A method and apparatus for determining important histological characteristics of tissue, including a determination of the tissue's health. Electrical pulses are converted into meaningful numerical representations through the use of Fourier Transforms. These numerical representations are then used to determine important histological characteristics of tissue. This novel invention does not require rectification and thus provides for detailed information from the ultrasonic scan.
FIG. 2
METHOD OF AND APPARATUS FOR
HISTOLOGICAL HUMAN TISSUE
CHARACTERIZATION USING
ULTRASOUND

CROSS-REFERENCE TO RELATED
APPLICATION

This application is a continuing application of commonly
owned patent application Ser. No. 08/592,833, filed Jan. 26,

ORIGIN OF THE INVENTION

The invention described herein was jointly made by
employees of the United States Government and an
employee of the University of Maryland Medical School. It
may be used by and for the Government for governmental
purposes without the payment of any royalties thereon or
therefor.

BACKGROUND OF THE INVENTION

1. Technical Field of the Invention

This invention relates to the medical classification of
human tissue as healthy or unhealthy. More specifically, the
invention uses ultrasound for determining histological char-
acteristics of tissue by converting the return energy pulses
into numerical terms, thus facilitating a quantitative analysis
for medical diagnosis.

2. Discussion of the Related Art

Ultrasound has routinely been used in the medical pro-
fession to determine the shape, size and thickness of human
tissue. Historically, this has been achieved through de detec-
tion of specular reflections from macroscopic tissue inter-
faces. Although this method allows for a general character-
ization of the tissue, it does not reveal its underlying health
and structure. In order to obtain such a detailed analysis,
reflections from the microscopic interfaces (scatterers) con-
tained within the tissue must also be detected. An improved
invention to detect these scatterers has yet to be discovered.

The prior art is able to determine general characteristics of
tissue from its macroscopic interface reflections. This is
commonly determined by transforming analog ultrasonic
radio frequency data into a visual display. This technique
requires the expertise of a skilled operator to interpret the
display which does not include an accurate determination of
the underlying pathology of the tissue.

Other prior art systems use Fourier Transforms to detect
microscopic reflections; however, these systems do not
allow for direct measurement of reflectance through self-
calibration, and therefore are subject to calibration prob-
lems. These methods separate the components of an ultra-
sonic pulse into corresponding frequencies, using the
Fourier Transform. This requires a reference plate to nor-
malize the Fourier energy from the reflected tissue and thus
the accuracy and range of available data is limited.

Similarly, the prior art taught by Sommer, Joynt, Carroll
and Macovski ("Ultrasonic characterization of abdominal
tissues via digital analysis of backscattered wavefronts.",
Radiology. 141:811–7, 1981) uses a Fourier analysis to
determine the mean spacing of scatterers in the liver and
spleen. This method, however, does not provide for the
determination of key variables that give ranges for specific
tissues and their state of health.

U.S. Pat. No. 5,417,215 of Evans et al. provides a method
of interpreting the microscopic interfaces which requires
demodulating the return energy pulses by full-wave rectifi-
cation to obtain the amplitude modulation of the pulses and
computing the power spectrum by performing a Fast Fourier
Transform on the rectified, digitized pulses. The requirement
of rectification limits this method in providing information
from the ultrasonic scan. It does not provide specific, well
established physical parameters of the body tissue under
investigation. It requires the comparison of Fourier energies
or ratios, as well as, comparisons based on correlations.

It is, therefore, an objective of the invention to provide an
improved ultrasound tissue characterization system for his-
torical tissue classification.

It is a further objective of the invention to provide a
system which does not require rectification, thereby allow-
ing a more detailed analysis.

SUMMARY OF THE INVENTION

The present invention converts electrical pulses into
meaningful numerical representations through the use of
Fourier Transforms. This information can be used to deter-
mine important histological characteristics of tissue, includ-
ing a determination of the tissue's health. This novel inven-
tion does not require rectification and thus provides for a
much more detailed information from the ultrasonic scan.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is an equipment diagram for data taking;
FIG. 2 is an illustration of an ultrasonic wave passing
through an iterated structure constructed from two acousti-
cally different tissue types;
FIG. 3 is a typical ultrasonic echo pattern received from
tissue reflections;
FIG. 4 is a plot of the Fourier Transform equation with
arbitrary amplitude; and
FIG. 5 is a plot of the Fourier Transform equation with
discrete interpolation.

DETAILED DESCRIPTION OF THE
INVENTION

Referring more particularly to the drawings, a well-
damped 10 MHz transducer one-eighth inch (1/8") diameter
crystal 12 is connected to a wide band pulser-receiver 14.
The pulser-receiver 14 is a sonic generator and receiver for
generating, sending and receiving waves. The wide-band
(non-rectified) output of the pulser-receiver 14 is connected
to a digital oscilloscope 16, which has a plotter 18 connected
to it to record the data output. The oscilloscope 16 provides
live visual reading of the output. The data-point plotter 18
gives a graphic reading of the output. The oscilloscope 16
also has Fast Fourier Transform capability.

The transducer 12 emits an ultrasonic pulse that travels
through the body 20 into the subcutaneous tissue that is
under examination. This tissue reflects a sequence of small
amplitude echoes back to the transducer 12. The sequence of
echoes from the tissue is received by the transducer 12,
which converts the ultrasonic pulse sequence into a
sequence of electrical pulses. The electrical pulse sequence
is amplified by the wide-band amplifier in the pulser-
receiver 14 and sent to the oscilloscope 16 for measurement.
The oscilloscope 16, further processes the data, displays it
on a visual monitor, and sends it to a plotter 18 for a
hard-copy record. The oscilloscope 16 has the ability to
perform Fast Fourier Transforms on the digitized pulses.

Specifically, the transforming equations used are as fol-
lows:
In general, any part of the transform may be used to express a relationship among the ultrasonic variables and, hence, give useful information about the significant tissue classifications. For purposes of illustration, the magnitude is used, although the real part, the imaginary part, the phase or any combination is just as instructive.

Next, the Fourier transform of the incident ultrasonic pulse.

\[ P = P_0 \exp \left( -\frac{2 \pi}{\lambda^2} \right) \cos 2 \pi f_0 t \]

is evaluated by substitution into equation (1a)

\[ F(h_0(t)) = \int_{-\infty}^{\infty} P \exp \left( -\frac{2 \pi}{\lambda^2} \right) \cos 2 \pi f_0 t \]

which upon evaluation gives

\[ F(h_0(t)) = \frac{P_0 \exp \left( -\pi \left( f - f_0 \right)^2 \right)}{2}, \quad f > 0 \]

Using standard algebraic techniques and trigonometric substitutions the magnitude is rewritten:

\[ |G(f) > 0, \quad |h_0(t) = P_0 \exp \left( -\pi \left( f - f_0 \right)^2 \right) | \]

where \( f_0 \) is the center frequency of the ultrasonic transducer. \( H_0 \) is \( \alpha_1 \alpha_2 \alpha_3 \), \( H_1 \) is \( \alpha_1 \alpha_2 \), \( H_2 \) is \( \alpha_1 \), \( T \) is \( T_1 T_2 T_3 \), \( t_2 \) is \( 1/\alpha_2 \), \( t_1 \) is \( 1/\alpha_1 \), \( H_1 \) is the attenuation coefficient of the type 1 material, and \( \alpha_2 \) is the attenuation coefficient of the type 2 material.

An analysis of equation (10) shows the shape and equation (6) is not greatly affected by letting \( m \) approach infinity, the rapid undulation. The numerator inside the radical also varies between

\[ |1 - (\cos \pi f T_3 \\exp (-2H_2))|, \quad \text{and} \quad |1 + (\cos \pi f T_3 \\exp (-2H_2))| \]

both values are perfect squares. This occurs when \( \cos 4\pi f \) varies between +1 and -1, for which \( 4\pi f = \pi f \) or

\[ \Delta f_f = \frac{1}{4(\alpha_1 + \alpha_2)} \]

where \( \Delta f_f \) is the smaller frequency interval for the more rapid undulation. The numerator inside the radical also varies between

\[ |1 - (\cos \pi f T_3 \\exp (-2H_2))|^2, \quad \text{and} \quad |1 + (\cos \pi f T_3 \\exp (-2H_2))|^2 \]
but with a frequency of
\[ \Delta f = \frac{1}{4\Delta f_1} \]

where \( \Delta f_1 \) is the frequency of the slower undulation. Solving equations (11) and (12) for \( l_1 \) and \( l_2 \) respectively it is determined:
\[ l_1 = \frac{c_1}{4\Delta f_1} \left( 1 - \frac{\Delta f}{\Delta f_1} \right) \]  
\[ l_2 = \frac{c_2}{4\Delta f_2} \]  

By measuring the frequency intervals, \( \Delta f_1 \) and \( \Delta f_2 \), one can determine an average thickness of a ground substance, \( l_1 \).

The plot of equation (10) reveals a series of maximum and minimum values. One can trace the envelopes of the relative maxima and minima by noting the occurrence when \( \cos 2\pi f t \) equals 1 and -1, respectively. The data, reported to be 1.733 \pm 0.056 cm/sec (Cross and O'Brien, 1979) has empirically determined that the velocity of sound in tissue, \( c \), depends upon the percent wet weight of collagen in the tissue's composition. \( C \), according to the following relation
\[ c = \frac{1.588 + 0.032 \log(C)}{10^3} \text{ cm/sec} \]

where \( C \) is the wet weight percent of collagen. \( \rho_1 \) is the density of the non-collagenous material in the tissue and \( \rho_2 \) is the density of the collagenous material.

The measurement and analysis technique gives \( Z_2 \). With equation (21) it is possible to determine the weight percent of collagen in the ground substance in-vivo if the density is known of the collagen fibers. But the density of collagen fibers depends in part on the health and nutrition of the patient. This makes the value of \( Z_2 \) a potentially good indicator of tissue health with the larger values of \( Z_2 \) indicating more and better grade collagen in the ground substance. By assuming a reasonable range of values for the
collagen fiber density the determination gives a range of values for the weight percent of collagen in tissues in-vivo. The linkage is the degradation of the mechanical properties of these tissues is directly involved with the failure of the tissue's mechanical properties. That connection is the weight percent of collagen and the collagen's density (the higher the density, the better its structural properties) in the ground substance.

Using a curve fitting algorithm for the experimentally determined quantity

\[
\left( \frac{e^{-1}}{e^1} \right)
\]

Both \( T \) and \( H \) can be determined by solving the equation

\[
T \exp(-2H) = \left( \frac{e^{-1}}{e^1} \right)
\]

where \( H \) is \( \alpha_1 + \alpha_2 \). Since \( \alpha_1 \) and \( \alpha_2 \) are determined according to equations 13(a), 13(b) and \( \alpha_1 \) can be estimated from scattering and absorption of ultrasonic waves by fat cells. one can determine \( \alpha_2 \)

\[
\alpha_2 = \frac{H_0 - \alpha_1 l_2}{l_2}
\]

which can be measured as a function of frequency. This information can be used to assess the quality of collagen fibers and the areal density of the fiber network (weave) in the ground substance. A correlation with invasive measurements and to a lesser extent to in vitro measurements will permit the best estimates of these quantities.

In this manner, it is clear that more than a broad classification of healthy or unhealthy can be realized for smaller regions of interest. Most significantly, a diagnosis for the development of pressure ulcers can be facilitated through the use of this invention.

It is specifically intended that the present invention not be specifically limited to the embodiments and illustrations contained herein, but embrace all such modified forms thereof as come within the scope of the following claims.

What is claimed is:

1. A method for detecting histological properties of human tissue, composed of an iterated stacking sequence of cellular and collagen containing structural components, using data obtained from ultrasonic ray inputs, comprising the steps of:
   - emitting a high-frequency ultrasonic pulse into human tissue;
   - collecting a subsequent sequence of reflected unrectified echoes from said tissue;
   - converting said unrectified echoes into a sequence of unrectified electrical pulses;
   - amplifying said sequence of unrectified electrical pulses;
   - performing a Fourier transform upon said sequence of unrectified electrical pulses;
   - selecting any part of said transform;
   - plotting a display of said transform in terms of said part;
   - evaluating said display to quantitatively determine a percentage of collagen in said collagen containing structural component, wherein said percentage can be used to assess the quality of said tissue.

2. The method as in claim 1 wherein said selecting comprises using a magnitude value of said transform to determine histological tissue characteristics.

3. The method as in claim 1 wherein said selecting comprises using a real value of said transform to determine histological tissue characteristics.

4. The method as in claim 1 wherein said selecting comprises using an imaginary value of said transform to determine histological tissue characteristics.

5. The method as in claim 1 wherein said selecting comprises using a phase value of said transform to determine histological tissue characteristics.

6. The method of claim 1 wherein said selecting step includes selecting any part of said transform to express a relationship among ultrasonic variables, and further comprising the step of
   - detecting pressure ulcers in muscle tissue based on said expressed relationship among ultrasonic variables.

7. The method of claim 1 wherein said selecting step includes selecting any part of said transform to express a relationship among ultrasonic variables, and further comprising the step of
   - detecting pressure ulcers in adipose tissue based on said expressed relationship among ultrasonic variables.

8. Apparatus for classifying histological characteristics of human tissue comprising:
   - means for generating ultrasound pulses
   - means for applying said ultrasound pulses to said tissue and receiving returned ultrasound from said body
   - means for converting said returned ultrasound pulses into a sequence of unrectified electrical pulses
   - means for amplifying said pulses
   - means for performing Fast Fourier Transforms on said amplified pulses
   - means for determining said histological characteristics using any part of said transform.

9. The apparatus of claim 8 wherein said means for determining histological characteristics is adapted to determine a magnitude value of said transform.

10. The apparatus of claim 8 wherein said means for determining histological characteristics is adapted to determine a real value of said transform.

11. The apparatus of claim 8 wherein said means for determining histological characteristics is adapted to determine an imaginary value of said transform.

12. The apparatus of claim 8 wherein said means for determining histological characteristics is adapted to determine a phase value of said transform.

13. The apparatus of claim 8 wherein said means for determining is adapted to determine the histological characteristic of pressure ulcers in muscle tissue.

14. The apparatus of claim 8 wherein said means for determining is adapted to determine the histological characteristic of pressure ulcers in adipose tissue.

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