Tissue Characterization With Ultrasound

Volume I
Methods

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Chapter 2

TEMPERATURE DEPENDENCY OF ULTRASONIC PROPAGATION PROPERTIES IN BIOLOGICAL MATERIALS

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I. INTRODUCTION

The interaction of low-intensity ultrasound (with assumed infinitesimal wave propagation) and biological material can be summarized with three primitive variables: density, adiabatic compressibility, and absorption. These variables determine physical properties that are more readily measurable: density and compressibility determine the velocity of propagation of the ultrasound; spatial variation in density and compressibility determine the refraction, diffraction, and scattering; scattering and absorption yield attenuation. Measuring these tissue properties is the first step in tissue characterization.

The most popularly measured ultrasound properties are velocity, attenuation (in general), and absorption (in specific). The thermal dependence of these properties can be appreciated in the most general sense from a simplified view of the physics involved. As temperature increases, density decreases (since most materials experience a volume expansion with increased temperature). Lowering density while keeping the (adiabatic) compressibility constant should cause an increase in velocity. For heterogeneous media, if the velocities of the various constituent materials increase at differing rates so as to approach one another, the media should become "less" heterogeneous, resulting in a decrease in refraction and scattering amplitude. If the velocities increase so as to diverge from each other, both refraction and scattering should increase. (In either event, scattering as a function of frequency should experience a shift toward higher frequencies resulting from the increase in velocity.) Finally, absorption, if modeled as a relaxation process, should also show a shift of the relaxation frequency toward higher frequencies, resulting in increases or decreases in absorption, depending on the frequency at which the measurement is being made. (The attenuation follows from the absorption and scattering.) Thus, from this superficial modeling, velocity and attenuation should be temperature sensitive. It is the purpose of this review to present and discuss the temperature-dependent behavior of these ultrasonic properties in biological materials.

II. THERMAL DEPENDENCY COMPILATION

Tables 1 and 2 are compilations of temperature-dependent measurements of velocity and attenuation of biological tissues and fluids. Although many authors have published data on velocity and attenuation measurements at various temperatures, only those articles that showed a temperature dependence or provided sufficient data to approximate a temperature dependence were included.

Some of the information is second hand: references marked m(n) were taken from Reference m, although the measurements were originally in Reference n. All pertinent temperature information in Parry and Chivers[1] is included in the data taken from Goss et al.[2,3]

A. Ultrasonic Velocity of Propagation Table

Table 1 reports values of velocity (in meters per second) as a function of temperature (in degrees Celsius) at various ultrasonic frequencies (in megahertz). For each biological material, any available physiological state or age information is included. The ultrasonic frequency of the measurement is indicated where reported. In many cases, velocity information was available only in the form of graphs. Thus, velocity values marked with an (*) were interpolated from graphs. Where a velocity value was not reported, but a thermal coefficient (the rate of change of velocity with respect to change in temperature) was available, the missing velocity value was linearly estimated and marked with a (#). (As will be seen in Section III.A, velocity is not purely linear in temperature; thus, linear estimates of velocity will be accurate only over a limited temperature range.) The accuracy of the velocity measurement, where available, is provided in parentheses following the velocity, either in

Table 1
ULTRASONIC VELOCITY OF PROPAGATION AS A FUNCTION OF TEMPERATURE FOR BIOLOGICAL MATERIAL*

Species	Frequency (MHz)	Temp (°C)	Velocity value (dev) (m/sec)	Thermal coefficient (m/sec/°C)	Ref.
			Blood		
Human					
Fresh, heparinized, whole, 40% hct	5	25	1565*	2.20#	4(2)
		30	1576*	1.40#	
		40	1590*	(1.63)#	r = 0.99
Fresh, heparinized	5	26.8	1569.3	1.3	5(2)
		40.5	1587.1#		
<21 Days	1—15	27	1557*	1.48	6(2)
		44	1582.2#		
Heparinized	2	22.4	1565 (8%)	2.50#	7(2)
		22.6	1570 (1.5%)		
		23.2	1549.6(0.7%)	6.80#	
		24.2	1556.4(0.3%)		
Fresh, plasma	5	25	1522*	2.40#	4(2)
		30	1534*	1.40#	
		35	1541*	1.80#	
		40	1550*	(1.82)#	r = 0.99
NR, albumen 12.5%	NR	10	1500*	2.50#	8
		20	1525*	2.50#	
		30	1550*	2.00#	
		40	1570*	(2.35)#	r = 1.00
NR, albumen 6.2%	NR	10	1475*	3.00#	8
		20	1505*	2.50#	
		30	1530*	2.00#	
		40	1550*	(2.50)#	r = 1.00
Canine					
Fresh, heparinized, 26% hct	5	25	1541*	3.00#	4(2)
		30	1556*	1.00#	
		35	1561*	1.80#	
		40	1570*	(1.84)#	r = 0.98
			Breast, Fat with Parenchyma		
Human					
Excised	NR	22.5	1494.7(4.1)	−2.18#	9
		25.8	1487.5(5.5)	2.00#	
		27.8	1491.5(5.5)	2.63#	
		30.2	1497.8(5.7)	1.55#	
		32.2	1500.9(6.2)	−10.2#	
		35.1	1471.3(9.7)	0.00#	
		38.0	1471.3(13.1)	1.38#	
		40.1	1474.2(13.4)	0.71#	
		42.5	1475.9(12.8)	(−1.26)#	r = −0.71

Table 1 (continued)
ULTRASONIC VELOCITY OF PROPAGATION AS A FUNCTION OF TEMPERATURE FOR BIOLOGICAL MATERIAL*

Species	Frequency (MHz)	Temp (°C)	Velocity value (dev) (m/sec)	Thermal coefficient (m/sec/°C)	Ref.
Breast, Parenchyma					
Human					
Excised	NR	22.5	1539.4(4.5)	1.91#	9
		25.8	1545.7(4.0)	2.65#	
		27.8	1551 (4.6)	2.96#	
		30.2	1558.1(3.9)	2.00#	
		32.2	1562.1(4.1)	0.83#	
		35.1	1564.5(7.6)	−0.07#	
		38.0	1564.3(6.4)	2.52#	
		40.1	1569.6(6.3)	0.96#	
		42.5	1571.9(6.4)	(1.57)#	r = 0.97
Cerebrospinal Fluid					
Human					
Fresh	2	24.4	1515 (3.0%)	−9.17#	7(2)
		25.0	1509.5(0.5%)		
Eye					
Human					
p.m.	2.5	29	1560	1.50#	10(2)
		37	1572(5)		
Eye, Aqueous Humor					
Porcine					
8 hr	4	4	1462.51(2.13)	2.22#	11(2)
p.m.		15	1486.94(2.48)	2.03#	
		25	1507.25(2.86)	1.86#	
		37	1529.63(3.08)	(2.03)#	r = 1.00
Eye, Cornea					
Human					
24—48 hr	4	4	1542.03(4.05)	1.42#	11(2)
p.m.		15	1557.64(4.13)	1.23#	
		25	1569.91(3.76)	1.37#	
		37	1586.38(3.87)	(1.33)#	r = 1.00
Porcine					
8 hr	4	4	1537.68(4.02)	1.56#	11(2)
p.m.		15	1554.86(3.88)	1.36#	
		25	1568.43(4.10)	1.62#	
		37	1587.92(3.53)	(1.51)#	r = 1.00
Eye, Lens					
Human					
24—48 hr	4	4	1617.51(4.01)	1.13#	11(2)
p.m.		15	1629.98(2.98)	0.89#	
		25	1638.84(3.17)	0.69#	

Table 1 (continued)
ULTRASONIC VELOCITY OF PROPAGATION AS A FUNCTION OF TEMPERATURE FOR BIOLOGICAL MATERIAL*

Species	Frequency (MHz)	Temp (°C)	Velocity value (dev) (m/sec)	Thermal coefficient (m/sec/°C)	Ref.
		37	1647.11(3.53)	(0.89)#	r = 0.99
30—40 hr	2.5	29	1638.2	1.10#	10(2)
p.m.		37	1647		
Porcine					
Fresh,	4	23	1642.61	1.00	12(2)
within 2.5 hr		37	1654.61#		
8 hr	4	4	1638.71(3.65)	1.25#	11(2)
p.m.		15	1652.42(3.5)	0.98#	
		25	1662.20(3.72)	0.88#	
		37	1672.75(3.12)	(1.03)#	r = 1.00
Eye, Sclera					
Human					
24—48 hr	4	4	1609.12(3.76)	1.18#	11(2)
p.m.		15	1622.06(4.25)	1.31#	
		25	1635.12(3.71)	0.97#	
		37	1646.75(3.94)	(1.15)#	r = 1.00
Porcine					
8 hr	4	4	1616.07(4.14)	1.44#	11(2)
p.m.		15	1631.92(4.01	1.22#	
		25	1644.12(3.92)	0.97#	
		37	1655.76(3.86)	(1.20)#	r = 1.00
Eye, vitreous humor					
Human					
24—48 hr	4	4	1458.91(1.95)	2.01#	11(2)
p.m.		15	1481.02(1.86)	1.87#	
		25	1499.76(2.05)	1.95#	
		37	1523.20(2.14)	(1.94)#	r = 1.00
Bovine					
<10 days	5	27.0	1495	−5.00#	13
stored @ 0—5°C		27.4	1493 (0.5%)	52.5#	
		27.8	1514 (0.4%)	11.7#	
		29.6	1535 (2%)	(16.3)#	r = 0.95
Porcine					
Fresh,	4	23	1468.95	1.81	12(2)
within 2.5 hr		37	1494.29#		
8 hr	4	4	1463.88(2.27)	2.19#	11(2)
p.m.		15	1487.94(2.56)	1.82#	
		25	1506.12(3.10)	2.95#	
		37	1541.53(2.94)	(2.31)#	r = 1.00
Fat					
Bovine					
Fresh	1—7	20	1581(1%)	−10.1	14
		37	1430	−7.4	

Table 1 (continued)
ULTRASONIC VELOCITY OF PROPAGATION AS A FUNCTION OF TEMPERATURE FOR BIOLOGICAL MATERIAL[a]

Species	Frequency (MHz)	Temp (°C)	Velocity value (dev) (m/sec)	Thermal coefficient (m/sec/°C)	Ref.
		Fat, Breast			
Human					
Excised	NR	22.5	1480.7(2.5)	−4.18#	9
		25.8	1466.9(9.9)	2.60#	
		27.8	1472.1(9.8)	2.21#	
		30.2	1477.4(9.9)	0.35#	
		32.2	1478.1(11.4)	−14.4#	
		35.1	1436.3(15.6)	−0.24#	
		38.0	1435.6(18.4)	1.48#	
		40.1	1438.7(18.1)	1.29#	
		42.5	1441.8(17.5)	(−2.43)#	r = −0.83
		Fat, Orbital			
Human					
<2 Days p.m.	6—14	20	1582(20.4)	−7.06#	15(2)
		37	1462(23.7)		
		Fat, Peritoneal			
Bovine					
Fresh	10	10	1680*(1%)	−10.5#	14(3)
		20	1575*	−8.50#	
		30	1490*	−7.14#	
		44	1390*	−2.81#	
		60	1345*	(−6.73)#	r = −0.98
		Fat, Stomach			
Canine					
Fresh	5	35	1455*	−2.56#	16
		44	1432*		
	5	37	1411.9	−2.89	17
		40	1403.2#	−2.85	
		43	1394.7#	−2.86	
Refrig. 5 hr	5	37	1412.9	−3.43	17
		40	1402.6#	−2.86	
		43	1394.0#	−2.91	
		Heart			
Canine					
Fresh	5	35	1592*	1.25#	16
		43	1602*		
		Kidney			
Human					
Excised	NR	17.0	1508.5(4.3)	3.06#	9

Table 1 (continued)
ULTRASONIC VELOCITY OF PROPAGATION AS A FUNCTION OF TEMPERATURE FOR BIOLOGICAL MATERIAL[a]

Species	Frequency (MHz)	Temp (°C)	Velocity value (dev) (m/sec)	Thermal coefficient (m/sec/°C)	Ref.
		22.0	1523.8(4.6)	8.20#	
		23.5	1536.1(2.1)	0.07#	
		26.2	1536.3(5.2)	2.23#	
		30.2	1545.2(2.7)	2.07#	
		33.2	1551.4(1.4)	2.20#	
		35.2	1555.8(1.8)	2.20#	
		37.2	1560.2(1.8)	1.33#	
		39.0	1562.6(1.2)	0.94#	
		40.8	1564.3(0.9)	(2.25)#	r = 0.98
Canine					
In vivo	5	38.5	1566.6	1.27	16
			1580.7	1.18	
			1569.9	1.17	
			1568.6	1.14	
Fresh	5	37	1570.2	1.35	17
		40	1574.3#	1.16	
		43	1577.7#	0.98	
		37	1566.5	1.29	17
		40	1570.4#	1.11	
		43	1573.7#	0.93	
		37	1571.1	1.29	17
		40	1575.0#	1.11	
		43	1578.3#	0.94	
Fresh 5—30 min	5	38.5	1588.4	1.30	16
			1579.6	1.30	
			1580.2	1.28	
			1584.5	1.05	
		35	1576*	1.22#	16
		44	1587*		
		Liver			
Human					
p.m.	1—7	20	1584(1%)	1.86	14
		37	1607	0.96	
	10	5	1550*(1%)	1.71#	14(3)
		12	1562*	2.89#	
		21	1588*	1.33#	
		30	1600*	1.14#	
		37	1608*	0.33#	
		43	1610*	0.50#	
		47	1612*	(1.52)#	r = 0.97
Excised	NR	17.0	1547.0(2.5)	1.70#	9
		22.0	1555.5(1.8)	5.07#	
		23.5	1563.1(3.0)	0.56#	
		26.2	1564.6(2.8)	1.63#	

Table 1 (continued)
ULTRASONIC VELOCITY OF PROPAGATION AS A FUNCTION OF TEMPERATURE FOR BIOLOGICAL MATERIAL*

Species	Frequency (MHz)	Temp (°C)	Velocity value (dev) (m/sec)	Thermal coefficient (m/sec/°C)	Ref.
		30.2	1571.1(2.5)	0.80#	
		33.2	1573.5(1.8)	0.90#	
		35.2	1575.3(2.5)	1.40#	
		37.2	1578.1(2.9)	1.06#	
		39.0	1580.0(2.2)	0.94#	
		40.8	1581.7(1.5)	(1.39)#	r = 0.99
Bovine					
Fresh	1—7	20	1575(1%)	1.83	14
		37	1597	0.56	
		20	1627	1.01	14
		37	1639	0.31	
Fresh <30 min	10	8	1610*(1%)	1.15#	14(3)
		21	1625*	0.94#	
		37	1640*	0.20#	
		42	1641*	−0.85#	
		55	1630*	(0.52)#	r = 0.75
		9	1545*	2.27#	14(3)
		20	1570*	2.00#	
		30	1590*	0.77#	
		43	1600*	4.09#	
		65	1690*	(2.46)#	r = 0.97
Canine					
Fresh 5—30 min	5	38.5	1598.3	1.26	16
			1604.3	1.15	
			1603.3	1.06	
		35	1599*	1.13#	16
		43	1608*		
Fresh	5	37	1591.7	0.93	17
		40	1594.5#	0.78	
		43	1596.8#	0.62	
		37	1594.8	1.13	17
		40	1598.2#	0.96	
		43	1601.1#	0.80	
		37	1604.0	0.99	17
		40	1607.0#	0.72	
		43	1609.1#	0.46	
Porcine					
Homogenate	4	5.5	1490(0.2%)	4.33#	18(2)
		8.5	1503	5.43#	
		12.0	1522	1.71#	
		15.5	1528	2.00#	
		16.5	1530	3.33#	
		18.0	1535	3.75#	
		18.8	1538	1.48#	
		21.5	1542	2.78#	
		23.3	1547	2.00#	

Table 1 (continued)
ULTRASONIC VELOCITY OF PROPAGATION AS A FUNCTION OF TEMPERATURE FOR BIOLOGICAL MATERIAL*

Species	Frequency (MHz)	Temp (°C)	Velocity value (dev) (m/sec)	Thermal coefficient (m/sec/°C)	Ref.
		25.8	1552	5.71#	
		27.2	1560	37.5#	
		28.8	1620	33.3#	
		30.0	1660	(5.05)#	r = 0.85
		Milk			
Bovine					
Whole, 8% nonfat solids, 4% butter fat	NR	10	1488*	2.10#	19(3)
		20	1509*	1.90#	
		30	1528*	1.50#	
		40	1543*	1.00#	
		50	1553*	(1.64)#	r = 0.99
Skimmed, 8% nonfat solids	NR	10	1483*	3.30#	19(3)
		20	1516*	2.40#	
		30	1540*	1.40#	
		40	1554*	0.60#	
		50	1560*	(1.92)#	r = 0.96
		Muscle, Breast			
Human					
Excised	NR	22.5	1543.1(5.2)	2.52#	9
		25.8	1551.4(6.2)	1.40#	
		27.8	1554.2(6.5)	3.42#	
		30.2	1562.4(7.1)	1.55#	
		32.2	1565.5(6.4)	0.48#	
		35.1	1566.9(4.5)	1.31#	
		38.0	1570.7(6.9)	1.86#	
		40.1	1574.6(6.7)	2.04#	
		42.5	1579.5(5.4)	(1.70)#	r = 0.98
		Muscle, External to Eye			
Human					
<2 Days p.m.	6—14	20	1612(12.5)	1.12#	15(2)
		37	1631(15.3)		
		Muscle, Psoas			
Human					
Excised	NR	17.0	1542.5(3.0)	−16.6#	9
		22.0	1459.5(3.0)	63.5#	
		23.5	1554.8(1.1)	2.00#	
		26.2	1560.2(1.7)	1.55#	
		30.2	1566.4(2.2)	1.73#	
		33.2	1571.6(1.8)	0.95#	
		35.2	1573.5(1.8)	1.05#	
		37.2	1575.6(1.1)	1.11#	
		39.0	1577.6(2.1)	1.50#	
		40.8	1580.3(1.8)	(2.92)#	r = 0.65

Table 1 (continued)
ULTRASONIC VELOCITY OF PROPAGATION AS A FUNCTION OF TEMPERATURE FOR BIOLOGICAL MATERIAL[a]

Species	Frequency (MHz)	Temp (°C)	Velocity value (dev) (m/sec)	Thermal coefficient (m/sec/°C)	Ref.
Muscle, Skeletal					
Canine					
Fresh 5—30 min	5	38.5	1608.7	0.88	16
			1629.3	0.56	
		35	1606*	1.00#	16
		41	1612*		
Fresh	5	37	1589.1	1.23	17
		40	1592.8#	1.03	
		43	1595.9#	0.82	
		37	1603.3	1.13	17
		40	1606.7#	0.92	
		43	1609.5#	0.71	
		37	1588.8	1.16	17
		40	1592.3#	0.95	
		43	1595.1#	0.78	
		37	1591.6	1.08	17
		40	1594.8#	0.87	
		43	1597.5#	0.65	
Nervous Tissue, Brain					
Human					
Fetal, spontaneous labor gest.: 17 weeks	5	0	1435	2.13#	20(2)
		8	1452	2.38#	
		16	1471	2.38#	
		24	1490	2.50#	
		30	1505	2.14#	
		37	1520	(2.33)#	r = 1.00
Fetal, 17 weeks		0	1435	2.75#	20(2)
		8	1457	2.25#	
		16	1475	2.50#	
		24	1495	2.50#	
		30	1510	1.86#	
		37	1523	(2.39)#	r = 1.00
Fetal, 18 weeks		0	1430	3.13#	20(2)
		8	1455	2.88#	
		16	1478	1.50#	
		24	1490	3.00#	
		30	1508	1.29#	
		37	1517	(2.35)#	r = 0.99
Fetal, 19 weeks		0	1433	3.25#	20(2)
		8	1459	3.25#	
		16	1485	1.38#	
		24	1496	2.00#	

Table 1 (continued)
ULTRASONIC VELOCITY OF PROPAGATION AS A FUNCTION OF TEMPERATURE FOR BIOLOGICAL MATERIAL[a]

Species	Frequency (MHz)	Temp (°C)	Velocity value (dev) (m/sec)	Thermal coefficient (m/sec/°C)	Ref.
		30	1508	1.57#	
		37	1519	(2.29)#	r = 0.99
Fetal, 24 weeks		0	1438	2.75#	20(2)
		8	1460	2.50#	
		16	1480	1.88#	
		24	1495	2.50#	
		30	1510	1.86#	
		37	1523	(2.28)#	r = 1.00
Fetal, 28 weeks		0	1437	3.25#	20(2)
		8	1463	3.00#	
		16	1487	1.38#	
		24	1498	2.33#	
		30	1512	2.29#	
		37	1528	(2.37)#	r = 0.99
		0	1440	3.25#	20(2)
		8	1466	2.38#	
		16	1485	2.13#	
		24	1502	2.17#	
		30	1515	2.00#	
		37	1529	(2.36)#	r = 1.00
Fetal, 29 weeks		0	1438	3.50#	20(2)
		8	1466	2.50#	
		16	1486	1.75#	
		24	1500	2.67#	
		30	1516	1.86#	
		37	1529	(2.40)#	r = 0.99
Fetal, 38 weeks		0	1459	2.75#	20(2)
		8	1481	2.25#	
		16	1499	1.88#	
		24	1514	3.00#	
		30	1532	1.14#	
		37	1540	(2.22)#	r = 1.00
Fetal, 40 weeks		0	1449	3.75#	20(2)
		8	1479	3.13#	
		16	1504	2.13#	
		24	1521	1.83#	
		30	1532	1.14#	
		37	1540	(2.46)#	r = 0.98
		0	1457	2.88#	20(2)
		8	1480	3.00#	
		16	1504	2.50#	
		24	1524	1.00#	
		30	1530	1.43#	
		37	1540	(2.28)#	r = 0.99

Table 1 (continued)
ULTRASONIC VELOCITY OF PROPAGATION AS A FUNCTION OF TEMPERATURE FOR BIOLOGICAL MATERIAL[a]

Species	Frequency (MHz)	Temp (°C)	Velocity value (dev) (m/sec)	Thermal coefficient (m/sec/°C)	Ref.
Fetal, induced labor, gest.: 17 weeks	5	0	1424	2.38#	20(2)
		8	1443	3.75#	
		16	1473	2.50#	
		24	1493	2.50#	
		30	1508	1.43#	
		37	1518	(2.66)#	r = 0.99
Fetal, 17 weeks		0	1435	3.13#	20(2)
		8	1460	3.63#	
		16	1489	2.25#	
		24	1507	2.50#	
		30	1522	1.14#	
		37	1530	(2.64)#	r = 0.99
		0	1433	3.00#	20(2)
		8	1457	2.75#	
		16	1479	3.38#	
		24	1506	3.17#	
		30	1525	1.00#	
		37	1532	(2.81)#	r = 0.99
Fetal, 18 weeks		0	1441	3.25#	20(2)
		8	1467	2.75#	
		16	1489	3.13#	
		24	1514	1.50#	
		30	1523	0.71#	
		37	1528	(2.45)#	r = 0.98
		0	1443	3.63#	20(2)
		8	1472	1.13#	
		16	1481	1.00#	
		24	1489	3.33#	
		30	1509	2.86#	
		37	1529	(2.11)#	r = 0.98
		0	1447	3.50#	20(2)
		8	1475	2.63#	
		16	1496	2.00#	
		24	1512	1.83#	
		30	1523	1.57#	
		37	1534	(2.31)#	r = 0.99
Fetal, 19 weeks		0	1441	4.25#	20(2)
		8	1475	1.75#	
		16	1489	2.38#	
		24	1508	1.83#	
		30	1519	1.57#	
		37	1530	(2.32)#	r = 0.99
Fetal, 20 weeks		0	1437	3.75#	20(2)
		8	1467	3.13#	
		16	1492	2.00#	
		24	1508	2.00#	

Table 1 (continued)
ULTRASONIC VELOCITY OF PROPAGATION AS A FUNCTION OF TEMPERATURE FOR BIOLOGICAL MATERIAL[a]

Species	Frequency (MHz)	Temp (°C)	Velocity value (dev) (m/sec)	Thermal coefficient (m/sec/°C)	Ref.
		30	1520	1.43#	
		37	1530	(2.49)#	r = 0.99
Fetal, 21 weeks		0	1440	2.38#	20(2)
		8	1459	2.88#	
		16	1482	2.75#	
		24	1504	2.50#	
		30	1519	2.00#	
		37	1533	(2.58)#	r = 1.00
Fetal, induced labor, gest.: 21 weeks	5	0	1441	2.63#	20(2)
		8	1462	3.38#	
		16	1489	2.38#	
		24	1508	2.50#	
		30	1523	1.57#	
		37	1534	(2.59)#	r = 1.00
Fetal, induced labor, gest.: 16 weeks	5	0	1427	2.63#	20(2)
		8	1448	3.25#	
		16	1474	2.00#	
		24	1490	2.33#	
		30	1504	1.29#	
		37	1513	(2.38)#	r = 0.99
Fetal, 18 weeks		0	1440	2.50#	20(2)
		8	1460	2.88#	
		16	1483	2.00#	
		24	1499	1.33#	
		30	1507	1.00#	
		37	1514	(2.05)#	r = 0.99
Canine					
Fresh	5	35	1565*	0.56#	16
		44	1570*		
Fresh, white matter	5	37	1563.2	0.67	17
		40	1562.2#	0.62	
		43	1567.1#	0.26	
Feline					
Fresh	4.2	25	1558*	0.80#	21(2)
		30	1562*	1.86#	
		37	1575*	−5.00#	
		40	1560*	2.86#	
		47	1580*	−2.25#	
		51	1571*	(0.62)#	r = 0.68
	4.2	38	1568*	−1.00#	21(2)
		42	1564*	1.80#	
		47	1573*	1.00#	
		52	1578*	0.00#	
		57	1578*	−2.80#	
		62	1564*	0.20#	
		67	1565*	(−0.03)#	r = −0.06

Table 1 (continued)
ULTRASONIC VELOCITY OF PROPAGATION AS A FUNCTION OF TEMPERATURE FOR BIOLOGICAL MATERIAL[a]

Species	Frequency (MHz)	Temp (°C)	Velocity value (dev) (m/sec)	Thermal coefficient (m/sec/°C)	Ref.
			Nervous Tissue, Optic Nerve		
Human					
<2 Days	6—14	20	1644(25.4)	−1.71#	15(2)
p.m.		37	1615(3.1)		
			Nervous Tissue, Spinal Cord		
Human					
Excised	NR	17.0	1509.0(4.5)	2.80#	9
		22.0	1523.0(4.6)	0.00#	
		23.5	1523.0(5.3)	1.11#	
		26.2	1526.0(3.0)	1.65#	
		30.2	1532.6(3.2)	1.80#	
		33.2	1538.0(2.6)	0.00#	
		35.2	1538.0(3.5)	2.20#	
		37.2	1542.4(3.3)	0.78#	
		39.0	1543.8(3.0)	−48.5#	
		40.8	1456.5(2.0)	(−0.16)#	r = −0.05
			Spleen		
Human					
Excised	NR	17.0	1528.0(1.8)	2.16#	9
		22.0	1538.8(1.8)	3.67#	
		23.5	1544.3(1.8)	1.78#	
		26.2	1549.1(1.6)	1.83#	
		30.2	1556.4(2.0)	1.83#	
		33.2	1561.9(1.7)	−7.95#	
		35.2	1546.0(2.1)	10.6#	
		37.2	1567.1(2.3)	1.22#	
		39.0	1569.3(2.6)	2.06#	
		40.8	1573.0(2.1)	(1.68)#	r = 0.92
Canine					
Fresh	5	37	1601.3	1.31	17
		40	1605.2#	1.07	
		43	1608.4#	0.84	
			Water		
Distilled	60	23.41	1492.27(0.1)	2.79#	22
		23.79	1493.33	2.81#	
		24.20	1494.48	2.56#	
		24.63	1495.58	2.74#	
		25.02	1496.65	2.69#	
		25.41	1497.70	2.55#	
		25.83	1498.77	2.54#	
		28.00	1504.29	2.43#	
		29.00	1506.72	2.46#	
		29.93	1509.01	2.54#	
		30.06	1509.34	2.12#	
		31.00	1511.33	2.13#	

Table 1 (continued)
ULTRASONIC VELOCITY OF PROPAGATION AS A FUNCTION OF TEMPERATURE FOR BIOLOGICAL MATERIAL[a]

Species	Frequency (MHz)	Temp (°C)	Velocity value (dev) (m/sec)	Thermal coefficient (m/sec/°C)	Ref.
		34.99	1519.81	1.80#	
		40.00	1528.83	1.51#	
		45.00	1536.36	(2.10)#	r = 1.00

[a] NR indicates data not reported. Values marked with an (*) were interpolated from graphs. Values marked with a (#) were estimated by the authors (see text for details). Thermal coefficients in parentheses, followed by r = ... , are least-square linear approximations, followed by the correlation coefficient of the fit. References marked m(n) were measurements made by m, but the data were taken from n.

Table 2
ULTRASONIC ATTENUATION COEFFICIENT AS A FUNCTION OF TEMPERATURE FOR BIOLOGICAL MATERIAL[a]

Species	Frequency (MHz)	Temp (°C)	Attenuation coeff (dev) (db/cm)	Thermal coeff (db/cm/°C *10³)	Ref.
			Blood		
Human					
NR,	1	10	0.012*	0.00#	8
average of		20	0.012*	−0.20#	a/(g protein·100 cc)
red cells,		30	0.01*	−0.10#	
HGB, albumin		40	0.009*	(−0.11)#	r = −0.95
	2	10	0.025*	−0.20#	8
		20	0.023*	−0.20#	
		30	0.021*	−0.20#	
		40	0.019*	(−0.20)#	r = −1.00
	3	10	0.036*	−0.20#	8
		20	0.034*	−0.20#	
		30	0.032*	−0.20#	
		40	0.03*	(−0.20)#	r = −1.00
NR,	1	10	0.013*	−0.10#	8
plasma		20	0.012*	−0.20#	
		30	0.01*	−0.10#	
		40	0.009*	(−0.14)#	r = −0.99
	2	10	0.028*	−0.30#	8
		20	0.025*	−0.30#	
		30	0.022*	−0.30#	
		40	0.019*	(−0.30)#	r = −1.00
	3	10	0.046*	−0.80#	8
		20	0.038*	−0.40#	
		30	0.034*	−0.40#	
		40	0.03*	(−0.52)#	r = −0.98
Canine					
Fresh,	0.58	30	0.11*	−2.00#	27(2)

Table 2 (continued)
ULTRASONIC ATTENUATION COEFFICIENT AS A FUNCTION OF TEMPERATURE FOR BIOLOGICAL MATERIAL*

Species	Frequency (MHz)	Temp (°C)	Attenuation coeff (dev) (db/cm)	Thermal coeff (db/cm/°C *10³)	Ref.
citrated		40	0.09*		
	0.97	30	0.165*	−0.50#	27(2)
		40	0.16*		
	1.8	30	0.3*	−1.00#	27(2)
		40	0.29*		
	3.0	30	0.6*	−2.00#	27(2)
		40	0.58*		
	4.8	30	1.15*	−5.00#	27(2)
		40	1.1*		
NR Plasma	1.2	20	0.08	−0.50#	28(2)
		40	0.07		
	2.4	20	0.16	−1.50#	28(2)
		40	0.13		
			Bone		
Equine NR	1.43	10	28.5*	150.0#	29(2)
		20	30*	100.0#	
		30	31*	200.0#	
		40	33*	200.0#	
		50	35*	(160.0)#	r = 0.99
	2.86	5	41*	200.0#	29(2)
		10	42*	220.0#	
		20	44.2*	180.0#	
		30	46*	200.0#	
		40	48*	200.0#	
		50	50*	(199.2)#	r = 1.00
	4.5	10	72*	300.0#	29(2)
		20	75*	150.0#	
		30	76.5*	150.0#	
		40	78*	120.0#	
		50	79.2*	180.0#	
		60	81*	(168.9)#	r = 0.99
			Fat		
Porcine Fresh, stored @ 5°C, backfat	2	4	9.0*(1.5)	−125.0#	30(3)
		20	7.0*	−235.0#	
		37	3.0*	−83.33#	
		49	2.0*	(−165.8)#	r = −0.99
	4	4	20.8*	−343.8#	30(3)
		20	15.3*	−576.5#	

Table 2 (continued)
ULTRASONIC ATTENUATION COEFFICIENT AS A FUNCTION OF TEMPERATURE FOR BIOLOGICAL MATERIAL*

Species	Frequency (MHz)	Temp (°C)	Attenuation coeff (dev) (db/cm)	Thermal coeff (db/cm/°C *10³)	Ref.
		37	5.5*	−166.7#	
		49	3.5*	(−410.0)#	r = −0.99
	6	37	8.5*	−208.3#	30(3)
		49	6.0*		
	8	37	12.5*	−291.7#	30(3)
		49	9.0*		
	9.9	37	17.5*	−333.3#	30(3)
		49	13.5*		
			Fat, Peritoneal		
Bovine Fresh, peritoneal	1	10*	6.0* (10%)	−200.0#	14(3)
		20	4.0*	−200.0#	
		30	2.0*	14.29#	
		37	2.1*	39.13#	
		60	3.0*	(−55.06)#	r = −0.63
	2	20	6.6*	−340.0#	14(3)
		30	3.2*	−85.71#	
		37	2.6*	60.87#	
		60	4.0*	(−44.42)#	r = −0.43
	3	20	9.5*	−490.0#	14(3)
		30	4.6*	−200.0#	
		37	3.2*	147.8#	
		60	6.6*	(−41.45)#	r = −0.26
	4	30	7.2*	−428.6#	14(3)
		37	4.2*	134.8#	
		60	7.3*	(36.06)#	r = 0.32
	5	30	10.0*	−571.4#	14(3)
		37	6.0*	95.65#	
		60	8.2*	(−21.24)#	r = −0.17
	6	30	12.5*	−785.7#	14(3)
		37	7.0*	86.96#	
		60	9.0*	(−65.97)#	r = −0.37
	7	30	16.0*	−1143#	14(3)
		37	8.0*	65.22#	
		60	9.5*	(−146.5)#	r = −0.54
			Heart		
Canine			cm^{-1}		
Fresh, 15 min, left ventrical	2	19.5	0.10(0.02)	−0.65#	31
		35	0.09(0.02)		

Table 2 (continued)
ULTRASONIC ATTENUATION COEFFICIENT AS A FUNCTION OF TEMPERATURE FOR BIOLOGICAL MATERIAL*

Species	Frequency (MHz)	Temp (°C)	Attenuation coeff (dev) (db/cm)	Thermal coeff (db/cm/°C $*10^3$)	Ref.
	4	19.5	0.49(0.03)	−1.29#	31
		35	0.17(0.02)		
	6	19.5	0.34(0.02)	−2.58#	31
		35	0.30(0.03)		
	8	19.5	0.48(0.03)	−3.23#	31
		35	0.43(0.03)		
	10	19.5	0.65(0.03)	−5.81#	31
		35	0.56(0.03)		
Fresh, 2 hr, left ventrical	2	19.5	0.10(0.02)	−0.65#	31
		35	0.09(0.02)		
	4	19.5	0.20(0.02)	−0.65#	31
		35	0.19(0.03)		
	6	19.5	0.36(0.02)	−1.29#	31
		35	0.34(0.03)		
	8	19.5	0.50(0.03)	−1.94#	31
		35	0.47(0.03)		
	10	19.5	0.70(0.03)	−5.81#	31
		35	0.61(0.04)		
Fresh, 4 hr, left ventrical	2	19.5	0.10(0.02)	0.65#	31
		35	0.11(0.02)		
	4	19.5	0.20(0.02)	1.29#	31
		35	0.22(0.03)		
	6	19.5	0.35(0.02)	1.29#	31
		35	0.37(0.03)		
	8	19.5	0.49(0.03)	1.94#	31
		35	0.52(0.03)		
	10	19.5	0.69(0.03)	−3.23#	31
		35	0.64(0.04)		
Fresh, left ventrical	2	20.5	0.10(0.02)	0.00#	31
		25	0.10(0.02)	0.00#	
		30	0.10(0.02)	1.43#	
		37	0.11(0.02)	(0.59)#	r = 0.84
	4	20.5	0.19(0.02)	0.00#	31
		25	0.19(0.02)	−4.00#	
		30	0.17(0.02)	2.86#	
		37	0.19(0.02)	(−0.25)#	r = −0.18

Table 2 (continued)
ULTRASONIC ATTENUATION COEFFICIENT AS A FUNCTION OF TEMPERATURE FOR BIOLOGICAL MATERIAL*

Species	Frequency (MHz)	Temp (°C)	Attenuation coeff (dev) (db/cm)	Thermal coeff (db/cm/°C $*10^3$)	Ref.
	6	20.5	0.34(0.03)	−2.22#	31
		25	0.33(0.03)	−4.00#	
		30	0.31(0.03)	0.00#	
		37	0.31(0.03)	(−1.94)#	r = −0.92
	8	20.5	0.48(0.03)	−6.67#	31
		25	0.45(0.03)	−4.00#	
		30	0.43(0.03)	−2.86#	
		37	0.41(0.03)	(−4.14)#	r = −0.98
	10	20.5	0.64(0.03)	−6.67#	31
		25	0.61(0.03)	−6.00#	
		30	0.58(0.03)	−2.86#	
		37	0.56(0.03)	(−4.85)#	r = −0.98
Canine			cm $^{-1}$/MHz		
Fresh, 15 min, left ventrical	2—10	19.5	0.072(0.002)	−0.71#	31(2)
		35	0.061(0.003)		
Fresh, 2 hr, left ventrical	2—10	19.5	0.075(0.002)	−0.45#	31(2)
		35	0.068(0.003)		
Fresh, 4 hr, left ventrical	2—10	19.5	0.075(0.002)	−0.26#	31(2)
		35	0.071(0.003)		
Fresh, left ventrical	2—10	10.5	0.071(0.002)	−0.21#	31(2)
		25	0.068(0.002)	−0.80#	
		30	0.064(0.002)	−0.86#	
		37	0.058(0.002)	(−0.47)#	r = −0.93
			Kidney		
Porcine			(db/cm)		
Fresh, <1 hr, p.m. stored @ 5°C	2	4	1.3* (1.5)	−50.0#	30(3)
		20	0.5*	88.2#	
		37	2.0	(21.9)#	r = 0.48
	4	4	3.2*	−43.8#	30(3)
		20	2.5*	70.6#	
		37	3.7	(15.7)#	r = 0.43
	6	4	5.5*	−93.8#	30(3)
		20	4.0*	58.8#	
		37	5.0	(−14.4)#	r = 0.31
	8	4	8.5*	−156.0#	30(3)
		20	6.0*	52.9#	
		37	6.9	(−47.4)#	r = −0.62

Table 2 (continued)
ULTRASONIC ATTENUATION COEFFICIENT AS A FUNCTION OF TEMPERATURE FOR BIOLOGICAL MATERIAL[a]

Species	Frequency (MHz)	Temp (°C)	Attenuation coeff (dev) (db/cm)	Thermal coeff (db/cm/°C *10³)	Ref.
	9.9	4	12.6*	−300.0#	30(3)
		20	7.8*	70.6#	
		37	9.0*	(−107.2)#	r = −0.71
			Liver		
Human p.m.	1	5	1.2* (10%)	50.0#	14(3)
		11	1.5*	9.09#	
		22	1.6*	0.00#	
		30	1.6*	0.00#	
		42	1.6*	(9.04)#	r = 0.77
	2	5	2.1*	0.00#	14(3)
		11	2.1*	−27.3#	
		22	1.8*	0.00#	
		30	1.8*	−8.33#	
		42	1.7*	(−11.9)#	r = −0.94
	3	5	3.0*	−50.0#	14(3)
		11	2.7*	−18.2#	
		22	2.5*	−12.5#	
		30	2.4*	−16.7#	
		42	2.2*	(−20.0)#	r = −0.97
	4	5	3.8*	−83.3#	14(3)
		11	3.3*	−45.5#	
		22	2.8*	−37.5#	
		30	2.5*	−8.33#	
		42	2.4*	(−37.6)#	r = −0.95
	5	5	4.3*	−83.3#	14(3)
		11	3.8*	−54.6#	
		22	3.2*	−25.0#	
		30	3.0*	−16.7#	
		42	2.8*	(−39.9)#	r = −0.96
	6	5	5.7*	−166.7#	14(3)
		11	4.7*	−81.8#	
		22	3.8*	−37.5#	
		30	3.5*	−25.0#	
		42	3.2*	(−64.8)#	r = −0.94
	7	5	7.2*	−200.0#	14(3)
		11	6.0*	−100.0#	
		22	4.9*	−50.0#	
		30	4.5*	−25.0#	
		42	4.2*	(−78.3)#	r = −0.94
Autopsy, refrig 60 hr, micronodular cirrhosis	2	4	4.2*(1.5)	−100.0#	30(3)
		20	2.6*	−35.3#	
		37	2.0*	(−66.3)#	r = −0.96

Table 2 (continued)
ULTRASONIC ATTENUATION COEFFICIENT AS A FUNCTION OF TEMPERATURE FOR BIOLOGICAL MATERIAL[a]

Species	Frequency (MHz)	Temp (°C)	Attenuation coeff (dev) (db/cm)	Thermal coeff (db/cm/°C *10³)	Ref.
	4	4	8.0*	−125.0#	30(3)
		20	6.0*	−88.2#	
		37	4.5*	(−105.9)#	r = −1.00
	6	4	13.0*	−218.8#	30(3)
		20	9.5*	−88.2#	
		37	8.0*	(−150.9)#	r = −0.97
	8	4	18.6*	−312.5#	30(3)
		20	13.6*	−123.5#	
		37	11.5*	(−214.2)#	r = −0.97
	9.9	4	24.0*	−381.3#	30(3)
		20	17.9*	−141.2#	
		37	15.5*	(−256.4)#	r = −0.97
Bovine Fresh, <30 min	1	8	2.0*(10%)	0.00#	14(3)
		21	2.0*	6.25#	Sample 1
		37	2.1*	137.5#	
		45	3.2*	0.00#	
		58	3.2*	(27.6)#	r = 0.85
	2	8	2.9*	−38.5#	14(3)
		21	2.4*	6.25#	
		37	2.5*	162.5#	
		45	3.8*	0.00#	
		58	3.8*	(23.9)#	r = 0.69
	3	8	4.7*	−92.3#	14(3)
		21	3.5*	−12.5#	
		37	3.3*	150.0#	
		45	4.5*	0.00#	
		58	4.5*	(2.45)#	r = 0.07
	4	8	4.7*	−92.3#	14(3)
		21	3.5*	−18.8#	
		37	3.2*	212.5#	
		45	4.9*	7.69#	
		58	5.0*	(12.9)#	r = 0.30
	5	8	5.8*	−123.1#	14(3)
		21	4.2*	−37.5#	
		37	3.6*	212.5#	
		45	5.3*	46.2#	
		58	5.9*	(6.62)#	r = 0.13
	6	8	6.9*	−138.5#	14(3)
		21	5.1*	−56.3#	
		37	4.2*	225.0#	
		45	6.0*	53.9#	
		58	6.7*	(−0.34)#	r = −0.01

Table 2 (continued)
ULTRASONIC ATTENUATION COEFFICIENT AS A FUNCTION OF TEMPERATURE FOR BIOLOGICAL MATERIAL*

Species	Frequency (MHz)	Temp (°C)	Attenuation coeff (dev) (db/cm)	Thermal coeff (db/cm/°C *10^3)	Ref.
	7	8	8.7*	−184.6#	14(3)
		21	6.3*	−62.5#	
		37	5.3*	212.5#	
		45	7.0*	66.7#	
		57	7.8*	(−14.5)#	r = −0.21
	1	9	1.7*	0.00#	14(3)
		20	1.7*	0.00#	Sample 2
		30	1.7*	7.69#	
		43	1.8*	9.09#	
		65	2.0*	(5.56)#	r = 0.92
	2	9	2.2*	−18.8#	14(3)
		20	2.0*	−10.0#	
		30	1.9*	−7.69#	
		43	1.8*	22.7#	
		65	2.3	(1.61)#	r = 0.17
	3	9	2.9*	−63.6#	14(3)
		20	2.2*	−20.0#	
		30	2.0*	0.00#	
		43	2.0*	45.5#	
		65	3.0*	(3.71)#	r = 0.16
	4	9	3.3*	−72.7#	14(3)
		20	2.5*	20.0#	
		30	2.7*	0.00#	
		43	2.7*	45.5#	
		65	3.7*	(10.5)#	r = 0.45
	5	9	3.8*	−72.7#	14(3)
		20	3.0*	−20.0#	
		30	2.8*	0.00#	
		43	2.8*	68.2#	
		65	4.3*	(10.8)#	r = 0.35
	6	9	4.7*	−109.1#	14(3)
		20	3.5*	−50.0#	
		30	3.0*	7.69#	
		43	3.1*	104.6#	
		65	5.4*	(15.3)#	r = 0.31
	7	9	5.5*	−109.1#	14(3)
		20	4.3*	−30.0#	
		30	4.0*	7.69#	
		43	4.1*	118.2#	
		65	6.7*	(24.3)#	r = 0.45
Formalin fixed, 2 months 4%	3	18	2.4*(10%)	−40.0#	14(3)
		28	2.0*	0.00#	Sample 1
		40	2.0*	0.00#	
		58	2.0*	(−8.11)#	r = −0.70

Table 2 (continued)
ULTRASONIC ATTENUATION COEFFICIENT AS A FUNCTION OF TEMPERATURE FOR BIOLOGICAL MATERIAL*

Species	Frequency (MHz)	Temp (°C)	Attenuation coeff (dev) (db/cm)	Thermal coeff (db/cm/°C *10^3)	Ref.
	4	18	3.4*	−50.0#	14(3)
		28	2.9*	−16.7#	
		40	2.7*	−11.1#	
		58	2.5*	(−21.0)#	r = −0.93
	5	18	4.3*	−70.0#	14(3)
		28	3.6*	−25.0#	
		40	3.3*	−16.7#	
		58	3.0*	(−30.4)#	r = −0.94
	6	18	5.5*	−90.0#	14(3)
		28	4.6*	−33.3#	
		40	4.2*	−33.3#	
		58	3.6*	(−44.8)#	r = −0.97
	7	18	7.0*	−110.0#	14(3)
		28	5.9*	−66.7#	
		40	5.1*	−16.7#	
		58	4.8*	(−53.2)#	r = −0.93
	3	18	2.8*	−30.0#	14(3)
		28	2.5*	−16.7#	Sample 2
		40	2.3*	−11.1#	
		58	2.1*	(−16.9)#	r = −0.97
	4	18	3.5*	−30.0#	14(3)
		28	3.2*	−33.3#	
		40	2.8*	−11.1#	
		58	2.6*	(−22.8)#	r = −0.97
	5	18	4.5*	−70.0#	14(3)
		28	3.8*	−41.7#	
		40	3.3*	−16.7#	
		58	3.0*	(−36.3)#	r = −0.95
	6	18	5.6*	−80.0#	14(3)
		28	4.8*	−66.7#	
		40	4.0*	−11.1#	
		58	3.8*	(−44.6)#	r = −0.93
	7	18	7.0*	−100.0#	14(3)
		28	6.0*	−83.3#	
		40	5.0*	−33.3#	
		58	4.4*	(−64.4)#	r = −0.97
Porcine Fresh <1 hr, stored @ 5°C	2	4	3.3*(1.5)	−6.25#	30(3)
		20	3.2*	47.1#	
		37	4.0*	(21.5)#	r = 0.81
	4	4	7.2*	−43.8#	30(3)
		20	6.5*	−29.1#	
		37	6.0*	(−36.3)#	r = −0.99

Table 2 (continued)
ULTRASONIC ATTENUATION COEFFICIENT AS A FUNCTION OF TEMPERATURE FOR BIOLOGICAL MATERIAL*

Species	Frequency (MHz)	Temp (°C)	Attenuation coeff (dev) (db/cm)	Thermal coeff (db/cm/°C *10^3)	Ref.
	6	4	12.0*	−106.3#	30(3)
		20	10.3*	−76.5#	
		37	9.0*	(−90.8)#	r = −1.00
	8	4	17.3*	−162.5#	30(3)
		20	14.7*	−158.8#	
		37	12.0*	(−160.6)#	r = −1.00
	9.9	4	23.3*	−143.8#	30(3)
		20	21.0*	−294.1#	
		37	16.0*	(−222.0)#	r = −0.98
Homogenate	4.0	4.0	1.32(5%)	−33.3#	18(2)
		5.2	1.28	−75.0#	
		6.0	1.22	−20.0#	
		7.0	1.20	−7.90#	
		10.8	1.17	−28.1#	
		14.0	1.08	30.0#	
		15.0	1.11	−16.7#	
		18.0	1.06	−50.0#	
		18.8	1.02	−46.7#	
		20.0	0.964	2.67#	
		23.0	0.972	−18.9#	
		24.8	0.938	3.75#	
		28.0	0.95	−13.3#	
		28.9	0.938	−47.3#	
		30.0	0.886	(−14.9)#	r = −0.97
			Nervous Tissue, Brain		
Bovine Formalin fixed, 2 months, 10%	1	10	0.30*	50.00#	14(3)
		18	0.70*	21.05#	
		37	1.1*	−14.29#	
		58	0.8*	(9.84)#	r = 0.64
	2	10	2.3*	−62.50#	14(3)
		18	1.8*	−5.26#	
		37	1.7*	−14.29#	
		58	1.4*	(−15.93)#	r = −0.91
	3	10	4.4*	−75.00#	14(3)
		18	3.8*	−31.58#	
		37	3.2*	−23.81#	
		58	2.7*	(−33.59)#	r = −0.98
	4	10	6.8*	−137.5#	14(3)
		18	5.7*	−42.11#	
		37	4.9*	−33.33#	
		58	4.2*	(−49.97)#	r = −0.96
	5	10	9.0*	−125.0#	14(3)

Table 2 (continued)
ULTRASONIC ATTENUATION COEFFICIENT AS A FUNCTION OF TEMPERATURE FOR BIOLOGICAL MATERIAL*

Species	Frequency (MHz)	Temp (°C)	Attenuation coeff (dev) (db/cm)	Thermal coeff (db/cm/°C *10^3)	Ref.
		18	8.0*	−84.21#	
		37	6.4*	−23.81#	
		58	5.9*	(−63.99)#	r = −0.96
Feline In vivo	1.0	25	0.85		32
			0.97		
		27	0.88		
		28	1.04		
			0.81		
		29	0.73		
p.m.	1.0	25	0.84		32
			0.91		
		27	0.85		
		28	1.07		
			0.80		
		29	0.74		
			Nervous Tissue, Spinal Cord		
Murine			cm^{-1}		
Neonatal, 24 hr, 3rd lumbar vertebra	0.26	2	0.048*	−0.21#	26
		10	0.0463*	−0.17#	Absorption
		20	0.0446*	−0.27#	
		30	0.0419*	−0.13#	
		40	0.0406*	(−0.20)#	r = −1.00
			(db cm)		
	0.05	2	1.13(10%)	−32.5#	24(2)
		10	0.87	−17.0#	Absorption
		20	0.7	−2.50#	
		40	0.65	(−11.6)#	r = −0.88
Neonatal	0.7	2	0.77	17.5#	24(2)
		10	0.91	5.00#	
		30	1.01	−10.0#	
		40	0.91	0.00#	
		45	0.91	(2.66)#	r = 0.58
	1.0	40	0.100	1.80#	24(2)
		45	0.109		
			cm^{-1}		
Neonatal, 24 hr, 3rd lumbar vertebra	1.0	2	0.02*	3.75#	26
		10	0.05*	2.65#	Absorption
		27	0.095*	1.54#	
		40	0.115*	1.00#	
		45	0.12*	(2.30)#	r = 0.99

Table 2 (continued)
ULTRASONIC ATTENUATION COEFFICIENT AS A FUNCTION OF TEMPERATURE FOR BIOLOGICAL MATERIAL*

Species	Frequency (MHz)	Temp (°C)	Attenuation coeff (dev) (db/cm)	Thermal coeff (db/cm/°C *10³)	Ref.
			*Spleen		
Bovine			(db/cm)		
Formalin	1	10	1.2*(10%)	25.0#	14(3)
fixed, 2 months		18	1.4*	26.3#	
4%		37	1.9*	−23.8#	
		58	1.4*	(5.29)#	r = 0.38
	2	10	2.9*	−50.0#	14(3)
		18	2.5*	−5.26#	
		37	2.4*	−19.1#	
		58	2.0*	(−16.4)#	r = −0.95
	3	10	4.5*	−62.5#	14(3)
		18	4.0*	−26.3#	
		37	3.5*	−28.6#	
		58	2.9*	(−31.6)#	r = −0.99
	4	10	6.2*	−50.0#	14(3)
		18	5.8*	−47.4#	
		37	4.9*	−42.9#	
		58	4.0*	(−45.8)#	r = −1.00
	5	10	8.1*	−50.0#	14(3)
		18	7.7*	−68.4#	
		37	6.4*	−61.9#	
		58	5.1*	(−63.5)#	r = −1.00
Porcine					
Fresh,	2	4	2.0*(1.5)	−6.25#	30(3)
<1 hr,		20	1.9*	−52.9#	
stored @ 5°C		37	1.0*	(−30.5)#	r = −0.92
	4	4	7.9*	−150.0#	30(3)
		20	5.5*	−117.6#	
		37	3.5*	(−133.2)#	r = −1.00
	6	4	14.0*	−318.8#	30(3)
		20	8.9*	−170.6#	
		37	6.0*	(−241.7)#	r = −0.99
	8	4	21.5*	−475.0#	30(3)
		20	13.9*	−347.1#	
		37	8.0*	(−408.5)#	r = −1.00
	9.9	4	31.8*	−768.8#	30(3)
		20	19.5*	−464.7#	
		37	11.6*	(−610.6)#	r = −0.99

* NR indicates data not reported. Values marked with an (*) were interpolated from graphs. Values marked with a (#) were estimated by the authors (see text for details). Thermal coefficients in parentheses, followed by r = . . . , are least-square linear approximations, followed by the correlation coefficient of the fit. References marked m(n) were measurements made by m, but the data were taken from n.

percent or as one standard deviation. The thermal coefficient (the rate of change of the velocity with respect to change in temperature), where reported, follows (in meters per second per degree Celsius). For a large number of cases, the thermal coefficient was not reported and hence was estimated by the authors as the difference in velocity divided by the difference in temperature. These estimated coefficients are marked with a (#). Thermal coefficients in parentheses follows by r = . . . represent linear least-squares estimates of the velocity as a function of temperature. The r value is the correlation coefficient of the fit. (The nonlinear relationship between velocity and temperature also limits the range of accuracy for linear estimates of the thermal coefficient. See Section III.A.)

B. Ultrasonic Attenuation Coefficient Table

Table 2 reports values of attenuation coefficients (in decibels per centimeter) as a function of temperature (degrees Celsius) at various ultrasonic frequencies (in megahertz). For each biological material, any available physiological state or age information is included. The ultrasonic frequency of the measurement is indicated where reported. In many cases, attenuation coefficient information was available only in the form of graphs. Thus, attenuation coefficient values marked with an (*) were interpolated from graphs. The accuracy of the attenuation coefficient measurement, where available, is provided in parentheses following the coefficient, either in percent or as one standard deviation. The thermal coefficient (the rate of change of the attenuation coefficient with respect to change in temperature), where reported, follows (in decibels per centimeter per degree Celsius × 10³). For a large number of cases, the thermal coefficient was not reported and hence was estimated by the authors as the difference in attenuation coefficient divided by the difference in temperature. These estimated coefficients are marked with a (#). Thermal coefficients in parentheses followed by r = . . . represent linear least-squares estimates of the attenuation coefficient as a function of temperature. The r value is the correlation coefficient of the fit. (As with velocity, the attenuation coefficient is not purely linear in temperature; thus, a linear estimate of the thermal coefficient will be accurate only over a limited temperature range.)

The results of Dunn,[23] Dunn and Brady,[24,25] and Johnston et al.[26] were all based on the same experimental apparatus and thus represent the same experiment at different frequencies.

III. MOLECULAR LEVEL

The ultrasonic propagation properties of tissue are considered to be determined largely at the macromolecular level.[33] This idea is supported by studies conducted at least 30 years ago. For instance, Carstensen et al.[8] found that the ultrasonic attenuation and speed in blood are determined mostly by protein content, and that the ultrasonic attenuation coefficient is directly proportional to the protein concentration. Several years later it was shown that a small fraction of the attenuation in blood arose due to its cellular organization.[34] An early study on liver tissue showed that approximately two thirds of its attenuation occurred at the macromolecular level, with the remaining one third being attributed to microscopic structure.[35]

Later, the ultrasonic attenuation coefficient and mean backscatter amplitude were measured in various tissues as a function of time after excision up to 120 hr post-mortem.[36] During this time period, the ultrasonic attenuation coefficient did not significantly change while the mean backscatter amplitude decreased substantially. It was suggested that the backscatter signal is associated with the relatively large parenchymal structures, which are the first to be disintegrated, while the attenuation is associated with the macromolecular structure, which degrades more slowly, thus lending support to the hypothesis that ultrasonic absorption occurs at the macromolecular level in biological materials.

The three tissue constituent materials of water, protein, and fat account for most of the

Table 3
PERCENTAGE CONCENTRATION RANGES FOR THE THREE CONSTITUENT MATERIALS OF WATER, TOTAL PROTEIN, AND FAT FOR VARIOUS BIOLOGICAL MATERIALS. THOSE IN PARENTHESES WERE CALCULATED[43]

Biological material	Water	Total protein	Fat	Ref.
Brain	72—85	(6—11)	8.6	37—40
Cartilage	70—73	20—25		38,41,42
Cerebro-spinal fluid	99	0.015—0.040	0.00	37,43
Eye — aq-vit humor	99—99.9	0.01—1.0	0.004—0.007	37,38,42,44,45
Fat	10—35	3.2—17.0	50—86	39,40,46,47
Heart	63—79.2	15—19	3.6—21	38—40
Kidney	75.9—82.7	15.4—16.8	3.3—6.7	38—40
Liver	66.9—80.3	16.5—21.2	3.7—10,	38—40, 48
Milk — whole	87—88	3—4	3.5—5	40,43
Striated muscle	63—75.7	17.3—21.8	4.0—13.3	38—40
Plasma	90—95	5.4—8.0	0.9—2.0	8,37,43,46,49,50
Spleen	74.4—77.4	17.1—18.8	3.0—3.9	38—40
Testis	84.0—85.0	(9—11)	0.045	51,52
Tongue	61—74.3	13.7—18.5	5.3—23	40

tissue. Table 3 shows their ranges for some biological materials. Each of these will be briefly discussed because certain aspects of their temperature-dependent behavior are known and may thus contribute to our understanding of the temperature dependency of the ultrasonic propagation properties for biological tissues.

A. Water

Water is the most abundant tissue constituent, making up as much as 70 to 80% of many tissues. Its concentration is nonuniformly distributed throughout the body. Adipose tissue contains about 10% water, whereas blood contains about 83% water. The total body water is about 60% of body weight for young males, about 50% for young females, and about 76% for babies. Total body water tends to decrease with age. Lean body tissue contains about 72% water.[46-50] Thus, due to its abundance and variability in tissues, the role of water is explored.

The temperature dependence of the velocity of propagation of ultrasound in water has been studied many times with various empirical results. For example, Willard proposed:

$$c = 1557 - 0.0245(T - 74)^2 \qquad (1)$$

where c is in meters per second and T is in degrees Celsius over the range of 25 to 85°C.[53] (Other single component liquids [alcohols, hydrocarbons, ethers, etc.] show a linear temperature dependence over the temperature range of 20 to 60°C. Only water appears to have a parabolic temperature dependence.) This representation clearly suggests a peak velocity (1557 m/sec) and the temperature at which that velocity is achieved (74°C). Willard further suggested that for low concentrations of other materials (principally salts) mixed with water, the peak velocity and peak temperature vary linearly with concentration. (For example, adding Na_2SO_4 increases the peak velocity and decreases the temperature of the peak to 1680 m/sec and 63°C, respectively, at 1 *M* concentration.[54]) The effect of increasing saline concentration resulting in elevated velocities is seen clearly in Table 4.

Several other models for the velocity of propagation in water have been presented. At laboratory temperatures, for degassed water in the neighborhood of 19°C,

$$c = 1461 + 3.44(T - 19) - 0.0185(T - 19)^2 \qquad (2)$$

Table 4
VELOCITY OF PROPAGATION IN SEAWATER AT 1 ATM AS A FUNCTION OF SALINITY AND TEMPERATURE. VELOCITIES ARE IN m/sec[55]

Temp (°C)	Saline conc				
	0%	10%	20%	30%	40%
0	1402.39	1415.85	1429.17	1442.48	1455.84
5	1426.15	1438.99	1451.63	1464.31	1477.12
10	1447.24	1459.52	1471.57	1483.68	1495.94
15	1465.88	1477.64	1489.20	1500.79	1512.51
20	1482.28	1493.58	1504.70	1515.83	1527.05
25	1496.62	1507.51	1518.25	1528.97	1539.73
30	1509.06	1519.59	1529.98	1540.34	1550.69
35	1519.74	1529.96	1540.04	1550.07	1560.09
40	1528.80	1538.76	1548.54	1558.29	1568.05

where velocities and temperatures are measured in meters per second and degrees Celsius, respectively.[56] A 20°C change in water temperature will produce a velocity change comparable to the difference between the velocity of ultrasound in water and the velocity of ultrasound in striated muscle. Higher-order models (involving polynomials in T up to the fifth order) have been reported by Millero and Kubinski:[55]

$$\begin{aligned} c = 1402.385 &+ (5.03522) \times T \\ &- (58.3087 \times 10^{-3}) \times T^2 \\ &+ (345.300 \times 10^{-6}) \times T^3 \\ &- (1645.13 \times 10^{-9}) \times T^4 \\ &+ (3.9625 \times 10^{-9}) \times T^5 \end{aligned} \qquad (3)$$

and

$$\begin{aligned} c = 1402.38754 &+ (5.03711129) \times T \\ &- (5.80852166 \times 10^{-2}) \times T^2 \\ &+ (3.34198834 \times 10^{-4}) \times T^3 \\ &- (1.47800417 \times 10^{-6}) \times T^4 \\ &+ (3.14643091 \times 10^{-9}) \times T^5 \end{aligned} \qquad (4)$$

and by Slutsky:[57]

$$\begin{aligned} c = 1402.73 &+ (5.03358) \times T \\ &- (5.79506 \times 10^{-2}) \times T^2 \\ &+ (3.31636 \times 10^{-4}) \times T^3 \\ &- (1.45262 \times 10^{-6}) \times T^4 \\ &+ (3.0449 \times 10^{-9}) \times T^5 \end{aligned} \qquad (5)$$

where c is in meters per second and T is in degrees Celsius.

In each of the above cases a first-order approximation can be found to linearize the model in the region of a specific temperature. In particular,

$$c(T) = c(T_0) + (T - T_0) \times dc/dT \qquad (6)$$

Table 5
FREQUENCY-FREE ULTRASONIC ATTENUATION COEFFICIENT AS A FUNCTION OF TEMPERATURE IN WATER[58]

Temp (°C)	a/f² (sec²/cm)	Temp (°C)	a/f² (sec²/cm)
0	56.9 × 10⁻¹⁷	50	11.99
5	44.1	60	10.15
10	35.8	70	8.71
15	29.8	80	7.89
20	25.3	90	7.24
30	19.1	100	6.87
40	14.61		

where $c(T_0)$ is a reference velocity known for temperature T_0, and dc/dT is the thermal coefficient. This approximation is valid only as long as the higher-order terms are insignificant compared to the linear term. The model given by Johnson et al.[56] is nearly in this form, with dc/dT equal to 3.44 m/sec/°C around 19°C. The higher-order term $[0.185(T - 19)^2]$ remains less than 10% of the linear term over the range 1 to 37°C. In the vicinity of 37°C, the same model can be linearized to give dc/dT of 4.106 m/sec/°C, with a 10% validity range of 15 to 59°C. Similarly, around 37°C, the model given by Willard[53] can be linearized to give dc/dT of 1.813 with a 10% validity range of 30 to 44°C. Thus, whenever a linear thermal coefficient is used to model temperature dependency, care must be taken in recognizing the range of validity.

The ultrasonic absorption of water is considered to be equal to the attenuation, since water is an isotropic, homogeneous liquid. The ultrasonic loss in water is much less than that in soft tissues, although the ultrasonic speed is comparable. As such, tissues containing exceptionally large amounts of water exhibit a relatively low ultrasonic attenuation as compared to tissues with less water. The frequency dependency of the attenuation and absorption coefficients of tissue differ from water in that, for tissue the loss coefficients are roughly linearly proportional to frequency, whereas for water the attenuation coefficient is proportional to the square of the frequency. At 37°C, the frequency-free attenuation coefficient is

$$a/f^2 \ @\ 37^\circ\mathrm{C} = 15.7 \times 10^{-17}\ \mathrm{s^2/cm} \tag{7}$$

where a is the ultrasonic attenuation coefficient in nepers per centimeter and f is the ultrasonic frequency in hertz.[58] Table 5 shows how the frequency-free attenuation coefficient for water varies with temperature. The temperature dependency of the attenuation coefficient can be modeled as a linear relationship comparable to Equation 6 for velocity over a limited temperature range. The thermal coefficient for the attenuation coefficient varies from −0.62 to -0.26×10^{-17} sec²/cm/°C over the temperature range of 25 to 45°C. The temperature dependency of a/f^2 around 37°C, that is, $d(a/f^2)/dT$, is approximately -0.447×10^{-17} sec²/cm/°C. At an ultrasonic frequency of 1 MHz, the temperature dependency of the attenuation coefficient is $-0.447 \times 10^{-5}\ \mathrm{cm^{-1}/^\circ C}$, and at 5 MHz it is $-11.2 \times 10^{-5}\ \mathrm{cm^{-1}/^\circ C}$. A 3°C temperature increase from 37°C would result in a 15.8% decrease in the ultrasonic attenuation coefficient. As with velocity, increased salt concentration produces an increased attenuation.[54]

B. Protein

There are two distinct types of proteins: one provides structural features to the body and the other provides necessary metabolic functions. The structural protein, collagen, plays an important role in the acoustical properties of tissues for several reasons. One reason is that collagen, a high tensile strength insoluble fiber, is the most abundant protein in the human body, constituting from 25 to 33% of the total protein and therefore about 6% of the body weight.[43] A second reason is that there is evidence which shows that collagen exhibits different acoustic properties from those of the other common tissue constituents.[11,59,60] It is known, for example, that collagenous fibers exhibit a static elastic modulus (Young's modulus) approximately 1000 times greater than that of other tissues.[59] Since ultrasonic speed is proportional to the square root of the elastic modulus, this suggests that the ultrasonic speed would be greater for collagen than for other constituents. Direct measurements of ultrasonic speed in tendon threads show this to be the case.[60,61] The higher speed in collagen implies that collagen also has a higher characteristic acoustic impedance. This in turn implies that there will be an impedance mismatch between collagen and surrounding tissue, and that collagen is therefore responsible for much of the reflections and scattering that occur in tissues. This idea is supported by Fields and Dunn,[59] for instance, who have suggested that collagen is largely responsible for the echographic visualizability of soft tissue.[59]

Although collagen is the most prevalent protein, the nonstructural proteins must also be considered, since qualitative relationships have been shown to exist between ultrasonic propagation properties and the total protein concentration. For example, in an attempt to characterize tissues according to their ultrasonic attenuation, a number of tissues, including brain, liver, kidney, blood, and articular tissues, were examined and grouped according to their function, such as: (1) metabolic material transport, (2) fat and water storage, (3) protoplasmic activity and physiological function, (4) structural supporting, stress conveying, high in structural proteins, (5) framework protection, (6) gaseous exchange.[26,62] Upon examination of this classification, it was found that there is a relatively narrow range of attenuation values within each group and that the speed of sound increases and the attenuation approximately doubles from group to group in order of increasing attenuation. Furthermore, as one proceeds in this manner, tissues of ever-increasing structural protein content are encountered. This suggests that ultrasonic attenuation can be used to characterize tissues according to functional criteria and/or their protein concentration.

The propagation properties of aqueous solutions of hemoglobin have been measured more comprehensively than those of any other solution of biological significance. One of the earliest works in this area is that of Carstensen et al., who investigated the ultrasonic absorption and speed in blood, plasma, and solutions of serum albumin and hemoglobin, and concluded that the acoustical properties of blood are largely determined by the protein concentration.[8] A number of other investigators have measured the propagation properties of hemoglobin solutions at frequencies ranging from 35 kHz to 1.0 GHz, thoroughly covering a major portion of the frequency range of relaxation absorption.[14,63-68]

Experimentally, Lang et al. found $\log(a/f^2)$ for human breast cyst fluid to vary roughly linearly with temperature, with a value of −0.01 Np/°C over the range of 25 to 40°C.[69] (They also conclude that at 25°C, from 1.7 to 115 MHz, the attenuation is $0.0088 \times f^{1.42}\ \mathrm{cm^{-1}}$ for cyst liquid and $0.0066 \times f^{1.41}\ \mathrm{cm^{-1}}$ for plasma.)

Ultrasonic velocity and attenuation coefficients have been determined in aqueous suspensions of collagen over an extended frequency range at 10 and 20°C.[70] As with aqueous solutions of other biopolymers, the temperature dependences of the velocity and attenuation coefficient for aqueous collagen suspension are positive and negative, respectively. At 8.87 MHz and a collagen concentration of 0.5 g/100 cm³, around 15°C, the thermal coefficient for velocity, dc/dT, is 3.28 m/sec/°C. When the concentration is 14.2 g/100 cm³, the thermal coefficient is 0 (around 15°C), indicating a peak in velocity as a function of temperature.

Frequency-free attenuation coefficients for collagen suspensions are reported in Table 6. The thermal coefficient of the attenuation coefficient, $d(a/f^2)/dT$, varies from −20.2 to -0.53×10^{-18} sec²/cm, depending on frequency and concentration.

Table 6
SUMMARY OF COLLAGEN SUSPENSION FREQUENCY-FREE ATTENUATION COEFFICIENT DATA AS A FUNCTION OF COLLAGEN CONCENTRATION AND FREQUENCY[70]

		$a/f^2 \times 10^{17}$ (sec²/cm)		20°C	
Frequency (MHz)	10°C (c = 0.49%)	20°C (c = 0.52%)	10°C (c = 0.23%)	c = 0.34%	c = 0.17%
8.87	35.5	33.1	14.0	19.3	10.1
14.8	25.9	18.7	9.9	12.5	5.8
20.7	28.2	14.7	11.2	9.3	4.6
26.7	28.7	13.8	14.0	10.0	3.2
32.6	30.2	10.0	11.0	9.2	2.5
38.6	26.6	7.6	10.6	6.6	1.0
44.4	25.2	7.0	9.9	6.9	0.6
50.5	18.5	5.3	9.5	5.4	0.4
56.4	15.4	—	7.1	3.2	3.5

Table 7
VELOCITY OF PROPAGATION AS A FUNCTION OF TEMPERATURE FOR CASTOR OIL AND PHENYLATED SILICONE DOW-CORNING 710 OIL[72]

Temp (°C)	Castor oil (m/sec)	Dow-Corning 710 (m/sec)
0	1580	1446
10	1536	1409
20	1494	1378
30	1452	1349
40	1411	1321

C. Fat

Fat is an almost water-free tissue. Thus, total body water is largely (inversely) dependent upon the total amount of body fat. Babies generally have less fat than young males, and young males generally have less fat than young females. This is reflected in the average total body water percentages of 76, 60, and 50, respectively.[71]

At least 10% of the body weight is lipids (fat). The most abundant type of lipid is triglycerides (neutral fat) which is found throughout the body, especially in adipose tissue.[41]

Although there are various reports of temperature dependence for fat and various fatty tissues,[9,14-17,30] there are no known reports of the temperature-dependent ultrasonic propagation properties for lipids. However, the ultrasonic attenuation and velocity of two oils, castor oil and phenylated silicone Dow-Corning 710, are known at 1 MHz.[72] Both oils exhibit a negative thermal dependency for both velocity (Table 7) and attenuation coefficient (Table 8). The thermal coefficient, dc/dT, for castor oil remains fairly constant, around −4.2 m/sec/°C over the range of 5 to 35°C, while for Dow-Corning 710, the coefficient varies from −3.7 to −2.8 m/sec/°C. At 37°C, the thermal coefficient of velocity for castor oil is −4.07 m/sec/°C, and −2.63 m/sec/°C for Dow-Corning 710.

The thermal coefficient for the attenuation coefficient, dα/dT, varies from −10.0 to −2.0 cm⁻¹/°C for castor oil over the range 5 to 35°C, while for Dow-Corning 710, the coefficient varies from −6.5 to 1.6 cm⁻¹/°C over the range 15 to 35°C. At 37°C, the thermal coefficient of the attenuation coefficient for castor oil is −1.07 cm⁻¹/°C, and −0.76 cm⁻¹/°C for Dow-Corning 710. Fyke et al. also found a negative thermal dependency for ultrasonic attenuation for castor oil, mineral oil, and an oil-polymer mixture under study as a potential tissue phantom.[73]

Table 8
ULTRASONIC ATTENUATION COEFFICIENT AT 1 MHz AS A FUNCTION OF TEMPERATURE FOR CASTOR OIL AND PHENYLATED SILICONE DOW-CORNING 710 OIL[72]

Temp (°C)	Castor oil (cm⁻¹)	Dow-Corning 710 (cm⁻¹)
0	0.26	—
10	0.16	0.135
20	0.096	0.070
30	0.057	0.040
40	0.037	0.024

IV. TISSUES

As an overview of the available data, and as an index, Tables 9 and 10 are provided. Table 9 is a summary of the ultrasonic velocity of propagation data in Table 1, indicating the tissues that have been studied and the range of values that have been reported. Table 10 is a summary of the ultrasonic attenuation coefficient data in Table 2, indicating the tissues that have been studied and the range of values that have been reported. Casual examination reveals that by comparison to velocity, little data have been reported on the thermal dependency of the attenuation coefficient for many tissues. Less casual examination reveals that many tissues have not been reported at all (e.g., lung, pancreas, tendon).

Another area of limited information is the distinction between normal and abnormal tissue. Only one set of data for attenuation in liver tissue reports thermal dependencies for abnormal tissue. Several authors have suggested that thermal property differences in tissues could be exploited for diagnostic visualization.[56,74-81] However, the limited amount of results suggests that the thermal property distinctions between normal and abnormal tissue may be too subtle to be of great utility in differentiating the tissues using the systems that have been suggested.

V. DISCUSSION

Throughout both Tables 1 and 2, linear least-squares estimates have been used to describe the thermal dependency of velocity and attenuation coefficients. These estimates appear in parentheses, followed by the correlation coefficient of the least-squares estimation. Values of the correlation coefficient near −1.0 or 1.0 suggest a high degree of confidence that the thermal dependency is linear, and can be accurately modeled by the thermal coefficient. Values between −0.8 and 0.8 suggest that either too little data are provided to confidently estimate the dependence, or that the dependence is not linear. (A value of 0.0 suggests that the process under study is random with respect to the dependent variable, temperature.) The least-squares estimation and the range of values themselves suggest some interesting interpretations of the data.

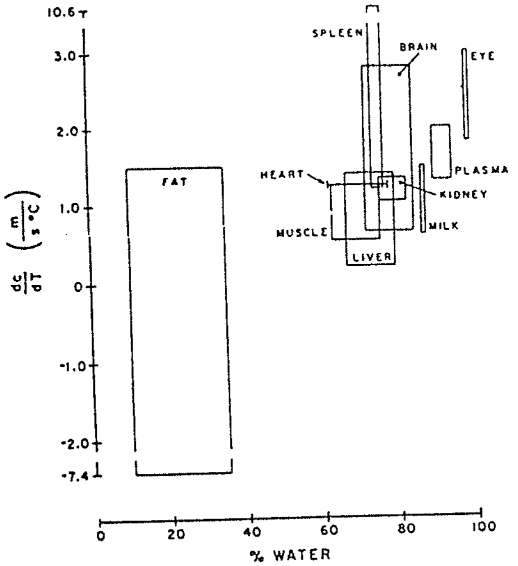

FIGURE 1. Thermal dependence of velocity with respect to water content.

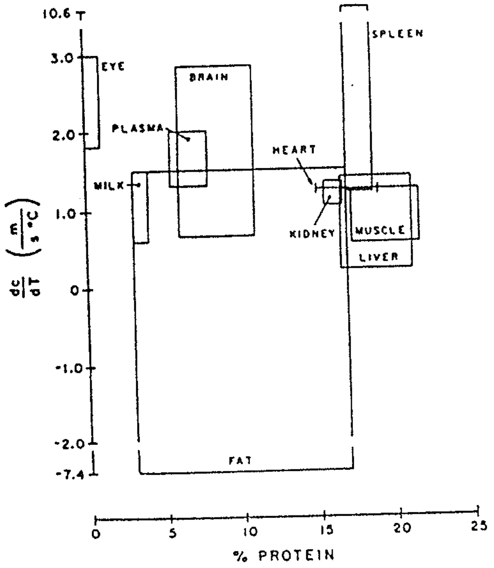

FIGURE 2. Thermal dependence of velocity with respect to protein content.

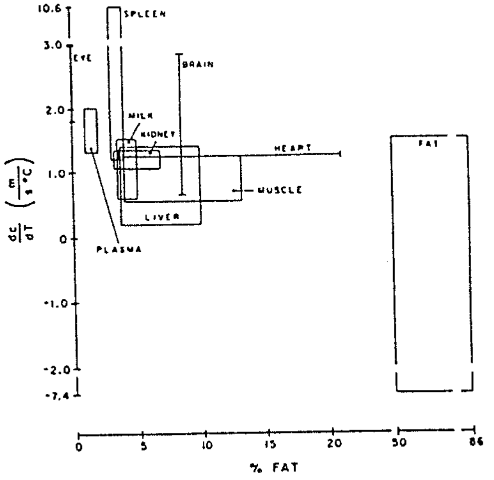

FIGURE 3. Thermal dependence of velocity with respect to fat content.

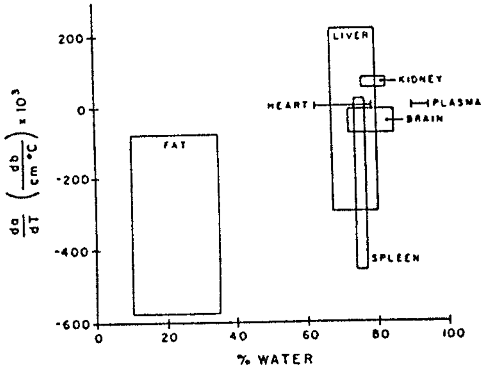

FIGURE 4. Thermal dependence of attenuation coefficient with respect to water content.

trend in the partial differences corresponds to a parabolic thermal dependence, which more nearly fits with models of relaxation processes. A parabolic thermal dependence provides for a temperature at which the thermal coefficient becomes 0, corresponding to the situation where the temperature has shifted the relaxation curve to the point where the peak of the curve occurs at the frequency under study.

As with velocity, three figures have been provided to present the relationship between the thermal dependence of the attenuation coefficient and the tissue constituents. Figure 4 presents da/dT with respect to percent water. Figure 5 presents da/dT with respect to percent protein. Figure 6 presents da/dT with respect to percent fat. Although Figure 5 does suggest a trend of increasing thermal dependence with increasing protein content, the principal

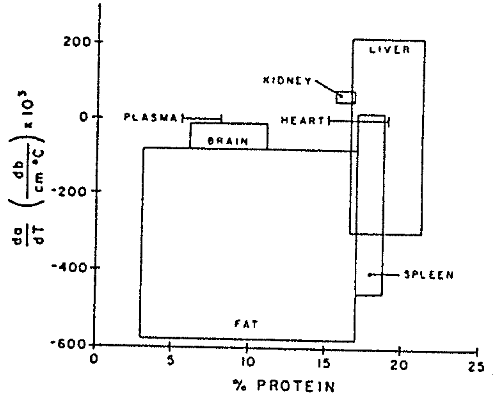

FIGURE 5. Thermal dependence of attenuation coefficient with respect to protein content.

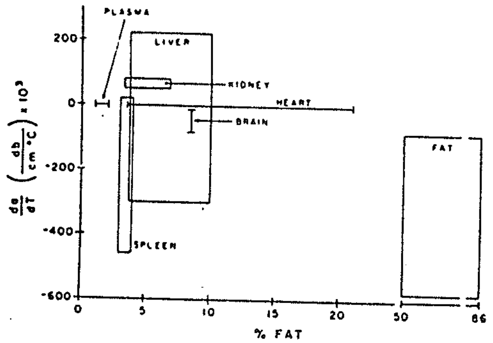

FIGURE 6. Thermal dependence of attenuation coefficient with respect to fat content.

conclusion drawn from these figures is that the range of values for the data are excessive. More measurements and comprehensive multitissue measurements are called for.

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