Measurement Uncertainty Assessment of the Scanning Laser Acoustic Microscope and Application to Canine Skin and Wound

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Abstract—**The assessment of measurement uncertainty of the scanning laser acoustic microscope (SLAM) has not been thoroughly evaluated experimentally. It is essential that the uncertainty of any measurement be fully understood. Both accuracy and precision were experimentally evaluated for the SLAM by measurements on homogeneous liquids of known ultrasonic properties. Using aqueous solutions of bovine serum albumin, the attenuation coefficient accuracy and precision are ±12 percent and ±15 percent, respectively. And from Dow Corning 710, a silicon oil, the speed accuracy and precision are ±2.9 percent and ±0.4 percent, respectively. Further, an application of the assessment of precision was conducted using duplicate samples of canine skin and wound tissue. From these evaluations of an heterogeneous tissue, the estimated precision in the measurement of the attenuation coefficient and speed was ±16 percent and ±1.7 percent, respectively.**

I. Introduction

AN ESSENTIAL feature of any measurement is the knowledge of its uncertainty. Numerous reports have provided quantitative values of ultrasonic attenuation coefficient and speed for various biological tissues from the scanning laser acoustic microscope (SLAM) operating at a frequency of 100 MHz. Yet no thorough experimental evaluation of the accuracy and the precision of these measurements has been reported.

When reporting the uncertainty of a measurement, consideration is made with respect to both accuracy and precision. These are defined in relation to a measurement process that can be described in statistical terms [1]. Accuracy describes the proximity of the measurement to the true value. Precision on the other hand describes the reproducibility of successive, independent measurements under specific conditions irrespective of how close the measurements are to the true value.

This paper addresses the issue of the uncertainty of ultrasonic speed and attenuation coefficient, from measurements on the SLAM, that operates at a frequency of 100 MHz. These are first assessed experimentally by measuring homogeneous liquids of known ultrasonic properties. For ultrasonic speed, Dow Corning 710 (a phenylated silicon oil) is used and for ultrasonic attenuation coefficient, an aqueous solution of bovine serum albumin is used. As an application, the precision (reproducibility) of ultrasonic speed and attenuation coefficient is assessed on duplicate samples of both normal canine skin and wound tissue from opposite sides of the back of four separate mongrel dogs. Duplicate cross-section and parallel tissue sections were obtained for four wound ages (ranging from 9 to 49 days), and for nearby control skin from four dogs. The results of this application take into account the overall uncertainty of the ultrasonic propagation properties determined on the SLAM as well as the repeatability of duplicate tissue samples for a relatively heterogeneous material.

II. Methods and Materials

A. SLAM Measurements

A scanning laser acoustic microscope (Sonomicroscope 100®) operating at an ultrasonic frequency of 100 MHz, was used to determine the ultrasonic attenuation coefficient and speed in the known liquids and also in the wound and skin specimens. The basic operating principles of the SLAM have been described in detail elsewhere. [2]–[5].

Ultrasonic speed was determined from the interference image of the SLAM that is composed of vertical interference lines, each of which represents equal phase wavefronts of the sound after having passed through the specimen. The interference lines shift to the right or left when passing from the reference into the specimen, indicating an increased or decreased speed of sound in the specimen

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relative to the reference. If the speed of sound in the surrounding reference medium and the thickness of the specimen are both known, then the speed of sound in the specimen can be determined from the magnitude the interference lines shift (known as the fringe shift) according to [2]

$$C_x = (C_o/\sin\theta_o)\sin\left\{\tan^{-1}\left[(1/\tan\theta_o) - N\lambda_o/T\sin\theta_o)\right]^{-1}\right\} \quad (1)$$

where

- C_x speed of sound in the specimen,
- C_o speed of sound in the reference medium,
- θ_o angle of sound (from the normal) in the reference medium,
- N normalized fringe shift,
- λ_o wavelength of sound in the reference medium, and
- T specimen thickness.

The only quantity required from the interference image is N, which is positive when $C_x > C_o$.

Several techniques have been developed to quantitate N. The spatial domain technique [3] allowed statistical parameters such as mean, mode, and standard deviation to be calculated so that some measure of specimen heterogeneity could be obtained. The technique worked well on fairly homogeneous specimens such as the rat liver, but often failed for more heterogeneous specimens such as dog skin.

The spatial frequency domain technique (SFDT) was developed [4] and modified [6] to analyze more heterogeneous specimens. For the SFDT, the normalized fringe shift was determined in the spatial frequency domain from the phase shift between the raster lines of the interference image. The SFDT is faster and more noise tolerant. It also provides more speed values per image area which results in more meaningful statistical values such as mean and standard deviation.

The attenuation coefficient was determined from the SLAM amplitude acoustic image by measuring the insertion loss (IL), i.e., decrease in acoustic amplitude, as a function of specimen thickness [5]. The slope of IL versus thickness yielded the attenuation coefficient. To minimize the effects of ultrasonic field nonuniformity over the 2 mm $\times$ 3 mm image, a small subarea of the image where the field was assumed to be uniform was used to determine IL. The subarea size was 96 pixels horizontally by 32 pixels vertically (approximately 400 μm $\times$ 250 μm). The SLAM video signal amplitude was adjusted so that the brightest, most uniform area of the image was located at the subimage area. The subimaging area video amplitudes were digitized and an average value for the subimage (W) was determined and expressed in dB, the details of which are found in [5].

To determine IL for any specimen, the specimen was placed on a moveable plastic sheet on the stage of the SLAM. Several values of W were recorded for the reference medium. The plastic sheet was moved so that the specimen to be examined was in the subimage area, and several values of W were recorded for the specimen. An IL value in dB for each value of W recorded for the specimen was calculated using

$$\mathrm{IL} = W_s - W_r \quad (2)$$

where W_r is the average of the W values recorded for the reference medium and W_s is the average value of W recorded for the specimen.

Precision electrical attenuators were used to evaluate the linearity and accuracy of the IL measurement. As shown in Fig. 1, the attenuators were located between the ultrasonic driver and the transducer. An impedance mismatch between the ultrasonic driver output and the electrical attenuators caused the driver output power to change whenever the attenuators are switched into the system. The mismatch problem was minimized by the addition of a large amount of baseline attenuation (20–40 dB). A wide-band amplifier (Amplifier Research, Unit 10 LA) was added between the attenuator output and the transducer input to increase power level and improve signal-to-noise (S/N) ratio.

Using the above system, the average subimage power was determined for a thin layer (< 10 μm) of saline as a function of inserted electrical attenuation (0–12 dB). Insertion loss for each electrical attenuation value was determined according to (2), and W_r was the average value recorded for 0 dB electrical attenuation. Fig. 2 is a plot of measured ultrasonic IL versus inserted electrical attenuation to verify the linearity of the SLAM over the useable dynamic range. The data were analyzed using linear least squares regression. A correlation coefficient, r, of 0.997 indicated the response to be very linear over the range 0–17 dB with the linear response starting to drop off at about 15 dB.

The IL accuracy was determined by measuring the variation in W obtained for layers of water (water and saline have the same ultrasonic attenuation coefficient at 100 MHz) with varying amounts of electrical attenuation inserted. Since water is a homogeneous medium, and the subimage area was not changed throughout the measurement, the variations in the values obtained were due to electrical noise, variation in the transducer or laser power, or other unknown variations in the measurement system. Twenty values were recorded for each of four different levels of attenuation and the mean and SD for each level were computed. The accuracy in W, calculated as 2 standard deviations (SD) of the mean was ± 0.4 dB. Since IL is determined by subtracting one W value from another, the accuracy in IL is computed according to

$$\Delta\mathrm{IL} = \sqrt{\left((\Delta W_s)^2 + (\Delta W_r)^2\right)} \quad (3)$$

where Δ refers to the accuracy in the associated quantities. Using an accuracy of ± 0.4 dB for ΔW_s and ΔW_r yields an accuracy for IL of ± 0.6 dB.

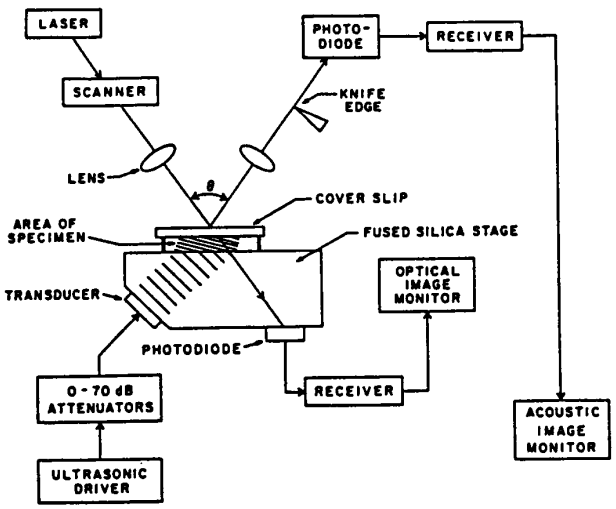

Fig. 1. Block diagram of SLAM.

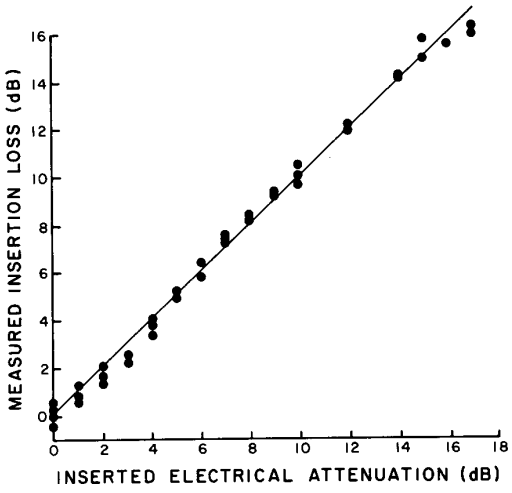

Fig. 2. Ultrasonic insertion loss measured for thin layer of saline (<10 μm) according to (3) as function of inserted electrical attenuation.

B. Specimen Temperature

Since ultrasonic propagation properties are a function of temperature, an accurate assessment of temperature during measurements on SLAM is required. A very fine copper/constantan thermocouple (30 AWG wire) and an amplifying digital thermometer (Bailey Instrument model BAT-8) were used to measure the temperature. The Bailey thermometer has a resolution of 0.1°C. The thermocouple temperature response was calibrated using a Fluke digital thermometer (model 2180A) with a platinum RTD probe (model Y2037). The resolution of the Fluke thermometer is 0.01°C and it has a maximum error of ±0.16°C. Therefore, the uncertainty of the temperature measurements was approximately ±0.2°C.

C. Tissue Preparation

Four duplicate pairs of incised skin wounds were made on the backs of the four mongrel dogs parallel to the spine

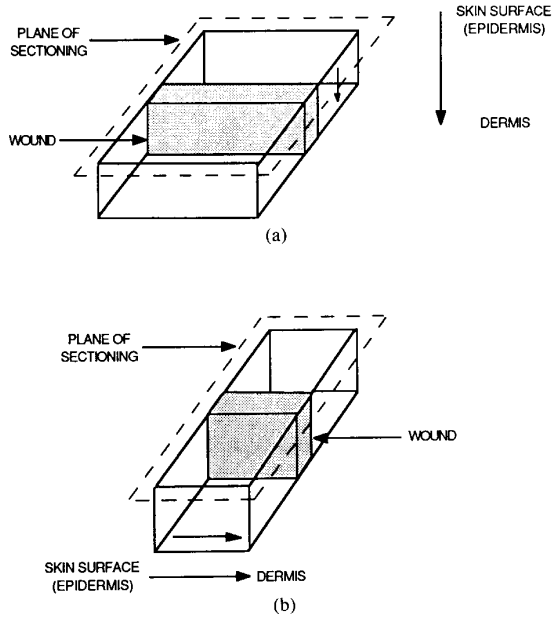

Fig. 3. Diagram of tissue mounted for sectioning skin surface, location of wound and plane of sectioning are indicated. (a) Parallel section. (b) Cross-section.

in a manner similar to that previously reported [7]. The ages of the wound pairs were 9, 20, 34, and 49 days. In order to determine the reproducibility of the ultrasonic measurements, duplicate contralateral samples for each wound age were taken from sites immediately opposite to one another on the animal and similar pairs of control samples (2–3 cm medial to the would) were taken as well. Blocks of tissue containing wound were excised and mounted with Ames Tissue-Tek OCT compound on 2-cm diameter circular pieces of cork. The unwounded control skin was similarly prepared. All samples, prepared at the University of Washington, Seattle, WA, were frozen in liquid nitrogen within 5 min of excision, sealed in Ziploc bags, shipped to the University of Illinois, Urbana, IL, on dry ice and stored in a −70°C Revco freezer until studied. The specimens were coded so that the wound age and control site were not known at the time of acoustical analysis.

For each wound and control sample, both cross-section (perpendicular to the epidermal surface) and parallel (parallel to the epidermal surface) sections were provided. Fig. 3 shows the orientation of the wound, skin surface, and plane of sectioning for each of these sections. Note that each parallel section represented a different but constant depth from the epidermal surface, while each cross-section section contained tissue at all depths, that is, epidermis, dermis, and subcutaneous fat.

At the time of ultrasonic analysis, the corks to which the specimens were attached were mounted on the object disk of a Lipshaw cryostat with OCT compound. Section thicknesses of 50, 100, and 150 μm were cut. Each specimen was completely analyzed prior to cutting the next specimen. The specimens were studied using normal sa-

line as a reference medium and the specimen temperature was determined to be 30° as discussed above. Total time required to evaluate each section specimen on the microscope was approximately 20 min.

III. Results and Discussion

To measure the specimen temperature, a drop of either saline, oil, or bovine serum albumin was placed on the stage, the thermocouple junction was centered in the liquid, and a coverslip was placed over the top. The stage was pushed into position under the laser beam and temperature was recorded for 10 to 12 min. The saline and bovine serum albumin reached an equilibrium temperature of 29.9°C and 30.0°C, respectively, in about 10 min, and the oil equilibrated at 33.2°C in about 6 min. This was expected since oil has a higher absorption coefficient than saline or BSA. Since it takes about 10 min to position a specimen on the stage and to adjust the SLAM signal levels to values appropriate for the data acquisition system, and since only a drop or two of oil was placed on the SLAM stage in saline, an equilibrium temperature of 30°C (that of saline) was used.

A. Speed Uncertainty

The accuracy and precision of the modified spatial frequency domain technique (SFDT) was assessed by determining the speed of sound in Dow Corning 710 oil. Normal saline was used as a reference. Published speed values are available for Dow Corning 710 at 1 MHz [8] and because it does not mix with saline, saline can be used as the reference medium. Further, unpublished speed values at 80 MHz [9] experimentally support the view that dispersion is negligible. The reported speed of sound for normal saline at 30°C is 1520 m/s and for Dow Corning 710 oil, 1340 m/s [8].

The speed of sound for Dow Corning 710 oil layers of varying thicknesses was determined from the interference image of the SLAM using the modified SFDT. A drop of oil was placed on the SLAM stage in the center of a metal spacer. The thickness of the spacer was measured to within ± 2.5 μm using a calibrated micrometer caliper (L. S. Starrett, model 230). The oil was surrounded by normal saline and a coverslip was placed on top of the spacer.

The results for several independent Dow Corning 710 oil experiments are given in Table I. The worst-case error for the speed measurements was -1.9 percent. The uncertainty in the literature speed of sound value for Dow Corning 710 oil was not reported. If a ± 1-percent error is assumed for the literature value, then an approximately ± 2.9-percent (sum of ± 1.0-percent and ± 1.9-percent) worst-case assumption was obtained for the accuracy at the speed measurement.

The precision of the Dow Corning 710 speed measurements, calculated as the average absolute difference between each speed value and the mean speed and expressed as a percentage of the mean value, was assessed to be the mean standard deviation, that is, ± 0.4 percent.

TABLE I
Speed[a]

Oil Layer Thickness (μm)	Mean (m/s)	S.D. (m/s)	Error (percent)
65	1333	3.2	−0.5
86	1315	4.0	−1.9
98	1322	1.5	−1.3
100	1324	2.5	−1.2

[a]Speed of sound in phenylated silicone oil, Dow Corning 710, determined from the SLAM interference image. Error is the percentage difference between the mean speed reported herein and the oil's literature value of 1340 m/s [8].

Sources of speed error of the Dow Corning 710 included the reference medium speed, the normalized fringe shift, the specimen thickness, noise and other unknown variations in the SLAM system. If saline were used as the reference medium, and the temperature at which the measurements are made were known, then the error due to the reference speed was minimal. The effect of an error in thickness on speed was assessed from (1) by varying the specimen thickness, T, and keeping all other quantities constant (see Table I).

For the Dow Corning 710 experiments the estimated thickness error (± 2.5 μm) corresponded to an average error in speed of ± 0.4 percent. This error in the determination of the thickness was exactly the same as the reproducibility of the speed measurements in oil (± 0.4 percent), thus suggesting that it could be entirely due to the error thickness determination.

B. Attenuation Coefficient Uncertainty

In order to evaluate the accuracy and precision of the attenuation coefficient technique, the attenuation coefficient for a 10-percent bovine serum albumin (BSA) solution (10.0 gm BSA per 100 ml distilled H_2O) was measured. The absorption coefficient for BSA solutions at various frequencies and temperatures has been determined independently at 100 MHz [10] with an overall uncertainty of ± 5 percent. Scattering is negligible in homogeneous liquids, so the attenuation coefficient was assumed to be equal to the absorption coefficient. The temperature of the BSA solution while on the SLAM stage was 30°C. The 10-percent BSA solution at 30°C and 100 MHz had an absorption coefficient of 4.18 dB/mm with an overall uncertainty of ± 0.21 dB/mm [10].

The attenuation coefficient was determined on the SLAM by measuring the IL for BSA layers of varying thicknesses. A very thin layer (< 10 μm) of BSA was used as the zero insertion loss reference and BSA layers of 0.721 mm, 0.875 mm, and 1.132 mm were obtained by placing the BSA solution in metal spacers (washers) of those thicknesses. The thickness accuracy of each spacer was ± 2.5 μm. Since this contributed less than 0.3 percent error in the case of attenuation coefficient, thickness uncertainty was ignored. Six to nine independent insertion loss values were determined for each thickness. A least squares regression analysis fit all of the IL versus thick-

ness data to yield the slope, and 95 percent confidence interval. The slope for the 10 percent BSA experiment was 3.9 dB/mm and the 95 percent confidence interval for the slope was 3.29 to 4.51 dB/mm (± 15 percent). The error in the attenuation coefficient, based on the known value of 4.18 dB/mm was -7 percent. With a ± 5 percent overall uncertainty for the literature value, then an approximate ± 12 percent (sum of ± 5 + ± 7 percent) was obtained for the accuracy uncertainty. And since the 95-percent confidence interval was ± 15 percent, the precision was therefore ± 15 percent.

C. Heterogeneous Specimen Uncertainty

The error in thickness of the skin specimens cut using the cryostat was estimated to be approximately ± 10 percent. The corresponding theoretical error in speed which would result from thickness errors from $+10$ percent to -10 percent for the range of speed values from 1550 m/s to 1700 m/s of the skin specimens are presented in Table II. The errors in speed range from -1.1 percent to $+1.4$ percent. These results came from an application of (1). If the thickness error were assumed to be the primary error source in the speed determination, then the error in the speed of sound measured in the skin specimens was approximately ± 0.5 percent for speeds less than 1600 m/s, and approximately ± 1 percent for speeds greater than 1600 m/s.

To quantify the speed precision for the heterogeneous specimens of canine control skin and wound, the absolute percent difference (APD) in the speed measured for duplicate wound and control skin samples was computed. The results of an ANOVA indicated that there were no significant differences between duplicate samples among different dogs and among wounds of the same ages, so the results (the APD values) for all dogs and wound ages were combined.

The precision of the ultrasonic speed measurements between duplicate contralateral samples in wound tissue and control skin for both cross-section and parallel sections are shown in Table III. The mean and range of the APD for duplicate samples obtained for all dogs and wound ages are given. The measurement precision was the same for the control skin and wound areas. However, the speed measurements appeared to be slightly more precise for parallel sections than for cross-section sections. For the parallel sections, the precision of the speed measurements (about ± 1 percent) was nearly the same magnitude as the error due to thickness uncertainty in the speed measurement method (± 0.5 to 1 percent). For the cross-section sections, the precision was about 1.7 percent. The speed precision of the skin measurements was about 0.6 to 1.3 of a percentage point greater than that of the measurement precision determined with a homogeneous liquid (± 0.4 percent). The reproducibility of the heterogeneous skin measurements included the effects of specimen to specimen variation in addition to thickness errors, so it would be expected to be somewhat greater.

One explanation for the finding that speed measurements for the parallel sections were more reproducible than measurements for the cross-section sections was that the tissues obtained by parallel sections were in fact more homogeneous. From the microscopic histology, however, one would expect more heterogeneity in cross-section sections than in parallel sections because cross-sections contain epidermis, papillary dermis, reticular dermis and subcutaneous fat. The collagen bundles in papillary dermis are finer and more fibrillar than the very coarse bundles in the reticular dermis. Parallel sections would be of primarily one or the other layer, hence more homogeneous. Qualitative observations of the specimens from the SLAM images did not support this, however. There was no difference in reproducibility between wound and control skin areas, which would also tend to discount the hypothesis that parallel sections are more homogeneous, since the wounds were observed to be more heterogeneous than the control skin. In the case of the wound pairs, however, the differences may be explained by real differences in the healing rate of wounds despite our attempts to minimize such differences.

The attenuation coefficient was determined for the control skin and wound specimens by measuring the IL for three thicknesses (50 μm, 100 μm, 150 μm). Three to five separate IL values from different areas of the specimens were obtained for both the wounds and control skin at each specimen thickness. A plot of the IL (in dB) versus specimen thickness (in mm) values, similar to Fig. 4, was made. The slope of the best fit line, determined from a linear least squares analysis, yielded the attenuation coefficient (in dB/mm). Note that the spread of each of the IL values for a given thickness in Fig. 4 was due to the specimen heterogeneity. The spread was not due to

TABLE II[a]

Actual Speed	Error in Speed For Thickness Error (+10 percent/−10 percent)
1550	−0.2/+0.3
1600	−0.4/+0.6
1650	−0.8/+0.9
1700	−1.1/+1.4

[a]Speed of sound error analysis for a +10 percent and a −10 percent error in specimen thickness as determined from (1) by varying thickness (T) and keeping all other quantities constant.

TABLE III[a]

Section Type	Control Skin	Wound
Cross-section	1.67 (0.13 − 4.15)	1.64 (0.06 − 4.44)
Parallel	0.97 (0.06 − 4.61)	1.01 (0.13 − 2.54)

[a]Experimental assessment of ultrasonic speed precision for control skin and wound tissues samples. The mean and range (in parenthesis) of the absolute percentage difference for duplicate samples are given as a function of section type.

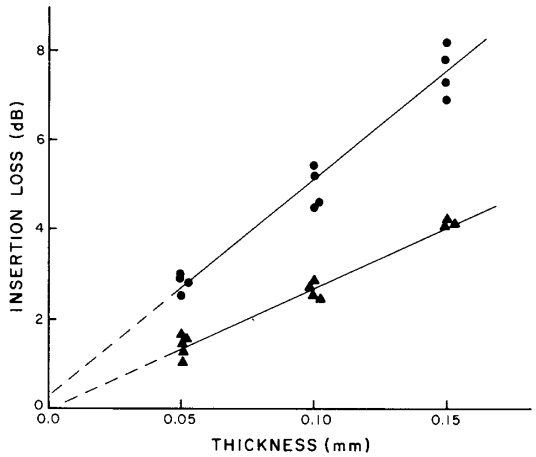

Fig. 4. Insertion loss versus thickness curves for control skin (●) and wound (▲) areas in cross-section tissue section with a 20-day old wound.

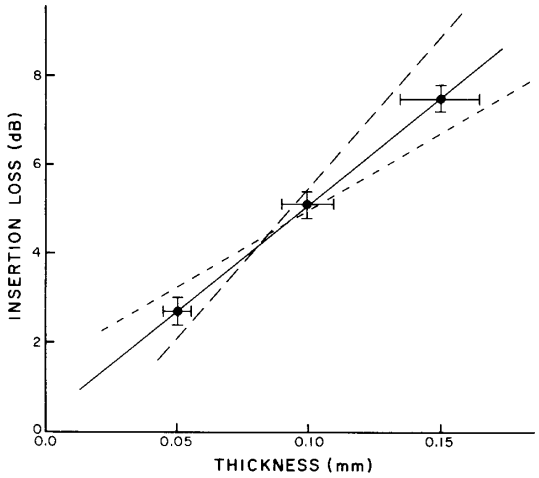

Fig. 5. Graphical determination of uncertainty in attenuation coefficient for given uncertainties in insertion loss and thickness for typical skin specimens. Dotted lines represent worst-case slopes (35.0 and 67.5 dB/mm), and solid line represents the best fit slope (48.0 dB/mm).

the uncertainty in IL, because each IL value represented a different area of the heterogeneous specimen.

The uncertainty assessment in the attenuation coefficient included both the uncertainty in IL and the uncertainty in thickness. To determine the uncertainty in the attenuation coefficient, the uncertainty in the slope of an IL versus thickness plot for given uncertainties in IL and thickness had to be assessed. Fig. 5 graphically shows a worst-case uncertainty analysis for typical values obtained for the control skin samples. The points for each of the three thicknesses represent the average of four IL values and the vertical and horizontal bars represent the uncertainty in IL and thickness, respectively. The thickness uncertainty was assumed to be ± 10 percent, and the uncertainty in the average of four IL values was assumed to be ± 0.3 dB. The average difference between the two worst-case slopes (35.0 and 67.5 dB/mm) and the best fit slope (48 dB/mm) was about ± 16 dB/mm, which corresponds to a worst-case imprecision in the attenuation coefficient of approximately ± 33 percent. This value was the very worst case and would not be typical in actual practice.

The precision data of the skin attenuation coefficient measurements are presented in Table IV in terms of *absolute percentage difference* for duplicate samples. In contrast to the speed measurements, there was no statistical difference in the precision of the attenuation coefficient measurements between cross-section and parallel sections. However, the wound attenuation coefficient measurements were less reproducible than the measurements in the skin. For all cases, the average reproducibility of the attenuation coefficient measurement (± 24 percent) was less in magnitude than the worst-case estimated attenuation coefficient measurement reproducibility (about ± 33 percent) for skin specimens and greater in magnitude than that for a homogeneous liquid (± 15 percent).

The attenuation coefficient reproducibility results of skin and wound specimens also indicated that specimen

TABLE IV[a]

Section Type	Control Skin	Wound
Cross-section	14.2 (2.6 – 54.4)	20.0 (0.6 – 42.9)
Parallel	15.7 (0.0 – 37.6)	24.1 (3.4 – 46.7)

[a]Experimental assessment of ultrasonic attenuation coefficient precision for control skin and wound samples. The mean and range (in parenthesis) of the absolute percentage difference for duplicate samples are given as a function of section type.

heterogeneity was not necessarily involved. Measurements in the more homogeneous wound area were less reproducible (± 24 percent) than measurements in the more heterogeneous skin areas (± 16 percent). This is in contrast to that of the homogeneous liquid value of ± 15 percent. Thus almost identical estimates of precision were obtained for the homogeneous liquid and heterogeneous skin. The reason for the worse precision in the wound tissue specimens may be dissimilar healing rates between the duplicate specimens, thus resulting in a greater APD. Thus, it would be reasonable to assume a measurement precision of ± 16 percent for measurements in heterogeneous tissues.

IV. Conclusion

Table V summarizes the measurement assessment of the scanning laser acoustic microscope capability to provide quantitative ultrasonic propagation property data. The accuracy and precision of SLAM for speed is ± 2.9 percent and ± 0.4 percent and for attenuation coefficient is ± 12 percent and ± 15 percent, as assessed from homogeneous, known liquids, respectively.

Since skin specimens have not been independently measured, only precision assessments could be made. The speed and attenuation coefficient precision assessments of

TABLE V
SUMMARY OF UNCERTAINTY ASSESSMENTS FROM HOMOGENEOUS, KNOWN LIQUIDS

	Speed	Attenuation Coefficient
Accuracy	±2.9 percent	±12 percent
Precision	±0.4 percent	±15 percent

SUMMARY OF PRECISION FROM HETEROGENEOUS TISSUE

Speed	±1.7 percent
Attenuation Coefficient	±16 percent

skin specimens (±1.7 percent and ±16 percent, respectively) were greater than those assessed from homogeneous specimens. The increase was generally attributed to specimen heterogeneity. Further, the speed measurement reproducibility on duplicate samples depended on section type (parallel versus cross-section), and the attenuation coefficient measurement was less reproducible in the wound tissue than in the control skin, thus suggesting dissimilar healing rates.

In our previous study [7] measurement precisions were estimated to be ±5 percent for insertion loss, ±10 percent for attenuation coefficient and ±1.5 percent for speed. These estimates were based upon our considerable experience with quantitative SLAM measurements. Comparisons of these estimates to the experimentally assessed precisions show an over estimate for insertion loss (±0.6 percent) and speed (±0.4 percent) and an under estimate for attenuation coefficient (±15 percent).

To apply these measurement uncertainties, the purpose for which the measurements were made must be considered. Accuracy provides the capability to compare results from one laboratory to another for purposes of assessing whether the measurements are in agreement with one another. Since to our knowledge this is the first comprehensive assessment of measurement accuracy with the SLAM technique, such comparison is not yet possible.

Accuracy also provides the capability to report quantitative data to within a specifically stated value of the true value. Thus, even if another technique were employed, as long as the measurement was made utilizing the same basic physical principles, intercomparisons are possible.

For the skin data reported herein and those reported previously [7], the speed and attenuation coefficients are provided to within the accuracies ±2.9 percent and ±12 percent, respectively. From an implementation stand point, these would be the mean values of a distribution of individual data points.

The data distribution for the SLAM technique was quantified as precision (reproducibility). For the SLAM system utilized herein, if one were to make a single speed or attenuation coefficient measurement of a homogeneous liquid, that value could be thought of as being within ±0.4 percent or ±15 percent, respectively, of the true value with a high degree of confidence. In the case of heterogeneous skin tissue, the spread would have to be greater.

Consider, for example, individual speed measurements on two different heterogeneous specimens. If the two values were different by 1 percent, then the two values would be considered essentially the same with a high degree of confidence. However, if the two values were different by greater than 3.4 percent, then they could be judged to be different with a high degree of confidence, as based upon the summary provided in Table V.

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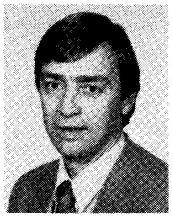

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