufficiently high, i.e., 0.87–0.96. In the case of BUA, as well, the correlation coefficient between s-BUA yielded by the conversion formula and the reference BUA (mean of three reference models) was sufficiently high, i.e., 0.80–0.95. These s-SOS and s-BUA conversion formulas appear to yield a relationship that sufficiently stands up to comparison of measurements between models. It should be noted, however, that s-SOS and s-BUA do not indicate SOS and BUA at a specific site based on a specific definition. Moreover, the conversion formulas are only valid for the models and measurement site investigated in this study. Phantoms used to confirm the operation of the QUS devices cannot be used for the conversion of indicated values between different models or for conversion into s-SOS and s-BUA. When any new QUS device becomes available for clinical measurement, it will be necessary to perform clinical measurements for the new model using the reference models in this study and calculate a formula for conversion to s-SOS and s-BUA by means of regression analysis.

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Compliance with ethical standards

Ethical statements All procedures followed were in accordance with the ethical standards of the responsible committee on human experimentation (institutional and national) and with the Helsinki Declaration of 1964 and later versions.

Conflict of interest The authors declare that there is no conflict of interest.

Informed consent Informed consent was obtained from all subjects (volunteers) for being included in the study.

References

1. Otani T. Standardization of QUS. Osteoporos Jpn. 2009;17:149–53 **(in Japanese)**.
2. Ludwig GD. The velocity of sound through tissues and the acoustic impedance of tissues. J Acoust Soc Amer. 1950;22:862–6.
3. Goldman DE, Hueter TF. Tabular data of the velocity and absorption of high-frequency sound in mammalian tissues. J Acoust Soc Amer. 1956;28:35–7.
4. Goldman DE, Hueter TF. Errata: Tabular data of the velocity and absorption of high-frequency sound in mammalian tissues. J Acoust Soc Amer. 1957;29:655.
5. Goss SA, Johnston RL, Dunn F. Comprehensive compilation of empirical ultrasonic properties of mammalian tissues. J Acoust Soc Amer. 1978;64:423–57.
6. Goss SA, O'Brien WD Jr. Direct ultrasonic velocity measurements of mammalian collagen threads. J Acoust Soc Amer. 1979;65:507–11.
7. Goss SA, Johnston RL, Dunn F. Comprehensive compilation of empirical ultrasonic properties of mammalian tissues II. J Acoust Soc Amer. 1980;68:93–108.
8. Langton CM, Palmer SB, Porter RW. The measurement of broadband ultrasonic attenuation in cancellous bone. Eng Med. 1984;13:89–91.
9. Bauer DC, Glüer CC, Genant HK, et al. Quantitative ultrasound and vertebral fracture in postmenopausal women. J Bone Miner Res. 1995;10:353–8.
10. Hans D, Dargent-Molina P, Schott AM, et al. Ultrasonographic heel measurements to predict hip fracture in elderly women: the EPIDOS prospective study. Lancet. 1996;348:511–4.
11. Nicholson PHF, Müller R, Lowet G, et al. Do quantitative ultrasound measurements reflect structure independently of density in human vertebral cancellous bone? Bone. 1998;23:425–31.
12. Kaufman JJ, Einhorn TA. Perspective: ultrasound assessment of bone. J Bone Miner Res. 1993;8:517–25.

13. Laugier P, Giat P, Berger G. Broadband ultrasonic attenuation imaging: a new imaging technique of the os calcis. Calcif Tissue Int. 1994;54:83–6.
14. Fournier B, Chappard C, Roux C, et al. Quantitative ultrasound imaging at the calcaneus using an automatic region of interest. Osteoporos Int. 1997;7:363–9.
15. Heaney PR, Avioli LV, Chestnut CH, et al. Osteoporotic bone fragility: detection by ultrasound transmission velocity. JAMA. 1989;261:2986–90.
16. Hosie CJ, Smith DA, Deacon AD, et al. Comparison of broadband ultrasonic attenuation of the os calcis and quantitative computed tomography of the distal radius. Clin Phys Physiol Meas. 1987;8:303–8.
17. Waud CE, Lew R, Baran DT. The relationship between ultrasound and densitometric measurements of bone mass at the calcaneus in women. Calcif Tissue Int. 1992;51:415–8.
18. Zagzebski JA, Rossman PJ, Mesina C, et al. Ultrasound transmission measurements through the os calcis. Calcif Tissue Int. 1991;49:107–11.
19. Glüer CC, Vahlensieck M, Faulkner KG, et al. Site-matched calcaneal measurements of broad-band ultrasound attenuation and single X-ray absorptiometry: do they measure different skeletal properties? J Bone Min Res. 1992;7:1071–9.
20. Sokal RR, Rohlf FJ. Biometry. 3rd ed. New York: W. H. Freeman; 1995.
21. Genant HK, Grampp S, Glüer CC, et al. Universal standardization for dual X-ray absorptiometry: patient and phantom cross-calibration results. J Bone Min Res. 1994;10:1503–14.
22. Hui SL, Gao S, Zhou XH, et al. Universal standardization of bone density measurements: a method with optimal properties for calibration among several instruments. J Bone Min Res. 1997;12:1463–70.
23. Chaffaï S, Padilla F, Berger G, et al. In vitro measurement of the frequency-dependent attenuation in cancellous bone between 0.2 and 2 MHz. J Acoust Soc Am. 2000;108:1281–9.
24. Wear KA. Ultrasonic attenuation in human calcaneus from 0.2 to 1.7 MHz. IEEE Trans Ultrason Ferroelectr Freq Control. 2001;48:602–8.