ULTRASONIC PROPERTIES OF BIOLOGICAL MEDIA

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INTRODUCTION

This paper comprises a brief review of the ultrasonic propagation properties of biological media, with particular attention to those properties that are considered to influence, or to be otherwise useful in, the obtaining of significant diagnostic ultrasound information and those properties important in producing and assessing biological effects. The properties are discussed according to categories which emerge readily from the reported literature(1,2). Generalizations are then employed to characterize tissues from these categorical suggestions.

SPEED OF SOUND

Data regarding the speed of sound comes largely from measurements of freshly excised tissues(1,2). An appreciable range appears in the reported values which is believed to result from different measuring methods being employed, from different methods of specimen preparation, and from different examples of specimens being chosen. The range of the data extends from approximately 5% for brain and muscle, to approximately 9% for fat. Nevertheless, the data show that an ordering of tissue specimens in terms of increasing speed of sound is also an ordering for increasing structural protein content, but for decreasing water content.

parenchymal tissues exhibit speeds of sound which are
y the same as that for water, it has become customary
the soft tissues as being liquid-like media having
d compressibilities much like water, but with
y different attenuation and absorption behavior,
reater magnitudes and a nearly linear, rather than
ependence upon frequency. However, the published
,2) exhibits a very appreciable range of reported values,
eflecting the greater difficulty in making such
and in interpreting the resulting data(3,4), though
noted that measurement methods and specimen preparations
d with time and experience as publication values have
. The reported attenuation range, in some cases, is

e few methods available for measuring absorption
and the transient thermoelectric method has been
studying freshly excised tissues as a function of
. The exponents on frequency have been found to vary
02 to 1.08 among testis, kidney, heart, brain, liver,
even though these tissues represent substantial
in their structural and chemical compositions. There
, very pronounced differences in the magnitudes of the
viz., tendon being 4 to 5 times greater than liver,
, and kidney, which in turn are about twice that of
should be noted that heart, brain, and kidney have
y 16-18% protein and 1-2% collagen, and about 71-76%
on, on the other hand, has a total protein content of
30% collagen, but with a water content of only 63%.
ery little collagen, about 12% protein, but has more
er. (Testis may have a greater water content than any
than fetal brain.) Though brain has lesser protein
do kidney, liver, and heart, its greater lipid and
gen contents may combine in some way to provide its
rption properties.

ies dependence of absorption for the single organ liver
g, cat, and mouse, in the frequency range 0.5-7 MHz,
has been studied, and shows little, possibly
difference in the observed values(6)

on of these absorption measurements with the average
ttenuation taken from the literature(1,2), yields
contrasts(6). Namely, there is little difference in
dependence of absorption and of attenuation in the

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frequency range 0.5-7 MHz, suggesting that whatever the source of differences in magnitude between attenuation and absorption values (i.e., scattering, reflection, measurement artifact, etc.), that mechanism is nearly linearly dependent upon frequency. It is to be noted that the magnitudes of attenuation and absorption are greatly different, with the former being nearly a factor of three greater than the latter for each tissue.

TEMPERATURE DEPENDENCE

Measurements of the temperature dependence of attenuation of excised tissues generally yield a decreasing dependence with temperature, as is expected when dealing with a fluid viscosity mechanism. However, the situation for *in vivo* absorption, which is the more pertinent quantity, may be considerably different. As it is very difficult to conduct observations as a function of temperature with an ordinary mammal, because of superior temperature controlling mechanisms, measurements have been made using young mice, approximately 24 hours after birth, which are essentially poikilothermic animals(7,8). The general demeanor of these studies is that the frequency-free absorption *vs* temperature comprises a family of curves whose maxima decrease and move toward ever increasing temperatures as a function of increasing frequency.

DEPENDENCE UPON CONSTITUENT MACROMOLECULES

It has long been known that the absorption of ultrasound in tissues is largely determined by the protein constituents and, because of this, aqueous solutions of globular proteins have been studied as model systems of tissue, wherein the tissue architecture may be relegated or associated with the remaining portion of the attenuation(4). These studies have involved only globular proteins (different size/structure) which carry out the biochemical events in the physiological processes of the various organs. Studies of the ultrasonic properties of structural proteins in aqueous suspension have now been carried out(9) and it is interesting to include these results with those of globular proteins and with tissues(10). Structural proteins provide a framework maintaining tissue structure integrity. It is to be noted that tissues comprised mainly of these proteins, mostly collagen, have much different elastic properties than do tissues having little collagen or are predominantly comprised of globular protein. Thus, it is found that values for the ultrasonic velocity of various tissues, as a function of the wet weight percentage of total protein, are contained between the two values (1) of the velocity in aqueous solutions of serum albumin (for the appropriate wet weight percentage of total protein) and (2) of the velocity in collagen suspensions. Accordingly, tissues predominantly comprised of globular protein

exhibit ultrasonic velocities near the value for
edia, with a tissue wholly so constituted exhibiting
a solution of globular protein at the specified
Similarly collagenous tissues, such as tendon, where
raction of the protein is in the form of collagen, are
ibit values well above the collagen-free, globular
This is borne out in that liver, kidney, heart, and
h approximately the same total protein, about 17%,
ittle, less than 1%, is collagen, have nearly the same
appear near the collagen-free value for their wet
ge of total protein. Tendon, which is largely
protein, 85% of this is collagen) exhibits the
for its wet weight percentage of total protein.
ontain little protein and their velocities are less
. Thus, it appears that the ultrasonic velocity in
rned, in some way, by the ultrasonic properties of
macromolecular constituents comprising them.

absorption appears to be governed by similar
That is, the absorption of tissues is found to fall
ues, at the appropriate wet weight percentage of
of the absorption of solutions of globular proteins
rption of suspensions of collagen(10).

pears that absorption in tissues may be considered
erposition of the absorption properties of their
uents, and tissues may further appear, at least as a
tion, as composite materials whose ultrasonic
governed by the individual ultrasonic properties of
l and globular protein contents.

an attempt to characterize tissues according to their
erties and biological function at 1 MHz. Here,
en grouped, in an apparent teleologic fashion, with
of attenuation (doubling) from group to group. It
so doing, the velocity increases in the same direc-
direction of increasing attenuation. Also,
he same direction, tissues of ever decreasing water
r increasing structural protein content become
ppears, thereby, that attenuation and velocity may
ssues according to functional criteria.

ture detailed measurements will allow assignment of
ue values to each tissue structure, including
entiable values for pathological states, so that
impedance values, as a function of state and of
eters, media, etc., should specify uniquely tissues

Table 1. Average attenuation of tissues by categories

Tissue attenuation categories	Attenuation at 1 MHz (cm^{-1})	Tissue	Assumed teleology	General trends		
1. Very low	0.03	serum	ion, metabolic, etc., transport, convection		Increasing structural protein content →	Increasing speed of sound →
	0.01	blood				
2. Low	0.06–0.07	adipose tissue	energy and (water) storage			
3. Medium	0.08–0.11	nervous tissue	physiological function			
	0.11	liver	parenchymal tissue			
	0.08–0.16	muscle				
	0.23	heart				
	0.3	kidney				
4. High	0.4	integument	structural integration,			
	0.5	tendon	stromal tissues			
	0.6	cartilage				
5. Very high	1 or more	bone (mineral-ized)	skeletal framework	← Increasing H_2O content		
	>4	pulmonary tissue	gaseous exchange			

for diagnostic purposes. However, it is clearly not necessary to have acoustic methods for discriminating say, between brain and liver, but it can be seen from the figure that certain classes of pathology should be easily identifiable and others not. For example, cirrhosis of the liver, as manifested by collagen deposited in place of normal tissues, could be easily identified, and is, while metasteses of say, nerve tissue neoplasm in liver, are probably not identifiable, at least in the early stages before cirrhosis of the liver tissue begins. A major problem of prediction, at present, is the paucity of available data on abnormal tissues.

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TRANSDUCERS AND SOUNDFIELDS

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The purpose of this paper is to present and to discuss
fundamental problems and solutions connected with piezoele
transducers and soundfields generated for ultrasonic medica
applications.

The first problem I should like to review is the gener
soundfields with piezoelectric transducers. To obtain suf
bandwidth, power and sensitivity the transducer must be ca
designed to be properly coupled with the electronic transmi
and receiver and with the biological medium in which ultra
waves propagate.

The theory of ultrasonic transducers performing thick
expander vibrations was given by Mason and is based on a o
dimensional approach(1). As a consequence many authors ap
electromechanical equivalent circuit but others have shown
imentally that the vibration patterns are very complex and
resemble one-dimensional vibrations(2). Fig. 1.(A) shows
displacement (amplitude and phase) distributions measured
transducer's surface along its diameter(3). The transduce
freely in thickness resonances near to 1.6 MHz. This is n
to explain using Mason's circuit.

However, we could show(3) -- using the capacitance me
method -- that with the increase of the mechanical load on
transducer's back surface the many resonances amalgamate t
resonance and the transducer's surface vibrates like a pis
1.(B) and (C)). Hence in diagnostical applications -- whe
transducer's back surface must be heavily loaded for obtai
short pulse -- the one-dimensional approach and Mason's ci
fully justified.