Nutrition 67–68 (2019) 110529

Contents lists available at ScienceDirect

Nutrition

journal homepage: www.nutritionjrnl.com

Applied nutritional investigation

Nutritional self-screening in <1 min: Evaluation of a measuring station using sonic measurement of height

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ARTICLE INFO

Article History:
Received 14 February 2019
Received in revised form 23 May 2019
Accepted 5 June 2019

Keywords:
Nutritional screening
Self-screening
MUST
Sonic
Outpatients

ABSTRACT

Objective: Since nutritional screening is not routinely and accurately performed by busy care workers, the aim of this study was to evaluate a self-screening electronic measuring station that includes sonic height measurements.

Methods: In all, 114 patients, 18 to 85 y of age and attending gastrointestinal outpatient clinics, followed automatically triggered audio-recorded instructions for weight and height measurements. The patients also provided information about unintentional weight loss to establish malnutrition risk using the Malnutrition Universal Screening Tool (MUST). In 56 healthy individuals, the effect of head/foot positions on height was examined using video-recordings. Laboratory studies examined the effects of hair/wigs, the position of a skull and horizontal plates and ambient conditions. Measurements were also made on a mechanical machine for comparison.

Results: Of the patients, 21.9% were malnourished, with 99% agreement between sonic and mechanical machine categorization. Patients self-screened in only 35.6 ± 14.8 s (median 32 s) and 77% rated the screening as *very easy* (22%, *easy*), despite encountering some remediable snags. Within-subject precision for height was 0.186 cm in healthy individuals and 0.368 cm in patients. Humidity and barometric pressure had negligible/undetectable effects on height measurements, but temperature corrections were confounded by calibration errors. In the most lateral standing positions, height was underestimated curvilinearly. In healthy individuals, height measurements were 0.353 ± 0.542 cm lower on the sonic than mechanical device, which was inadequately explained by standing position or body tilt, although hair was found to be "invisible" only to the sonic machine.

Conclusion: A method has been developed to rapidly and reliably self-screen for malnutrition using MUST, avoiding calculation and categorization errors, while providing results that can be immediately printed or transmitted electronically into patient notes.

Introduction

Although nutritional screening is recommended in various care settings, malnutrition remains underrecognized and undertreated. This is problematic because malnutrition adversely affects well-being, predisposes to disease, delays recovery from illness, and increases disease complications, at immense cost to social and health care services [1]. A reason why recommended nutritional screening is not performed routinely is that it is not a high enough priority among busy care workers (professionals such as doctors and nurses and/or assistants such as nurse assistant), which means that they may miss malnutrition [2,3]. Another reason [4] is that certain screening tools are time-consuming, not linked to care plans, and subject to calculation or categorization errors. Self-administered questionnaires can be valuable, but they typically lack objective measurements of weight, height, and body mass index (BMI), which are cornerstones of many nutrition screening tools. Self-screening using automated processes and a valid,

This study was made possible by the University of Southampton and the National Health Service (NHS), which allowed the study to be undertaken as a service delvelopment by staff already employed by these organisations, without financial support from external funding agencies.

Conception and design of the study: ME conceived of and designed the study and was responsible for generation and assembly of the study results, as well as analysis and interpretation of the data. ME, AC, TS, and TA collected the data. ME, AC, TS drafting and revised the manuscript and approved the final version of the manuscript.

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https://doi.org/10.1016/j.nut.2019.06.010
0899-9007/

reliable tool linked to care may overcome such difficulties [3]. Self-screening studies of hospital outpatients [5–7] showed that reproducible and accurate results could be obtained quickly using the Malnutrition Universal Screening Tool (MUST) [3]. One such study [7], using a modified digital weight and height machine with electronic transmission of results to a computer, reported self-screening in 1.29 min. It suggested considerably faster screening could occur if height was measured sonically, obviating the need to lower a horizontal plate over the head. However, sonic measurements can be confounded by ambient temperature and head position relative to the sonic emitter(s) and sensor(s). The purpose of this study was to critically evaluate a device with sonic technology, with respect to accuracy, reproducibility, user friendliness, and suitability for routine nutritional self-screening. In addressing this issue, the accuracy of height and BMI measurements were assessed, and results of MUST categorization obtained on the sonic machine were compared with those on a mechanical machine.

Methods

Laboratory studies

General

Unless otherwise stated, all sonic (40 kHz) height measurements of plates/skull and calibration bar (see later) were made at 19°C to 22°C, barometric pressure 101 to 104 kPA and humidity 40% to 60%, vertically above the central point of the horizontal standing platform. This point was defined as the midpoint of the rectangular area [16.5 cm (width) × 15 cm (depth)] enclosing two small footmarks. To ensure stable positions during measurements, the plates/skull were supported by wide vertical plastic cylinders (~12 cm diameter) and the calibration bar provided by the manufacturers by a wide base (~14 cm diameter; photograph in Supplementary material). Measurements (to nearest 0.05 kg and 0.1 cm) on the sonic device (Seca-287) were compared with those on a mechanical device (Seca-285; Secagmbh & co.kg. Hamburg, Germany). Both machines also measured weight. The sonic device (2.27 m high, 0.434 m wide, 0.466 m deep, weighing 16.5 kg; photograph in Supplementary material) has a vertical column, to which is attached at its upper end a to a horizontal ultrasound head fitted with three pairs of sensors and emitters to measure the height of individuals standing beneath it. The machine can transmit results wirelessly into electronic medical systems, printers, and computers.

Precision (reproducibility) and accuracy

Column tilt was established using spirit levels and plumb lines. The accuracy of weight measurements ranging 0 to 160 kg was established using certified reference weights (placed on the weighing machine in 20-kg increments), and that of height using metal pipes of certified lengths (122 and 183 cm [www.calibrate.co.uk]) and reference bars accompanying the mechanical (80 cm) and sonic machines (81.5 cm). The mechanical device was used to construct height calibration curves so that the heights of six other items (100–200 cm) could be established and used as secondary reference standards on the sonic machine. Three of these were horizontal plates [16.3 cm (length) × 12.4 cm (width)] nominally at 100, 150, and 200 cm; and the other three involved a plastic skull (H&S Health Alliance, Birmingham, UK) placed in the Frankfort plane above the plates, nominally at 118, 168, and 188 cm.

Precision and instrument drift were assessed by repeatedly measuring the heights of the same items in 19 time-series lasting 1 to 3 h: five involving the 81.5 cm reference bar; 12 involving plates and skull at six heights; and 2 involving plates at three heights, all measured consecutively at essentially the same time points (8 in study 1; 10 in study 2). The effect of incorrect external calibration on height measurements on the sonic machine was examined using two procedures: Placing the 81.5-cm calibration bar on a 0.3-cm board in the central position; and placing it without the board 5 cm sideways from the central position, where the recorded height was ~0.3 cm below its true height.

Changing the position of the plates, skull, and the reference bar

Height measurements at the central position were compared with those made sideways at 2.5-cm intervals, from −10 cm (left) to +10 cm (right), as well as in parallel planes in front (up to +10 cm) and behind (up to −7.5 cm) the central position. Corrections for instrument drift were made between the start and end of measurements in each lateral plane.

Temperature

Measurements of the 81.5-cm reference bar, plates (nominally, 100, 150, and 200 cm) and skull (nominally, 168 and 188 cm) were made sequentially in a temperature controlled room at 25°C, 30°C· 15°C, and 20°C, to within 0.2°C, while maintaining humidity at 50% to within 0.8%. At least quadruplicate measurements were made both before and after instrument calibration. Initial postcalibration measurements made at 20°C just before the study began, were compared with those at the end.

Humidity

Heights were measured at 55%, 75%, and 40% humidity, in that order, at 20°C using a similar protocol as for the temperature studies.

Barometric pressure

The effect of barometric pressure (101–104 kPA) on height measurements after machine calibration was examined using data obtained on different days.

Hair and wigs

The heights of two horizontal plates (nominally, ~100 and ~150 cm) were measured with and without an even covering of 25.2 g straight hair from a 33-y-old woman. The measurements on the sonic device (n = 6–11 at each level) were compared with those on the mechanical device (n = 4 at each level). The effects of two wigs with straight hair attached to thinly perforated cloths were examined by placing them on top of the skull, nominally at 168 cm.

Studies with healthy individuals

After machine calibration, measurements were made on 56 healthy men (n = 27) and women (n = 29; 52 white, 3 black, 1 Asian), 18 to 68 y of age, with a mean weight of 74.5 ± 13.7 kg, height of 169.67 ± 9.50 cm, and BMI 25.9 ± 4.46 kg/m^2. The amount of hair above the head was subjectively categorized as none (bald)/very little, intermediate, and large. Individuals were measured twice on the mechanical and sonic machines, wearing light clothing and no shoes.

When using the sonic device, individuals were asked to step on the standing platform and follow the automatically triggered audio-recorded instructions ("Please stand upright and look straight. Do not move. The measurement starts now. The measurement is completed. Please step off the platform"). High-definition wireless video cameras (Lorex FLIR 1080 P HD Wireless – 4 channel unit; Markham, Canada) were used to establish the Frankfort angle, the gap between the heels, as well as the spatial coordinates of various points on the feet, and body tilt in the anterior–posterior and lateral planes (see Supplementary material). Six sets of height measurements were also made on individuals (175–186 cm) standing 9 to 11 times on either side of the central part of the platform (0–10 cm sideways) in the same posture. Foot positions were marked on clear plastic covering the platform.

When using the mechanical device, a health care professional recorded height in the upright position during inspiration, with the head in the Frankfort plane and heels close together and touching the plate at the back of the standing platform.

Studies with patients

After excluding 1 wheelchair-bound patient and 2 pregnant women, 114 patients, 18 to 85 y of age, self-screened (Table 1) on the sonic machine. These consecutive patients attended the same gastroenterology clinic on three occasions. On one occasion, 13 patients were measured twice on the sonic machine but not on the clinic machine. On the other two occasions (n = 101) measurements were made on both machines (except for two patients on the clinic machine: one missed and one too unsteady). Of the 101 patients, 19 had duplicate measurements on the clinic machine. The clinic machine (Seca-799 fitted with Seca-220 rod) measurements were made by a health care professional to the nearest 0.1 kg and cm.

Space constraints prevented video-recordings and measurements with Seca-285, which did not fit in the low-ceiling room. The procedures were as for healthy individuals, but flat footwear was allowed.

Table 1
Characteristics of 114 patients who self-screened

Age, y*	49.3 ± 18.3†
Sex, M/F	49/65
Weight, kg*	75.07 ± 20.06
Height, m*	1.696 ± 0.095
BMI, kg/m^2*	26.07 ± 6.80
Any unplanned weight loss in last 3–6 mo, n (%)	39 (34.2)
Diagnosis, established in 107 patients, %	Crohn's disease, 35.3 Ulcerative colitis, 25.0 Irritable bowel syndrome, 19.0 Other, 20.7

*Mean ± SD.
†22.4% ≥65 y.

With the sonic device, patients followed the audio-recorded instructions (as previously presented) and answered the following queries on an integrated surface laptop:

1. Have you lost weight without trying in the previous 3 to 6 mo (Yes/No; if answer is Yes, items 2 and 3 appear; if No, item 4 appears).
2. Do you want to enter the weight loss in pounds (lb) or kilograms (kg)?
3. Enter the weight loss.
4. How easy did you find the procedure (*very easy, easy, difficult, very difficult, impossible*)?

Results of weight, height, BMI, weight loss, and MUST category were automatically calculated and printed on sticky labels. The duration of self-screening was recorded automatically from the moment patients were asked to stand on the sonic machine to follow the audio-recorded instructions to completion of self-screening (excluding question 4).

Ethics

Research and Development did not require ethical applications as the project was judged to be a Service Development. The printed screening results were added to the patient notes.

Statistical analysis

SPSS version 24 (SPSS, Chicago, IL, USA) was used to undertake statistical analyses, including bivariate and multiple regression analysis, curve estimation, intraclass correlation (two-way random effects model) and κ statistics. $P < 0.05$ (two-tailed) were considered significant.

Results

Laboratory studies

Instrument tilt

The column of the sonic machine (~213 cm) was tilted 0.6 cm to the left and 0.7 cm to the back (left and back referring to participant position during routine measurement). The midpoint of the middle two sensors/emitters was vertically above a point 0.6 cm to the left and 1.75 cm behind the central point of the standing platform.

Precision (reproducibility) and accuracy

On the sonic device, reference weights (0–160 kg) weighed only 0.003 ± 0.022 (SD) kg (0.003% ± 0.021%) more than the values attributed to them. The height of the 81.5 cm calibration bar was repeatedly confirmed to be exactly 81.5 cm on the mechanical machine, but on the sonic machine immediately after calibration it was 0.018 ± 0.107 cm higher, with an associated within-set precision of 0.040 cm. The corresponding combined values for eight other sets, involving six heights (three plate and three skull, 100–200 cm) were −0.061 ± 0.1424 cm (difference from the mechanical machine) and 0.076 cm (within-set precision). Table 2 shows the precision and accuracy established from 19 time series on the sonic machine, with amalgamated summaries in the footnote. Measured height differed significantly between time series ($P < 0.001$) and between time points in the same series ($P < 0.001$). Within the same time series, more of the variability was due to between than within time-point differences. In the two time series in which three plates were measured immediately after each other (test–retest), the mean errors correlated with each other (single and average measures intraclass correlations of 0.654 [$P = 0.001$] and 0.850 [($P = 0.001$], respectively for study 1, and 0.392 [$P = 0.025$] and 0.660 [$P = 0.025$] for study 2) and with calibration errors. Furthermore, over-calibration by 0.3 cm affected the mean recorded height of the reference bar by 0.283 cm ($P < 0.001$) and of the plates (nominally at 100, 150, and 200 cm) by 0.267 cm ($P < 0.001$). Under-calibration by 0.3 cm affected the measurements, in the opposite direction, by a mean of 0.300 cm ($P < 0.001$) and 0.327 cm ($P < 0.001$), respectively.

Position on standing platform (sonic device)

The further away the reference bar, plates, and skull were placed on either side of the central point, the more their heights were curvilinearly underestimated (and generally slightly more on the right; Fig. 1). The underestimation was considerably greater for the skull (0–0.3 cm at 2.5 cm, ≤0.4 cm at 5 cm, and up to ≥1 cm at 7.5–10 cm) than the plates, especially at the higher than lower skull height (nominally 188 versus 168 cm). Skull placements in lateral planes in front and behind the central point generally produced comparable results to those in the plane intersecting the central point. Skull heights measured at 2.5-cm intervals, ≤5 cm in front, back, left, and right of the central point, including the central point (25 positions) were 0.159 ± 0.214 cm lower than at the central point. When measured within 2.5 cm of the central point (nine positions) they were only 0.029 ± 0.163 cm lower.

Temperature

On the mechanical device, the calibration curves and the heights of all items were unaffected by temperature. On the sonic device, heights measured after machine calibration were overestimated by 0.146 ± 0.0174 (SD) cm, with progressively greater overestimation (+) at lower temperatures (mean of −0.059 cm [30°C], +0.176 cm (20°C), +0.224 cm (25°C), and +0.260 cm (15°C); $P_{\text{linear trend}} < 0.001$ for the combination of three plates (nominally at 100, 150, and 200 cm) and skull (nominally at 188 and 168 cm). The measurement errors (recorded minus referent height) for these five items were correlated at the given temperatures (intraclass correlation r[single measures] = 0.816, $P < 0.001$; r[average measures] = 0. 957; $P < 0.001$), and significantly related to those of the 81.5-cm reference bar. Comparable correlations were observed before machine calibration (r[single measures] = 0.796 and r[average measures] = 0.886), without significant linear temperature trends. The overall errors were no better immediately after than before machine calibration (e.g., 0.085 ± 0.127 and −0. 058± 0.177 cm, respectively, for the 81.5-cm bar at the four temperatures; $P = 0.005$). Finally, after calibration measurements of the 81.5-cm reference bar at 20°C revealed a smaller overestimation after the first (0.060 ± 0.089 cm; n = 5) than second calibration (0.300 ± 0.000 cm; n = 4), a pattern also seen for five plate + skull heights (0.168 ± 0.142 cm, n = 25 versus 0.224 ± 0.104 cm, n = 21, respectively; $P = 0.005$).

Humidity

On the sonic device the mean errors at each humidity level (40, 55, and 75%) were <0.1 cm and associated with mean calibration errors of <0.1 cm (undetectable on mechanical device).

Barometric pressure

Regression analysis found no significant effect of barometric pressure, within the range 101 to 104 kPA, on sonic height measurements.

Hair and wigs

Placing hair on the plates at nominal heights of 100 and 150 cm produced essentially no change in recorded height on the sonic device (−0.03 cm; $P = 0.465$), but a significant increase on the mechanical device (0.323 cm; $P < 0.001$). Placing two types of wigs on top of the skull (nominal height, 168 cm) produced a small nonsignificant change on the sonic device (0.05 and 0.075, cm respectively) and a significant increase on the mechanical device (0.1 cm, $P < 0.001$ and 0.175 cm, $P < 0.01$, respectively).

Table 2
Accuracy and reproducibility of sonic height measurements in central position in 19 time series

	Reference bar (81.5 cm)	Plates* and skull* (100–200 cm)	Plates (three plates measured immediately after each other; 100–200 cm)
Number of time series	5	12	2
Duration (h/series)	1–3	1.8–3	2
Number of time points	20	107	
Number of measurements	73	293 (194 plates, 99 skull)	18 (8 +10)
Measurements/time point	2–5	2–5	3
Overall measurement error, cm†	−0.049 ± 0.085	−0.101 ± 0.161	−0.161 ± 0.147
Within time point precision, cm‡	0.047	0.077 (0.078 cm plates, 0.075 skull)	0.079
Within-series precision, cm§	0.074	0.096	0.116

*Plates (nominally, 100 cm, 150 cm, and 200 cm); skull (nominally, 118 cm, 168 cm and 188 cm).
† −0.093 ± 0.146 cm (95% range, 0.574 cm) for combined series.
‡ 0.072 cm (95% range, 0.284 cm) for combined series.
§ 0.093 cm (95% range, 0.367 cm) for combined series.

Studies with healthy individuals

Five individuals were bald or had very little head hair, 44 had intermediate amounts, and 7 had large amounts. The average of duplicate height measurements on the sonic device (169.32 ± 9.47 cm) were 0.353 ± 0.542 cm lower than the mechanical device (0.353 ± 0.555 cm lower for single measurements; $P < 0.001$; Supplementary material). In contrast, there was no significant discrepancy in body weight (74.51 ± 13.70 versus 74.55 ± 13.69 kg, respectively). The within-subject precision (SD) for height was 0.186 cm (95% range, 0.737 cm) on the sonic device and 0.161 cm on the mechanical device. The respective precisions for weight were 0.05 kg and 0.09 kg, and for BMI 0.064 and 0.062 kg/m^2.

On the sonic device, the position of the head (Supplementary material) was related to that of the feet both in the lateral direction (midpoint of head versus midpoint of feet; $r = 0.613$, Standard error of the estimate (SEE) = 0.963 cm; n = 56 participants, $P < 0.001$) and the anterior–posterior direction (external auditory meatus versus position of feet; $r = 0.535$, SEE = 2.789 cm, n = 48 participants, $P < 0.001$). The head position varied two- to threefold more (ratio of SDs or 95% ranges) in the anterior–posterior direction (e.g., 2.3 ± 3.4 cm [SD] for the external auditory meatus) than in the lateral direction (e.g., −0.2 ± 1.4 cm for the midpoint of back of head). Only seven self-screening measurements (6%) were made with the midpoint of the head >2.5 cm sideways from the anterior–posterior reference plane, and only one >5 cm. Body tilt was also two- to threefold more variable in the anterior–posterior direction (0.45 ± 0.98 degrees) than in the lateral direction (0.29 ± 0.38 degrees).

In bivariate and stepwise multiple regression analyses, the amount of head hair, gap between heels, and variables defining the position of the head and feet and body tilt in the anterior–posterior and lateral directions did not significantly explain the height discrepancy between the two machines ($r^2 = 0.00–0.054$ in bivariate analysis; Supplementary material). The largest single discrepancy (1.95 cm higher on sonic machine), involving a woman of African descent with copious, curly, wiry head hair, accounted for more of the between-machine variance (17%) and between-machine difference (~10%) than any other variable applied to the entire group. After some of her hair was cut, the discrepancy was reduced to 1 cm, basically owing to reduced height on the mechanical device.

In the individuals (175–186 cm) who stood on the sonic machine 9 to 11 times, a curvilinear within-subject relationship was found between measured height and sideways distance from the platform's midline to the feet's midpoint (r[quadratic model] = 0.764–0.931). At 2.5 cm sideways the predicted height decreased by a mean of 0.16 cm, at 5 cm by 0.56 cm, and at 7.5 cm by 1.18 cm, generally consistent with the skull studies (Fig. 1).

Studies with patients

The within-subject precision for measurement of weight, height, and BMI was 0.034 kg, 0.368 cm (95% range, 1.60 cm), and 0.12 kg/m^2 on the sonic device (self-screening), and 0.15 kg, 0.51 cm, and 0.17 kg/m^2 on the mechanical device (health care professional screening). Mean height was only 0.074 cm higher on the mechanical device ($P = 0.686$). The prevalence of malnutrition was 21.9% (medium risk 10.5%, high risk 11.4%). There was almost perfect agreement in MUST categorization between the two types of devices. The only exception involved a patient whose BMI fell on either side of the 20 kg/m^2 cutoff point (19.92 kg/m^2 on the clinic machine (BMI and MUST score 1) versus 20.16 kg/m^2 on the sonic machine (BMI and MUST score 0), producing 99.1% agreement and 97.3% chance corrected agreement in MUST categorization ($\kappa = 0.973$).

Nine patients tended to look toward the sonic machine's screen rather than forward, as instructed. Five patients appeared uncertain about the magnitude of their weight loss, two had a language problem, one had difficulty hearing the audio instructions, and another had trouble reading the questions on the computer. Of the patients, 77% found the self-screening *very easy*, 22% *easy*, and 1% *difficult* (an obese, breathless patient who had difficulty standing).

The mean screening time was 35.6 ± 14.8 s (0.59 ± 0.25 min), median 32 s, and 5th to 95th percentile 20 to 65 s (Fig. 2). Ninety-four percent self-screened in <60 s and 98% in <70 s. In the group without weight loss, screening time was shorter than in the weight loss group (29.6 ± 9.9 s versus 47.2 ± 15.8; $P < 0.001$) and significantly related to age ($r = 0.256$; SEE 9.6 s; n = 39; Fig. 3). In the weight loss group, screening time was significantly related to age only after excluding two outliers (Fig. 3; one due to inadequate software to accommodate 30 kg genuine weight loss, and the other to prolonged uncertainty about weight loss). Screening time was not significantly affected by sex or perceived difficulty to self-screen, but it increased with MUST category (low risk 33.5 ± 12.5 s; medium risk 35.5 ± 12.1 s, high risk 50 ± 22.7 s; $P_{trend} < 0.001$) and associated history of weight loss (22.5%, 66.7%, and 84.6%, respectively).

Discussion

This study found that patients can reliably and accurately self-screen for malnutrition using a device that simultaneously measures height sonically and weight, with automated calculation of BMI, weight loss, and malnutrition categories. A series of studies also identified the strengths and limitation of the device.

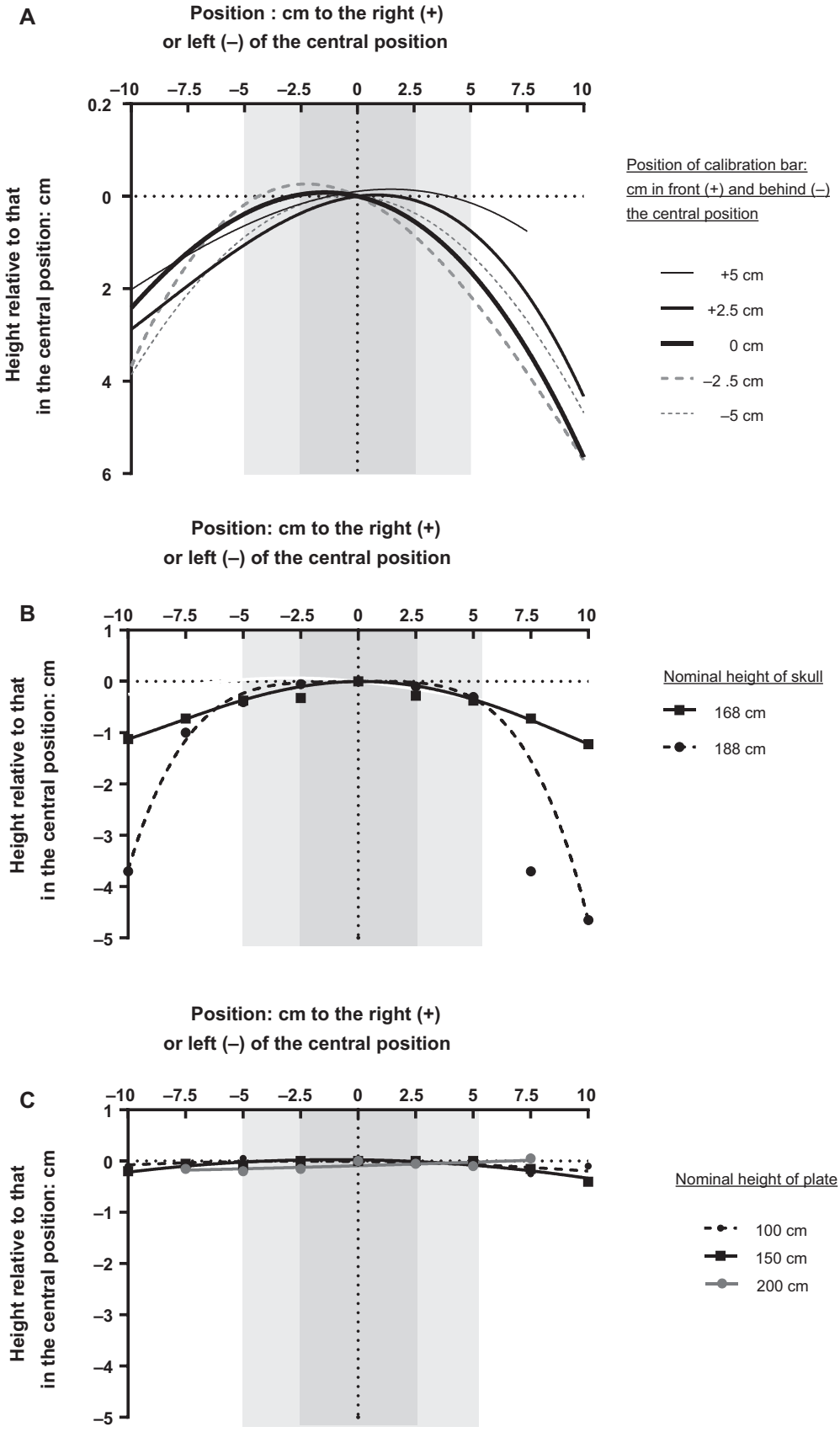

Fig. 1. Effect of placing items to the right (positive values) and left (negative values) of the central (zero) position of the standing platform on measured height. (**A**) The reference bar (81.5 cm), showing results in the central plane (bold curve), two planes in front (+2.5 and +5 cm) and two behind (−2.5 cm and −5.0 cm) the central plane. (**B**) The skull at two nominal heights. (**C**) Plates at three nominal heights. The darker gray area 2.5 cm on either side of the midline is likely to be used in routine practice, the light gray (±2.5–5 cm) occasionally used, and the white area beyond ±5 cm unlikely to be used.

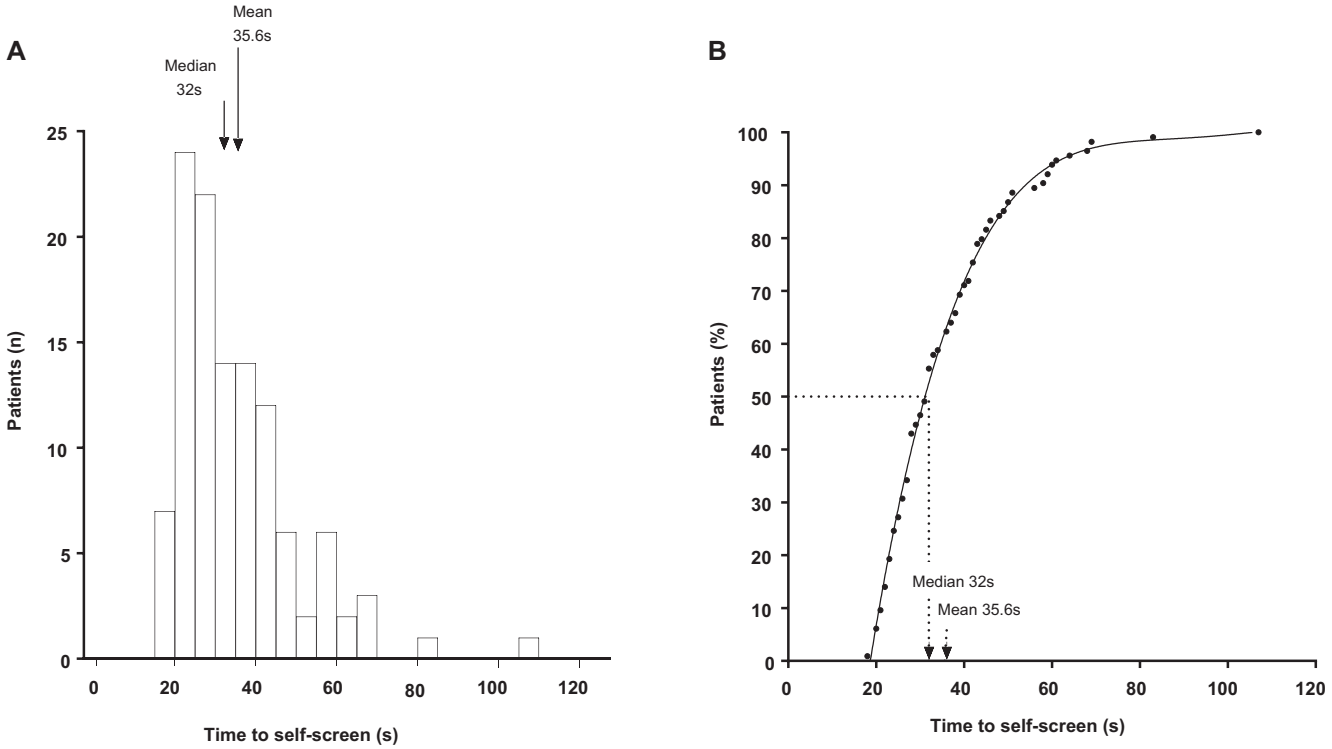

Fig. 2. Time for patients to self-screen on the sonic machine (N = 114): (**A**) frequency distribution; (**B**) percent cumulative frequency distribution.

Studies in the laboratory and with healthy individuals: Reproducibility and validity of sonic machine

Although the average measurement errors for the 81.5-cm reference bar, and horizontal plates/skull at six heights (100–200 cm) were generally small (≤0.1 cm at the central position), individual errors were substantially greater (95% range, ~0.5 cm). Measurements made immediately after each other were more reproducible than intermittent measurements over 1 to 3 h. Those made on inanimate objects were more reproducible (95% range, 0.28 cm) than in healthy individuals (0.74 cm) and patients (1.60 cm), probably because of greater variability in standing position and minor movement during measurements on participants. Because errors at different heights were related to each other and to calibration errors, care should be taken to place the calibration bar in the central part of the platform. At other positions, errors of ≥0.3 cm can occur. The value of frequent external calibrations in the central position is uncertain as measurements before calibration were not less accurate than after calibration. Routine measurement of the 81.5-cm reference bar immediately after instrument calibration could help assess calibration accuracy. Instrument drift is another source of variability, although this was adjusted for in the spatial position studies.

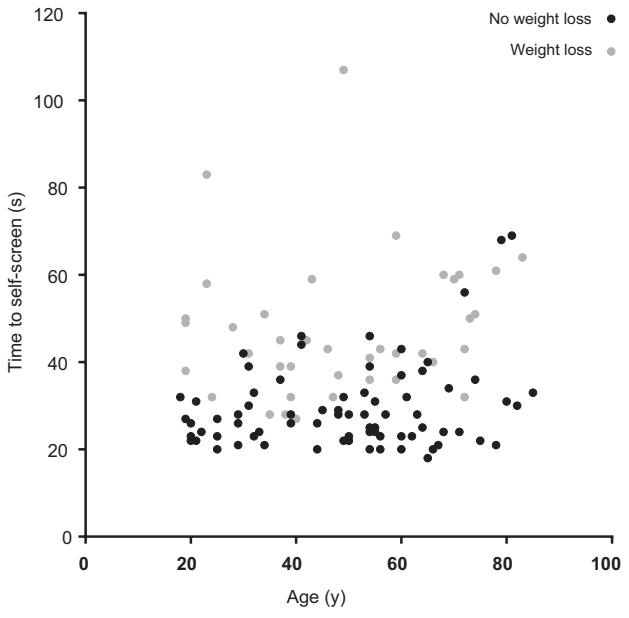

Fig. 3. Time for patients to self-screen on the sonic machine by age and weight loss in preceding 3 to 6 mo (N = 114).

The slight tilt of the column supporting the ultrasound head can be shown by Pythagoras' theorem to negligibly affect vertical distance (~0.001%), but it could potentially influence height measurements in another way. As the vertically supported calibration bar, plates, and especially skull (or individuals), stood increasingly sideways on either side of the central point (2.5, 5, and 7.5–10 cm), height was progressively underestimated (Fig. 1; in the case of the skull by 0–0.3, ≤0.4, and ≥1 cm, respectively). Given that the instrument calculates height from only a proportion of ultrasound waves (those with stable echo-amplitude taking the least time to be sent and received by the emitters/sensors), the height of items not vertically below the emitters/sensors are underestimated because sonic waves take longer to reach them. Furthermore, Pythagorean principles suggest that the heights of the more laterally placed items (especially tall items) will be curvilinearly underestimated, consistent with the curves in Figure 1. The skull curves were more pronounced than the plate curves, perhaps because as the skull, with its relatively flat top and curved sides, is moved sideways, its inner, lower surface becomes increasingly

exposed to the cone of emitted ultrasound waves, whereas its outer higher surface becomes less exposed, especially beyond the cone's boundary and at higher levels where the cone's cross-sectional area is smaller. Raising the emitters/sensors could attenuate any underestimation of height in the more lateral standing positions, but this may prevent the instrument from fitting into rooms with low ceilings. The curves also may be affected by the shape of the skull, which varies between individuals and racial groups.

Most curves in Figure 1 suggest that height is underestimated slightly less to the left than the right of the central point. This might be a chance finding, but it could also be favored by the slight left-sided instrument tilt, as the middle sensor/emitter was vertically above a point 0.6 cm to the left of the platform's midline (1.0 cm in another Seca287 instrument [unpublished]; and potentially more with inadvertent change or incorrect instrument assembly). The alignment of three pairs of sensors/emitters in the anterior–posterior plane could help explain why varying the position of objects in this plane produced smaller errors than in the lateral plane. Altering the arrangement of the sensors/emitters, and increasing their number could improve accuracy, although the latter would increase expenses, especially if the emitters/sensors used different signals in an attempt to establish better spatial coordinates.

Temperature influences the speed of sound/ultrasound in air, and therefore sonic height measurements. Raising ambient temperature from 15°C to 30°C at 50% humidity increases the speed by 2.77%, which if uncorrected would affect the height of a 150 cm-tall item by 4.155 cm. In the temperature studies, the mean measurement errors after instrument calibration ranged from +0.260 cm (overestimation) at 15°C to −0.059 cm (underestimation) at 30°C, producing an overall discrepancy between the two temperatures of 0.319 cm. As this corresponds to only 7.7% of the theoretical uncorrected error ($100 \times 0.319/4.155$), it is concluded that the instrument adjusts for temperature. However, it is difficult to assess the accuracy of the adjustment because of other effects, such as errors due to repeated calibrations. Humidity, within the range 40% to 75%, was found to have little effect on measured height (mean errors <0.1 cm), and barometric pressure, which does not influence the speed of sonic waves, had no significant effect.

Weight was reproducibly and accurately measured on both sonic and mechanical machines, but healthy subjects measured 0.353 ± 0.542 cm less on the sonic machine for various possible reasons. On the sonic device, the standing position was less controlled and less standardized, producing more variable deviation of the head from the Frankfort plane (fixed during mechanical measurements), more variable and sometimes wide gap between the feet, and potential slouching. Also, the sonic device calculates height from parts of the head closest to the sonic sensors/emitters over a period of time, whereas the mechanical device calculates it from the highest part of the head (including hair) at a point in time. The laboratory studies found that hair and two types of wigs were essentially invisible to the sonic machine but not to the mechanical machine. However, an effect of braided, knotted, or congealed hair (produced by certain creams) and different types of wigs on sonic measurements was not excluded. One individual with abundant curly, wiry hair, recording 1.95 cm greater height on the mechanical than sonic device, accounted for more of the between-machine difference and between-machine variability than individual variables (concerning standing position, posture, or amount of hair) applied to the whole group. Finally, the study indicates that individuals do not always stand upright on the sonic device despite instructions to do so and despite concordance between foot and head positions. Variations in head position and body tilt were considerably smaller in the lateral direction than in the anterior–posterior direction. Only 6% of measurements were made with the mid-head position >2.5 cm to the side of the vertical reference plane and in 1% >5 cm. This is reassuring as height is more likely to be underestimated in the lateral standing positions.

Studies with patients

There was almost perfect agreement in nutritional risk categorization between the two machines. The discrepancy in height between machines was generally small and unlikely to affect BMI and nutritional risk categorization, except in the small number of patients whose BMI was very close to BMI cutoff points (only one disagreement between machines in the current series).

Compared with previous self-screening studies using MUST [5–7], this study of outpatients with a high prevalence of malnutrition (21.9 versus 15–21.3%), is the first to use sonic technology linked to full automation and categorization. It found that self-screening was easier (*very easy* in 77 versus 55–72% [5–7]) and faster (mean, 0.59 versus 1.29–5 min [5–7]), with 50% of patients self-screening in 32 s and 93.9% in <60 s. It tended to be slower in older individuals, in those with weight loss who had to record the amount of weight loss, and in those with increased risk for malnutrition who were more likely to have weight loss.

Although these results are encouraging, further improvements could be made: By relocating the sonic machine's screen (to prevent patients, but not care workers, from looking at it during measurement), providing information about stone-pound conversions; and options for patients who are unsure about the extent of weight loss. Electronically assisted screening could probably be undertaken just as quickly, if not more quickly, by health care workers using a head piece to measure height. For inpatient screening, the care worker can also quickly provide a score (0 or 2) for the acute disease effect [3]. Care should be taken not to extrapolate the results of this study to other care settings, where patients may be unconscious, confused, or unable to stand up. In these circumstances, MUST can be used with input from care workers [3]. Other practical considerations involving the use of the sonic machine include the following: its cost (Seca 287); its height (2.27 m), which may prevent its use in low-ceiling rooms; the calibration procedure, which was discussed previously; and interference from air movement (e.g., due to the use of a strong fan) and from nearby objects, which can be avoided by ensuring there are no people or objects within the vicinity of the machine during measurement (0.5 m in front and side of the machine and 0.2 m behind the machine).

Conclusion

This study of ambulatory patients, involving self-screening using sonic height measurements, paves the way toward electronically assisted screening of malnutrition risk in routine practice. The procedure avoids calculation and categorization errors and produces results for almost immediate printing or electronically transmission into patient notes. Self-screening in the community (e.g., general practices and pharmacies) could help prevent malnutrition or facilitate early treatment.

Acknowledgments

The authors acknowledge the clinic staff for their support, Seca for information about its devices, and D Turville for programming for automation.

Supplementary materials

Supplementary material associated with this article can be found in the online version at doi:10.1016/j.nut.2019.06.010.

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