

Real-Time Sonography to Estimate Muscle Thickness: Comparison with MRI and CT

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Received 22 November 1999; accepted 8 December 2000

ABSTRACT: *Purpose.* We investigated the feasibility of using real-time sonography to measure muscle thickness. Clinically, this technique would be used to measure the thickness of human muscles in which intramuscular microstimulators have been implanted to treat or prevent disuse atrophy.

Methods. Porcine muscles were implanted with microstimulators and imaged with sonography, MRI, and CT to assess image artifacts created by the microstimulators and to design protocols for image alignment between methods. Sonography and MRI were then used to image the deltoid and supraspinatus muscles of 6 healthy human subjects.

Results. Microstimulators could be imaged with all 3 methods, producing only small imaging artifacts. Muscle-thickness measurements agreed well between methods, particularly when external markers were used to precisely align the imaging planes. The correlation coefficients for sonographic and MRI measurements were 0.96 for the supraspinatus and 0.97 for the deltoid muscle. Repeated sonographic measurements had a low coefficient of variation: 2.3% for the supraspinatus and 3.1% for the deltoid muscle.

Conclusions. Real-time sonography is a relatively simple and inexpensive method of accurately measuring muscle thickness as long as the operator adheres to a strict imaging protocol and avoids excessive pressure with the transducer. © 2001 John Wiley & Sons, Inc. *J Clin Ultrasound* 29:230–236, 2001.

Keywords: muscle thickness; real-time ultrasonography; deltoid; supraspinatus

Clinical studies of muscle atrophy and remediation commonly depend on methods to measure changes in muscle strength and size. The magnitude of maximum voluntary contractile force is known to be correlated with the cross-sectional area of muscle.^{1,2} However, maximum force-generating capacity (strength) cannot be measured accurately in muscles that cannot be contracted voluntarily. Thus, changes in muscle size (measured as cross-sectional area or thickness) are used as an index of muscle weakening and atrophy or, conversely, strengthening and hypertrophy.^{3,4}

We are undertaking studies in which microstimulators are implanted into the deltoid and supraspinatus muscles of stroke patients to remediate muscle atrophy. As part of these studies, we must be able to measure changes in the size of the stimulated muscles. Sonography may have advantages for this purpose over MRI or CT. However, sonography must be shown to be sufficiently sensitive to detect changes in muscle thickness of 10–20%, the range typical of muscle atrophy in vivo.^{5–7} Moreover, we must ensure that the presence of the microstimulator devices does not distort images in a way that interferes with muscle-thickness measurements.

The present study was undertaken to determine the accuracy and reproducibility of muscle-thickness measurements with sonography. We examined the effects of microstimulator implants on images obtained with MRI, CT, and sonography and compared measurements of muscle thickness made using sonography and other imaging modalities in porcine cadaver hindquarters

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Grant sponsor: Medical Research Council of Canada

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implanted with microstimulators and in intact human deltoid and supraspinatus muscles.

MATERIALS AND METHODS

Measurements in Porcine Muscles

This study was approved by the Queen's University Animal Care Committee on Research and by the Research Committee of the Radiology Department of Kingston General Hospital. Hindquarters were obtained from 3 pigs that had been anesthetized with sodium pentobarbital and then killed by exsanguination in an experiment not involving the skeletal musculature of the hindquarters. The skin above the biceps femoris and gluteus maximus was marked at 10-mm intervals along the natural direction of the muscle. A 10-gauge Angiocath needle (Becton Dickinson Infusion Therapy Systems, Sandy, UT) was used to place microstimulators (Advanced Bionics Corporation, Sylmar, CA) into the biceps femoris and gluteus maximus muscles at the inked sites (3–6 per pig). The hindquarters were then refrigerated for 2–72 hours before being imaged.

All scans were made perpendicular to the long axis of the femur at 10-mm intervals. Sonography was done with a Sonoline Elegra ultrasound system (Siemens Medical Systems, Issaquah, WA) and a 5-MHz curved-array transducer. Efforts were made to locate each microstimulator with the ultrasound transducer. One radiologist (E. E. S.) performed all of the sonographic scans. MR images were obtained with a Signa 1.5-T unit and CT scans with a CT High Speed Advantage system (both from GE Medical Systems, Milwaukee, WI).

Measurements in Human Subjects

The thickness of the deltoid and supraspinatus muscles was measured with sonography and MRI in 6 healthy subjects (3 men and 3 women, aged 24–51 years). All subjects were free of shoulder pain and had no history of neuromuscular disease or shoulder injury. Subjects provided written informed consent to participate before the experiment took place. This study was approved by the Queen's University Ethics Committee for Medical Research on Humans and by the Research Committee of the Radiology Department of Kingston General Hospital.

Two types of external markers were used to ensure consistency between images captured by the different scanning methods: oil capsules for MRI and flat metal washers for sonography. The

metal washers were not seen on sonography, but 2 comet-tail artifacts were apparent extending from the site of the disk into the deep tissues (Figure 1). The narrow space between the 2 shadows was assumed to be the center of the washer and was used to identify the site at which measurements were made.

For sonographic measurements, each subject was positioned prone with the arms held straight alongside the torso in a comfortable and relaxed position. The skin overlying the deltoid and supraspinatus muscles was marked with ink at 4 locations on each shoulder, 2 over the supraspinatus and 2 over the deltoid. At these sites, 8–10-mm-diameter stainless steel washers were glued to the skin surface with a cyanoacrylate skin adhesive (Dermabond; Johnson & Johnson, Montreal, Canada). Real-time sonographic measurements were obtained at each marked site in succession with a Sonoline Elegra system; a 5-MHz curved-array transducer was held perpendicular to the skin surface with the imaging plane transverse to the long axis of the muscle, as was done with the porcine muscles. Muscle thickness was measured beneath each metal marker by drawing a line parallel to the comet-tail artifact with the electronic calipers of the ultrasound unit (Figure 1). The 8 sites were imaged 3 separate times by the same operator, with sufficient time elapsed between measurements to ensure blinding to previous measurements.

For MRI assessments, the metal markers were replaced by ovoid oil capsules that were fixed to the skin with Dermabond. Subjects were positioned in the magnet in the same prone posture as that used for the sonographic assessment. A body

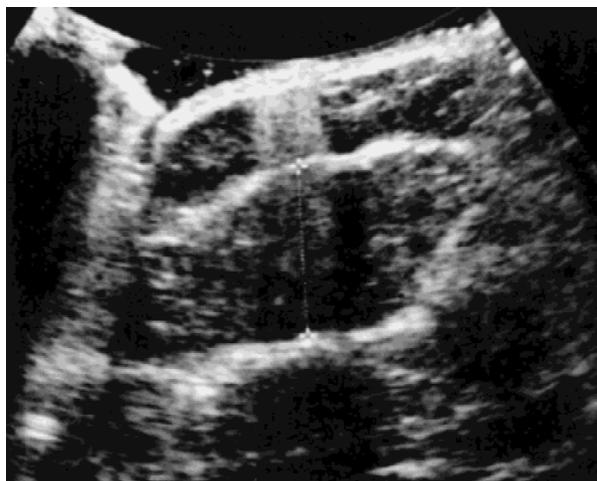


FIGURE 1. Sonographic measurement of muscle thickness under the shadow of a metal marker placed on the skin. White crosses, electronic calipers.

coil was used with a field of view of 24, number of excitations of 4, slice thickness of 5 mm (with no interslice gaps), T1 weighting, echo time of 14 msec, and repetition time of 200 msec. Muscle thickness was measured perpendicular to the skin surface beneath the oil markers (Figure 2). One subject declined MRI measurements because of unanticipated claustrophobia; however, sonographic measurements from his shoulders were included in certain analyses. In 2 subjects, the location of 1 of the external markers could not be visualized on the MR images, so these data were excluded from the comparisons of MRI and sonography.

Statistical Analysis

Paired *t*-tests were used to compare measurements between any 2 imaging methods. Repeated-measures analysis of variance was used to test for differences in muscle-thickness measurements between the 3 sonographic measurements obtained at each site. Regression analyses were performed using the method of least squares to determine the level of correlation between muscle-thickness measurements with different methods. In comparisons of MRI and sonographic values, only the first of the 3 sonographic measurements at each site was used for graphical and statistical analyses. Results were stratified first by muscle and then by subject. Statistical analyses were carried out using Excel software (Microsoft, Redmond, WA).



FIGURE 2. MRI thickness measurement under an oil-capsule marker. The black line indicates the direction of measurement under the oil capsule; the white line indicates muscle thickness.

RESULTS

Measurements in Porcine Muscles

The microstimulators implanted in the porcine muscles were located easily by sonography (Figure 3A), CT (Figure 3B), and MRI (Figure 3C). Each device appeared on sonography as a hyper-echoic line, which occasionally could be confused with a muscle border (Figure 3A).

The difference between matched MRI and CT measurements was small, ranging from 0.0 to 8.8 mm (mean \pm standard deviation, 2.2 ± 2.0 mm; $6.1\% \pm 4.3\%$ difference). CT measurements were found to be slightly larger than MRI measurements by a mean of 0.6 mm (2.1% difference).

CT measurements were used as the standard with which to compare sonographic measurements in porcine muscles. CT and sonographic thickness measurements were strongly correlated ($r = 0.98$; Figure 4).

Measurements in Human Shoulder Muscles

The deltoid and supraspinatus muscles were easily located by MRI, but the oil markers on the skin were occasionally missed. Muscle borders were easily identified on sonography, and measurements of muscle thickness presented few problems. Muscle motion during voluntary activation could be seen on real-time imaging.

Muscle thickness measured by MRI ranged from 13.2 to 33.9 mm for the supraspinatus muscle and from 16.9 to 39.4 mm for the deltoid muscle. Supraspinatus muscles were typically thinner than deltoid muscles. Sonographic measurements differed from MRI values taken at the same site by less than 2.0 mm (mean difference between the first of 3 sonographic measurements and MRI measurement at each site, 1.4 ± 1.3 mm for the supraspinatus and 1.5 ± 1.0 mm for the deltoid). Correlation coefficients associated with the regression lines describing relationships for the supraspinatus (0.96) and deltoid (0.98) muscles were high (Figure 5). When data were stratified by subject, correlation coefficients were similarly high, ranging from 0.88 to 0.99.

Sonographic measurements made at the same site (3 scans at each location) had a mean absolute difference between measurements of 1.9 ± 1.4 mm (range, 0.2–5.2 mm; median, 5.4% difference) for the deltoid and 0.9 ± 0.6 mm (range, 0.3–2.1 mm; median, 3.3% difference) for the supraspinatus. The coefficient of variation for between-scan variance was 3.1% for the deltoid and 2.3% for the supraspinatus, and the coefficients of correlation

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FIGURE 3. Sonogram (A), CT scan (B), and MR image (C) of a porcine muscle implanted with a microstimulator. Arrows point to the microstimulator in A and B and to the halo-shaped artifact in C.

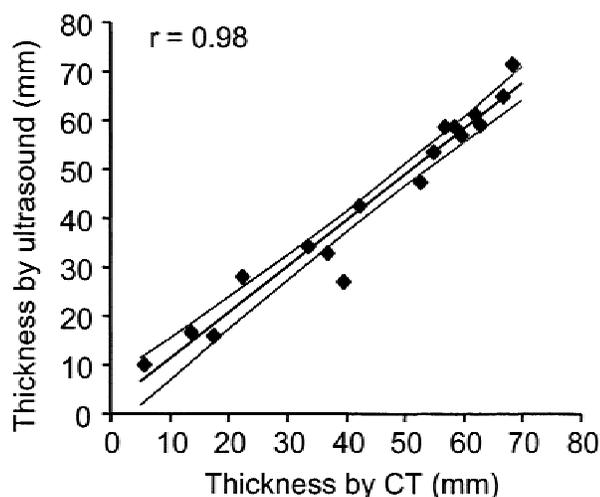


FIGURE 4. Correspondence of sonographic and CT measurements of porcine-muscle thickness. The lines on either side of the regression line indicate the 95% confidence intervals.

for repeated measures were $r = 0.99$ for both the deltoid and the supraspinatus. Repeated-measures analysis of variance could not detect differences between matched repeated muscle-thickness measurements. The errors in measurements were found to be correlated with muscle thickness ($r = 0.52$) at the location being measured.

In all subjects, care was taken to rest the transducer lightly on the skin to minimize muscle compression. However, in 1 subject, we also tested the degree to which thickness measurements could be changed by increasing the pressure with which the transducer was applied over the deltoid muscle. We found that the muscle could be flattened by 50% or more when strong pressure was applied (Figure 6).

DISCUSSION

This study was performed as a means of validating the use of sonography as a clinical tool for

measuring changes in the thickness of muscles implanted with microstimulators. In general, sonographic measurements were accurate and correlated well with those made with other imaging modalities. However, several potential sources of error must be considered.

The first potential source of error arises from the need to match scan landmarks precisely. Failure to do so was an important contributor to differences in thickness measurements between sonography and CT in the porcine muscles. On CT, a single external landmark was used from which distances were calculated to ensure matched samples at different cross-sectional levels. However, the orientation of the structure in the scanner is crucial because nonidentical orientations will result in nonidentical cross sections on the images. When we could not match the cross-sectional level of the porcine muscles imaged by CT with that imaged by sonography on preliminary studies (results not shown), we modified the method for human studies so that external markers other than ink were used to improve correspondence between the sections.

Other potential sources of error in sonographic measurement (compared to MRI or CT measurements) include difficulty in recognizing muscle borders or varying the angle or pressure of the transducer. Because planimetry involves averaging large numbers of operator estimates of the muscle boundary, the constant error due to border estimation is reduced as well. Variations in the angle at which the transducer is held relative to the surface of the skin result in error that increases with the size and depth of the imaged muscle. For example, a variation in transducer angle from 90° to 60° relative to the skin results in an error of 15% for a nontapering muscle. This error becomes much greater if the muscle size or shape changes along the axis perpendicular to the plane of the image, particularly if the muscle is deep under the skin. The operator therefore must ensure that the transducer angle is consistent

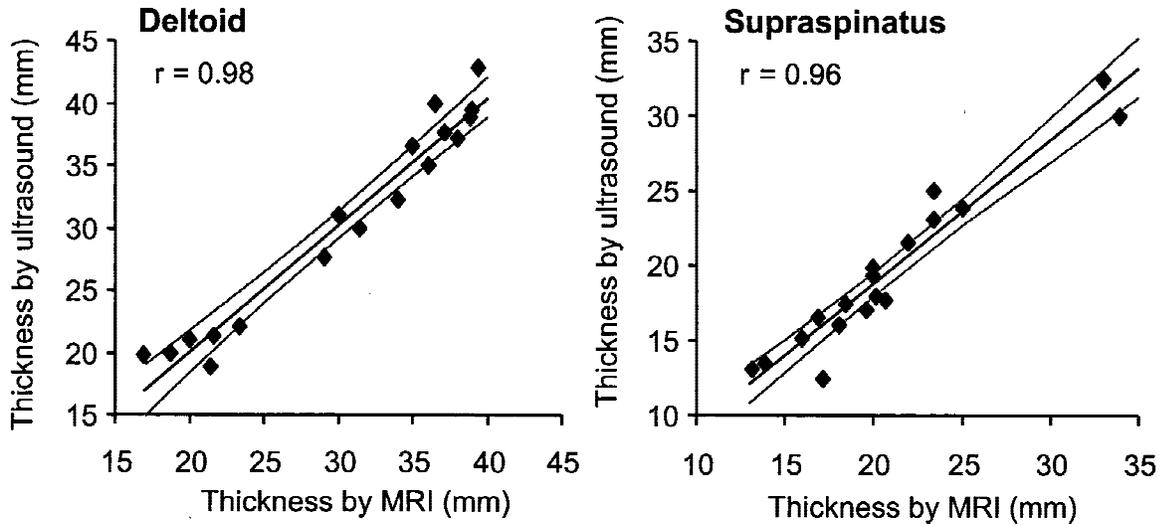


FIGURE 5. Correspondence of sonographic and MRI measurements of human deltoid (left) and supraspinatus (right) muscle thickness. The lines on either side of the regression line indicate 95% confidence intervals.

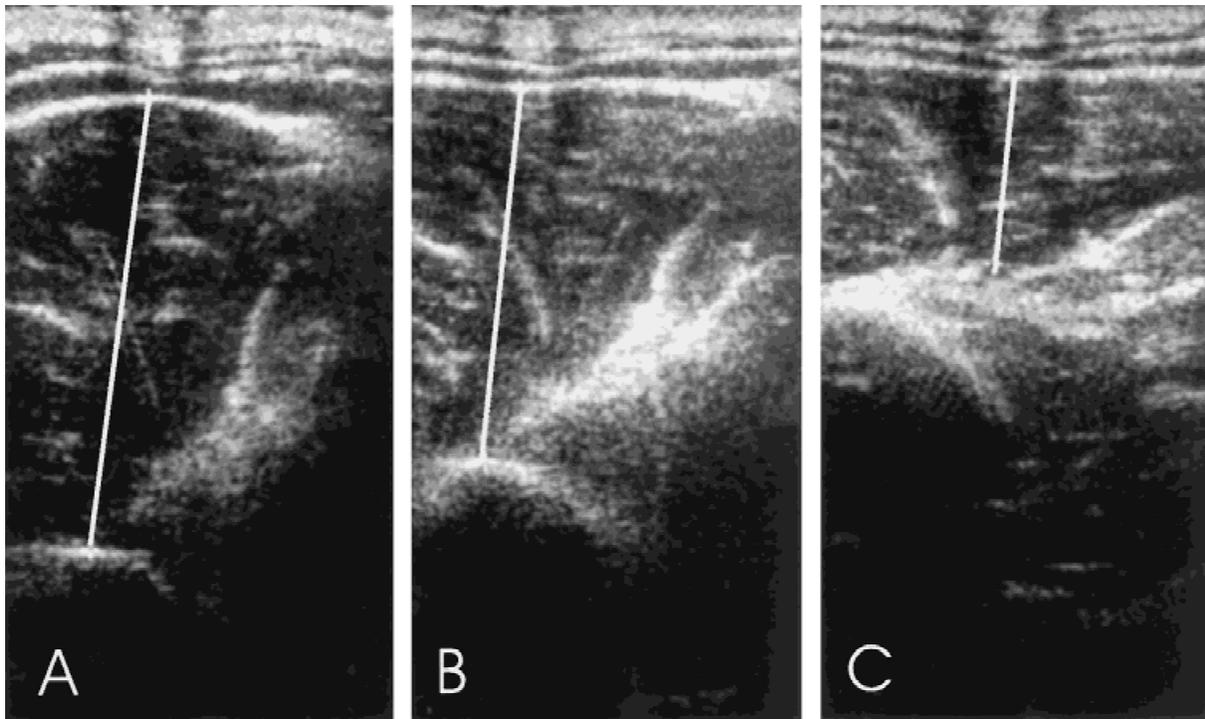


FIGURE 6. Effect on deltoid muscle thickness of progressively increasing the pressure of the ultrasound transducer on the skin over the muscle. (A) With minimal pressure, the muscle thickness is 42.1 mm. (B) With medium pressure, the muscle thickness is 35.0 mm. (C) With maximum pressure, the muscle thickness is 17.6 mm.

from one scan to another and is taken at the same angle as the matched MRI sections if measurements are going to be compared between modalities.

We also found that applying strong pressure with the ultrasound transducer could flatten the deltoid muscle by 50% or more. Because this error

is proportional to muscle size, the absolute error in muscle-thickness measurement would be even greater for larger muscles. Flattening can be minimized by using a generous amount of gel and applying the lightest pressure that maintains contact between the transducer and the skin.^{4,8} Heckmatt et al⁶ recommend observing the outline

of the skin surface on the monitor and releasing the pressure if the skin becomes deformed. Ideally, one sonographer should perform all measurements for an individual to minimize variation in the amount of pressure applied.

This flattening error presumably would be greater for thickness measurements than for cross-sectional area measurements, since the reduction in one dimension presumably would be compensated by bulging in another dimension and the volume of the muscle would remain constant. The fact that we measured thickness instead of cross-sectional area may account for our results having somewhat lower correlations than those of Hides et al,⁹ who reported correlation coefficients of 1.00 in comparing cross-sectional areas measured with MRI and sonography. Although accuracy might be improved by using volumetric measurements after full 3-dimensional reconstruction of the imaged muscles, this would complicate the use of imaging for re-evaluation considerably and would eliminate the advantages of using readily available sonographic procedures. Fortunately, the results from this study suggest that such an approach would not be necessary, at least for the proposed application.

The near-identical muscle-thickness values we found with sonography and MRI suggest that sonography is a valid method for measuring muscle-thickness changes. The correlation coefficients of 0.98 for the deltoid and 0.96 for the supraspinatus muscle are only modestly lower than the value obtained by Hides and coworkers,⁹ who found a correlation coefficient of 1.00 for matched measurements of cross-sectional areas of the multifidus muscles. On the other hand, our values are much higher than those found by Raadsheer et al¹⁰ in their study of the thickness of the human masseter muscle, in which *r* values for sonography and MRI ranged from 0.32 to 0.71. The poor correlation in that study could be related to some of the factors discussed above.

The high accuracy of our sonographic muscle-thickness measurements was confirmed by results from multiple scans at the same sites. The low coefficients of variation (3.1% for the deltoid and 2.3% for the supraspinatus muscle) and the high coefficients of correlation (0.99 for both the deltoid and the supraspinatus muscle) are comparable to those obtained by other researchers who performed similar repeated measurements of the cross-sectional area (alone or in addition to thickness). Hides et al⁴ found coefficients of variation of 4.6% for measurements of lumbar multifidus muscle thickness and 3.0% for measurements of cross-sectional area. Similarly, Kennelly and

Stokes¹¹ obtained a coefficient of variation of 3.7% for cross-sectional area measurements of the paraspinal muscles in teenagers, and Soltani and coworkers⁸ found a coefficient of variation of 2.7% for repeated measurements of the cross-sectional area of the splenius capitis muscle in the neck. Finally, Weiss and Clark¹² obtained a correlation coefficient of 0.99 for repeated measurements of the cross-sectional area of calf muscles. We could not compare the variability of thickness measurements with variability of cross-sectional area measured by sonography because the deltoid and supraspinatus muscles are too large to image in a single real-time sonogram. However, we did find that errors in measurement were correlated with the thickness of the muscle ($r = 0.52$), which of course is affected by flattening by and angle of the transducer.

We conclude that sonography can be used to measure the thickness of the deltoid and supraspinatus muscles in humans. Measurements were highly accurate, and the low coefficient of variation between repeated measurements showed that sonography can detect changes in muscle thickness of 10–20%, which correspond to changes in cross-sectional area of 20–40%. Further, sonography may be preferable for measuring muscle-thickness changes in cases in which cost, availability of equipment, or the presence of contraindicating factors precludes repeated MRI or CT scanning.

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