Physics in Medicine & Biology

NOTE

Acoustical properties of selected tissue phantom materials for ultrasound imaging

To cite this article: K Zell *et al* 2007 *Phys. Med. Biol.* **52** N475

IOP Publishing Physics in Medicine and Biology

Phys. Med. Biol. **52** (2007) N475–N484 doi:10.1088/0031-9155/52/20/N02

NOTE

Acoustical properties of selected tissue phantom materials for ultrasound imaging

K Zell[1], J I Sperl[2], M W Vogel[2], R Niessner[1] and C Haisch[1]

[1] Chair for Analytical Chemistry, Technische Universität München, Munich, Germany
[2] GE Global Research–Europe, Advanced Medical Applications Laboratory, Garching b. München, Germany

Received 24 May 2007, in final form 17 August 2007
Published 1 October 2007
Online at stacks.iop.org/PMB/52/N475

Abstract

This note summarizes the characterization of the acoustic properties of four materials intended for the development of tissue, and especially breast tissue, phantoms for the use in photoacoustic and ultrasound imaging. The materials are agar, silicone, polyvinyl alcohol gel (PVA) and polyacrylamide gel (PAA). The acoustical properties, i.e., the speed of sound, impedance and acoustic attenuation, are determined by transmission measurements of sound waves at room temperature under controlled conditions. Although the materials are tested for application such as photoacoustic phantoms, we focus here on the acoustic properties, while the optical properties will be discussed elsewhere. To obtain the acoustic attenuation in a frequency range from 4 MHz to 14 MHz, two ultrasound sources of 5 MHz and 10 MHz core frequencies are used. For preparation, each sample is cast into blocks of three different thicknesses. Agar, PVA and PAA show similar acoustic properties as water. Within silicone polymer, a significantly lower speed of sound and higher acoustical attenuation than in water and human tissue were found. All materials can be cast into arbitrary shapes and are suitable for tissue-mimicking phantoms. Due to its lower speed of sound, silicone is generally less suitable than the other presented materials.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Tissue-mimicking phantoms are an important tool for performance testing and optimization of medical ultrasound systems and photoacoustic devices as well as for medical training purposes. Photoacoustic imaging is a combination of optical excitation and acoustic detection (see, e.g., Gusev and Karabutov (1993), Haisch *et al* (2006), Karabutov *et al* (2000) and Niederhauser *et al* (2005) with citations therein). Hence, the ideal phantom material possesses acoustic and optic properties similar to those of human tissue. As a first step to a full

characterization, we focus in this note on the acoustical properties of the materials. The relevant parameters are the acoustic impedance and the speed of sound, and, like tissue, a low acoustical attenuation. A significant deviation of the impedance from real tissue leads to a reflection of the ultrasound wave at the phantom/transducer interface and thus to a lower signal output, while a differing speed of sound induces image blurring due to maladjusted acoustical beam forming.

Previous studies have shown that hydrogels can be efficiently used for phantom design (Spirou *et al* 2005, Viator and Prahl 1999) and as coupling media for ultrasound (Prokop *et al* 2003). These gels are hydrophilic, cross-linked polymers which are expanded in water. Most of them can be shaped into arbitrary solid structures. Due to their mechanical properties, they are attractive for biomedical applications. They have low acoustic attenuation, and the impedance and speed of sound are similar to biological tissue because they mainly consist of water. Application of hydrogel is described as a phantom for optics, acoustics and photoacoustics. The most common materials are polyvinyl alcohol gel (PVA) (Manohar *et al* 2004, Kharine *et al* 2003, Devi *et al* 2005), polyacrylamide gel (PAA) (Takegami *et al* 2004, Lafon *et al* 2005, Howard *et al* 2003), gelatine (Doyley *et al* 2001, Quan *et al* 1993) with different additives (Madsen *et al* 2006) and agar (Cubeddu *et al* 1996, 1997) including the influence of added substances on the acoustic properties (Madsen *et al* 1998, Rownd *et al* 1997). A material which is less frequently described in literature is silicone (Matre *et al* 2003).

Searching through the relevant literature reveals a general problem. Many publications, even as informative and comprehensive works as White and Wambersie (1998), present valuable information, but do not reveal all acoustical parameters for each material under investigation, or consider only a limited frequency range. Furthermore, different preparation methods as well as measuring procedures strongly influence the result, meaning, that literature values can hardly be compared.

This work presents the characterization of acoustic properties of agar, PVA, PAA and silicone, and the assessment of the results as possible tissue-mimicking materials. The objective was to establish long-term stable and easy-to-handle breast phantoms for optoacoustical measurements. As the source of the signal formation in optoacoustical imaging is an optical contrast and not the reflection of ultrasound waves, the acoustical backscattering of the materials was not examined in this study. To identify the most suitable material, acoustical properties of the different materials were compared under identical conditions. The experimental approach was the sound wave transmission measurement in a frequency range from 4 MHz to 14 MHz, where the speed of sound, impedance and acoustic attenuation were determined simultaneously for each material.

All materials investigated are transparent and can be mixed with absorbing and scattering material in order to achieve optical properties similar to the different types of tissues. In this note, we focus on the acoustical properties; optical features will be discussed elsewhere.

2. Materials and methods

2.1. Agar

The preparation of agar into any desired shape is mostly straightforward and fast. Handling and preparation are harmless. Stored under water at about 4 °C, it is stable for several weeks.

A 2% solution of Danish agar powder (Carl Roth GmbH & Co., Karlsruhe, Germany) in distilled water is heated to a temperature of 160 °C under continuous stirring until the solution becomes transparent and viscous. This solution is cast into the desired form, where it is cooled down at room temperature and takes a solid form.

2.2. Silicone

Silicone can easily be shaped into arbitrary 3D solids. It is stable for months and even years and, in contrast to agar, insensitive to rough handling. Like agar, it is non-toxic during preparation and application.

For the preparation of silicone plates, a two-compound silicone was used (Elastosil RT 601, Wacker-Chemie GmbH, Munich, Germany). Component A contains the platinum catalyst, component B (hardener) the cross-linker to form the silicone framework. The components are mixed in a 9:1 (A:B) ratio of mass. The curing time depends on temperature, i.e. the higher the temperature the shorter the curing time. Hence, it is advantageous to fill the silicone into a pre-cooled mould to avoid fast curing. Small air bubbles, which get mixed into the silicone polymer during preparation, need to be eliminated by applying slightly reduced pressure to the silicone until it is free of visible bubbles. This procedure takes about 1 h.

2.3. Polyvinyl alcohol gel

The preparation of PVA is somewhat time consuming due to the necessary dissolving of the granulate and a freezing cycle of 24 h. It can easily be formed and stored for several months, if kept under water close to the freezing point. If prepared with dimethylsulfoxide (DMSO, Carl Roth GmbH & Co., Karlsruhe, Germany), according to the method we applied, it becomes transparent, but DMSO is an irritating chemical agent, so care has to be taken during preparation.

PVA, with a 99.0–99.8 mol% degree of hydrolysis and an averaged molecular weight of ∼145 000 Da (Fluka, Buchs SG, Switzerland), was used to prepare an aqueous solution. The preparation was done following the instructions of 'method II' of the publication by Kharine *et al* (2003), using a mixture of water and DMSO to dissolve the PVA.

2.4. Polyacrylamide gel

PAA can be moulded into arbitrary forms, but it takes additional preparation steps to achieve a smooth and plain surface. The preparation of PAA requires precautions, as it is performed by polymerization of the monomer acrylamide, which is carcinogenic and neurotoxic. Polyacrylamide is suspected to depolymerize to acrylamide under environmental conditions, such as heat and UV light (UV: ultraviolet) and it is discussed that it always may contain a small amount of the monomer after production (Friedman 2003). In summary, great care has to be taken during preparation and handling of PAA.

A 10% PAA gel was prepared from a 40% solution of acrylamide:bisacrylamide (29:1, *Rotiphorese* Gel 40, Carl Roth GmbH & Co., Karlsruhe, Germany). To produce 10 ml of gel composition, 2.5 ml of the *Rotiphorese* Gel was mixed with 4.8 ml distilled water and 2.5 ml of a 1.5 M Tris/HCl buffer solution (pH 8.8). 4 μl N, N, N', N'-tetramethylethylendiamine (TEMED, 99% p.A. for electrophoresis, Carl Roth GmbH & Co., Karlsruhe, Germany) and 100 μl 10% ammonium peroxodisulfate (APS, Carl Roth GmbH & Co., Karlsruhe, Germany) were added to the mixture and stirred. This mixture was poured into a mould to cure at room temperature for about 45 min.

3. Experimental section

3.1. Acoustic velocity and attenuation coefficient

The insertion technique (Bamber 1997) is used to measure the acoustic properties of the different materials. This technique is a relative measurement method which employs water

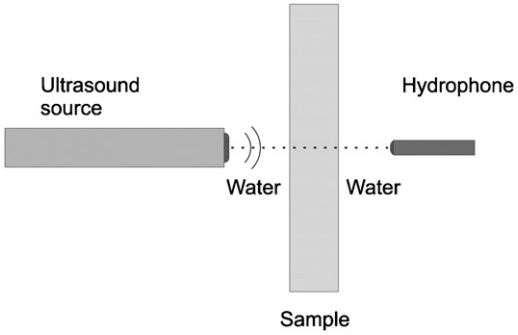

Figure 1. Experimental configuration for the speed of sound (c_S) and acoustic attenuation (α_S) measurements.

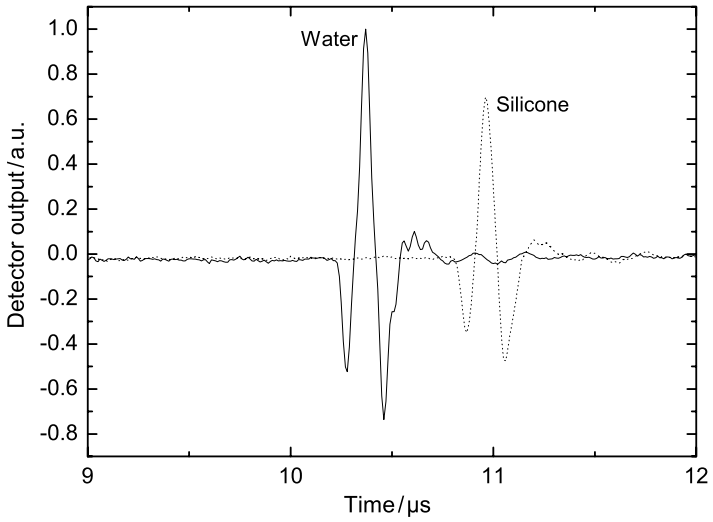

Figure 2. Typical ultrasound pulse trace in water without sample and behind a 2 mm silicone sample. The 5 MHz transducer is used as the source.

as the reference to study the transmission of longitudinal ultrasonic waves through solid media embedded in an aqueous environment. The experimental geometry is represented schematically in figure 1. Essentially, it consists of an ultrasound source and a hydrophone as a detector. Figure 2 depicts a typical signal of an ultrasound pulse transmitted through water without the sample, i.e. a reference signal, exemplarily correlated to a signal transmitted through silicone. Both signals were recorded at a frequency of 5 MHz.

The unknown sound velocities in the samples are deduced from the temporal shift (Δt) between the pulse transit times with and without samples. The speed of sound (c_S) can be calculated as

$$c_S = \left(\frac{1}{c_W} - \frac{\Delta t}{\Delta x} \right)^{-1} \tag{1}$$

knowing the sound velocity in water (c_W) and the thickness of the sample (Δx).

Table 1. Thicknesses of the silicone, agar, PVA and PAA samples.

	Δx_1 (mm)	Δx_2 (mm)	Δx_3 (mm)
Silicone	2.0	4.0	6.0
Agar 2%	5.5	9.5	16.1
PVA	6.1	12.1	18.4
PAA	2.8	5.6	12.1

Attenuation coefficients (α_S) are measured by applying the same experimental configuration and calculated according to the following equation:

$$\alpha_S = \alpha_W - \frac{1}{\Delta x}[\ln A_S - \ln A_W - 2\ln(1 - R)], \tag{2}$$

where A_i is the amplitude of the received ultrasound pulse with indices W and S representing water and the sample, respectively. Δx is the thickness of the sample and R is the acoustical reflection coefficient at the water/sample interface. For the transition of a sound wave from medium 1 to medium 2 with a change in the impedance $z_{i=1,2}$, R follows the following equation:

$$R = \frac{z_2 - z_1}{z_2 + z_1}. \tag{3}$$

Here the impedances $z_{i=1,2}$ are those of water and the sample. Due to its dependence on the impedances, R also depends on sound velocity (c) and density (ρ). The impedance is defined as

$$z = \rho_S c_S, \tag{4}$$

where ρ_S represents the density and c_S represents the sound velocity.

The acoustic properties of silicone, agar 2% solution, PVA and PAA were determined. All materials were cast into rectangular blocks (80 × 80 mm^2) of three different thicknesses each. These dimensions are summarized in table 1. The measurements were carried out in a water tank at room temperature (25 °C) with the samples placed 20 mm behind the source. The distance between the ultrasound source and detector was 74 mm. Two transducers (Subminiature Immersion Probe H 10 M and H 5 M, GE Inspection Technologies, Ahrensburg, Germany) with central frequencies of 5 MHz and 10 MHz and outer diameters of 5 mm were used as ultrasound sources. The detector was a PVDF needle hydrophone (MH28–5, FORCE Technology, Brondby, Denmark) (PVDF, polyvinylidenefluoride). A pulse generator (33250A, Agilent Technologies, Santa Clara, USA) excited the ultrasound pulses (five cycles) by a pulsed voltage of ±5 V. The sound waves detected by the hydrophone were monitored with a digital storage oscilloscope (54641D, Agilent Technologies). The recorded data were transferred to a personal computer via the GPIB interface.

The values for each material were determined by averaging 20 measurements per sample thickness and by calculating the mean of the results of the three thicknesses with regard to the unit thickness. The error results from the combination of the error from the averaging process, of the error of the mean over the three thicknesses and that of the thickness measurements.

3.2. Density and impedance

For determination of phantom material densities, the mass of three cubes for each material with a defined volume was measured. Knowing densities and acoustic velocities, acoustic impedances can be calculated according to (4).

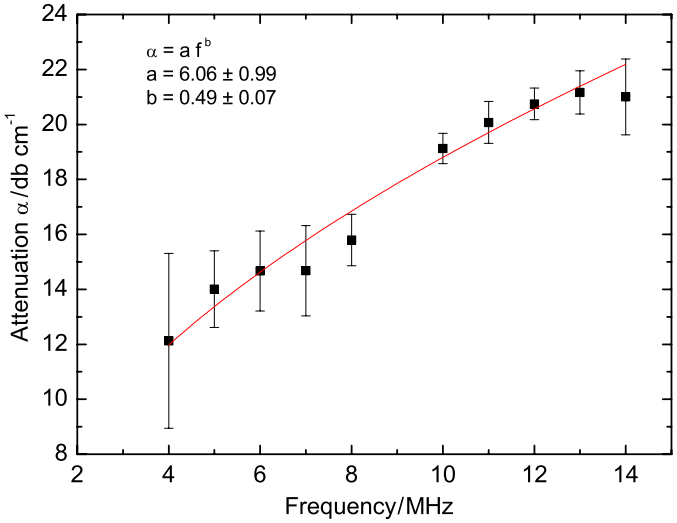

Figure 3. Acoustic attenuation coefficients of silicone as a function of frequency in a range from 4 MHz to 14 MHz.

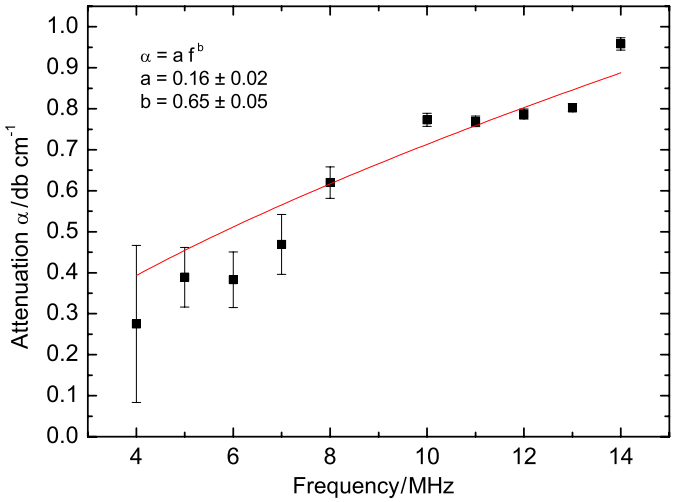

Figure 4. Acoustic attenuation coefficients of agar as a function of frequency in a range from 4 MHz to 14 MHz.

4. Results and discussion

The acoustic attenuations were determined using (2) and 8.686 as the conversion factor from cm^{-1} to dB cm^{-1} (Spirou *et al* 2005). To obtain the absolute value for each sample, the attenuation coefficient of water, $\alpha_W = 2.5 \times 10^{-4} f^2$ (Park *et al* 1996, Markham *et al* 1951), was used, where the attenuation coefficient is given in cm^{-1} and the frequency f in MHz. For water, the acoustic attenuation coefficient increases proportionally to the squared frequency. The measured data for the different samples are presented in figures 3–6. All data were fitted by the frequency power law $\alpha = af^b$. In the frequency range from 4 to 14 MHz, the

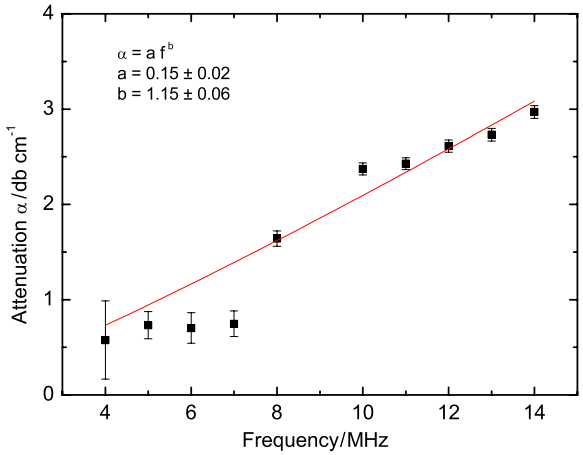

Figure 5. Acoustic attenuation coefficients of PAA as a function of frequency in a range from 4 MHz to 14 MHz.

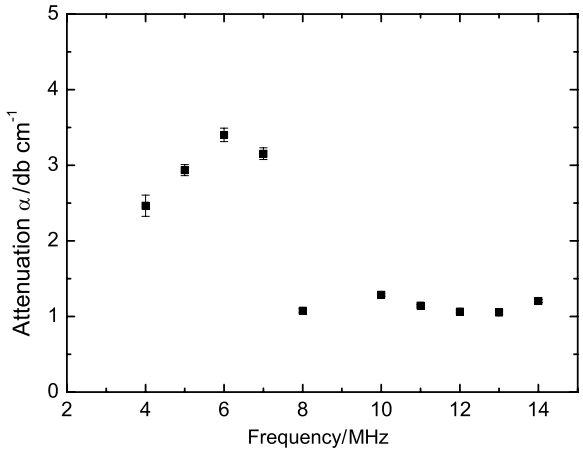

Figure 6. Acoustic attenuation coefficients of PVA as a function of frequency in a range from 4 MHz to 14 MHz.

frequency-dependent attenuation coefficients are $\alpha = 6.06\,f^{0.49}$ dB cm^{-1} MHz^{-1} for silicone, $\alpha = 0.15\,f^{1.15}$ dB cm^{-1} MHz^{-1} for PAA and $\alpha = 0.16\,f^{0.65}$ dB cm^{-1} MHz^{-1} for agar. For PVA, no reasonable fitting according to the frequency power law was possible over this frequency range. The errors were mainly caused by the fluctuations of the results of the measurements at three different thicknesses that were normalized to unit length. Another reason lies in the imprecision of the transducers around the centre frequency.

The acoustic velocities were calculated according to (1), assuming a sound velocity in water of 1482.3 m s^{-1} (Duck 1990). With knowledge of the speed of sound and the measured density, the impedance was calculated. Acoustic velocities and impedances show, within experimental uncertainties, a vastly linear and constant frequency dependence. In table 2, the results of the acoustic velocities, the impedances and densities as well as some results of our acoustic attenuation experiments are summarized and compared to literature data

Table 2. Sound velocities, densities, impedances, and acoustic attenuation coefficients of silicone, agar, PVA and PAA in comparison to the values of human tissues and literature values.

Material	Velocity, c_S (10^3 m s^{-1})	Density, ρ (10^3 kg m^{-3})	Impedance z (10^6 kg m^{-2} s^{-1})	Acoustic attenuation coefficient, α (dB cm^{-1})	Frequency (MHz)	References
Human breast tissue	1.43–1.57	0.99–1.06	1.42–1.66[b]	9.5 –12.6	7	Duck 1990
Human skin	1.54[a]	1.11–1.19	1.71–1.83[b]	9.2 ± 2.2	5	Duck 1990
Silicone	1.03 ± 0.06[c]	1.07 ± 0.03	1.10 ± 0.05[c]	14.0 ± 1.4	5	our measurement
				14.7 ± 1.6	7	
PVA	1.57 ± 0.02[c]	1.10 ± 0.05	1.74 ± 0.08[c]	2.9 ± 0.1	5	our measurement
				3.2 ± 0.1	7	
	1.58 ± 0.03	1.07 ± 0.02	1.71 ± 0.06	2.1	5	Kharine *et al* 2003
PAA (10%)	1.58 ± 0.05[c]	1.09 ± 0.09	1.73 ± 0.08[c]	0.7 ± 0.1	5	our measurement
				0.7 ± 0.1	7	
	–	1.02 ± 0.01	–	0.4 ± 0.1	5	Prokop *et al* 2003
Agar 2%	1.50 ± 0.03[c]	1.04 ± 0.11	1.57 ± 0.08[c]	0.4 ± 0.1	5	our measurement
				0.5 ± 0.1	7	
	1.54	–	–	–	–	Browne *et al* 2003

[a] Fetal, 7 mo.
[b] Calculated from columns 1 and 2.
[c] Measured at 7 MHz.

of phantom materials and human tissue. Of our results, only those measured in the frequency ranges similar to the cited literature data were selected.

Agar possesses acoustic velocity, impedance and density similar to human tissue. The acoustic attenuation coefficient at the measured frequency is lower than that of breast tissue and skin. Our results for the sound velocity are confirmed by the results of Browne *et al* (2003). The acoustic velocity and impedance of silicone are lower than those of human tissue, but has a density similar to human tissue. Its acoustical attenuation lies in between the values of breast tissue and that of skin in the frequency range investigated. The acoustic velocity, impedance and density we found for PVA are comparable to those of human tissue and similar to those found in literature (Kharine *et al* 2003). Only the acoustic attenuation determined in our experiments is lower than that of breast tissue. Our measured acoustical properties and a density value for PAA are similar to those of human breast tissue and skin. However, the acoustic attenuation of PAA is significantly too low to simulate these types of human tissues. These findings are in good agreement with the results of Prokop *et al* (2003), but the potential toxicity of PAA has to be kept in mind.

5. Summary

In summary, all presented materials are suitable for tissue-mimicking phantoms under different conditions. The actual choice of material mostly depends on the frequency range of the ultrasound equipment, on practical handling considerations and the question, which part of the human body is to be simulated. As mentioned above, we concentrated on the simulation of human breast tissue. Regarding primarily the acoustical properties, PVA fits best to this tissue, especially up to 10 MHz, but it has the clear disadvantage of a rather time-consuming preparation procedure. Generally, agar is well suited when quick and easy preparation, without the necessity for long-term stability, is desired. Its acoustical properties are satisfactory, but they are not suitable for repeated application over several days or weeks. Herein the major advantage of silicone is seen. Although its acoustical properties do not fit perfectly, it is a

good material for stable phantoms, particularly for training, due to its extreme stability and robustness. Due to its potential toxicity, primarily during preparation, PAA seems to be less appropriate for phantom production. As mentioned above, the acoustical and especially the optical properties of all materials can be adjusted (Madsen *et al* 1998) to the desired values. Optical properties of these materials will be discussed in a separate communication.

Acknowledgments

The authors would like to acknowledge Christian Schiller and John-Christian Eilert (Faculty of Biology, Ludwig-Maximilians-Universität, Munich, Germany) for the preparation of the PAA samples. The financial support of the Bayerische Staatsministerium für Wirtschaft, Verkehr und Technologie within the framework of the BayMed programme is gratefully acknowledged.

References

Bamber J C 1997 *Acoustical Characterisation of Biological Media Encyclopedia of Acoustics* 4th edn (New York: Wiley)

Browne J E, Ramnarine K V, Watson A J and Hoskins P R 2003 Assessment of the acoustic properties of common tissue-mimicking test phantoms *Ultrasound Med. Biol.* **29** 1053–60

Cubeddu R, Pifferi A, Taroni P, Torricelli A and Valentini G 1996 Time-resolved imaging on a realistic tissue phantom: μ_s' and μ_a images versus time-integrated images *Appl. Opt.* **35** 4533–40

Cubeddu R, Pifferi A, Taroni P, Torricelli A and Valentini G 1997 A solid tissue phantom for photon migration studies *Phys. Med. Biol.* **42** 1971–9

Devi C U, Vasu R M and Sood A K 2005 Design, fabrication, and characterization of a tissue-equivalent phantom for optical elastography *J. Biomed. Opt.* **10** 044020

Doyley M M, Bamber J C, Fuechsel F and Bush N L 2001 A freehand elastographic imaging approach for clinical breast imaging: system development and performance evaluation *Ultrasound Med. Biol.* **27** 1347–57

Duck F A 1990 *Physical Properties of Tissue: a Comprehensive Reference Book* (London: Academic)

Friedman M 2003 Chemistry, biochemistry, and safety of acrylamide. a review *J. Agric. Food Chem.* **51** 4504–26

Gusev V E and Karabutov A A 1993 *Laser Optoacoustics* (New York: AIP Press)

Haisch C, Hoffmann L and Niessner R 2006 Design and characterization of a highly directional photoacoustic sensor probe *Proc. SPIE* **6086** 60860E

Howard S, Yuen J, Wegner P and Zanelli C I 2003 Characterization and FEA simulation for a HIFU phantom material *IEEE Ultrasonic Symp.* pp 1270–3

Karabutov A A, Savateeva E V, Podymova N B and Oraevsky A A 2000 Backward mode detection of laser-induced wide-band ultrasonic transients with optoacoustic transducer *J. Appl. Phys.* **87** 2003–14

Kharine A, Manohar S, Seeton R, Kolkman Roy G M, Bolt Rene A, Steenbergen W and de Mul Frits F M 2003 Poly(vinyl alcohol) gels for use as tissue phantoms in photoacoustic mammography *Phys. Med. Biol.* **48** 357–70

Lafon C, Zderic V, Noble M L, Yuen J C, Kaczkowski P J, Sapozhnikov O A, Chavrier F, Crum L A and Vaezy S 2005 Gel phantom for use in high-intensity focused ultrasound dosimetry *Ultrasound Med. Biol.* **31** 1383–9

Madsen E L, Frank G R and Dong F 1998 Liquid or solid ultrasonically tissue-mimicking materials with very low scatter *Ultrasound Med. Biol.* **24** 535–42

Madsen E L, Hobson M A, Frank G R, Shi H, Jiang J, Hall T J, Varghese T, Doyley M M and Weaver J B 2006 Anthropomorphic breast phantoms for testing elastograhy systems *Ultrasound Med. Biol.* **32** 857–74

Manohar S, Kharine A, van Hespen J C G, Steenbergen W and van Leeuwen T G 2004 Photoacoustic mammography laboratory prototype: imaging of breast tissue phantoms *J. Biomed. Opt.* **9** 1172–81

Markham J J, Beyer R T and Lindsay R B 1951 Absorption of sound in fluids *Rev. Mod. Phys.* **23** 353–411

Matre K, Ahmed A B, Gregersen H, Heimdal A, Hausken T, Ødegaard S and Gilja O H 2003 *In vitro* evaluation of ultrasound Doppler strain rate imaging: modification for measurement in a slowly moving tissue phantom *Ultrasound Med. Biol.* **29** 1725–34

Niederhauser J J, Jaeger M, Lemor R, Weber P and Frenz M 2005 Combined ultrasound and optoacoustic system for real-time high-contrast vascular imaging in vivo *IEEE Trans. Med. Imaging* **24** 436–40

Park H K, Kim D, Grigoropoulos C P and Tam A C 1996 Pressure generation and measurement in the rapid vaporization of water on a pulsed-laser-heated surface *J. Appl. Phys.* **80** 4072–81

Prokop A F, Vaezy S, Noble M L, Kaczkowski P J, Martin R W and Crum L A 2003 Polyacrylamide gel as an acoustic coupling medium for focused ultrasound therapy *Ultrasound Med. Biol.* **29** 1351–8

Quan K M, Christison G B, MacKenzie H A and Hodgson P 1993 Glucose determination by a pulsed photoacoustic technique: an experimental study using a gelatin-based tissue phantom *Phys. Med. Biol.* **38** 1911–22

Rownd J J, Madsen E L, Zagzebski J A, Frank G R and Dong F 1997 Phantoms and automated system for testing the resolution of ultrasound scanners *Ultrasound Med. Biol.* **23** 245–60

Spirou G M, Oraevsky A A, Vitkin I A and Whelan W M 2005 Optical and acoustic properties at 1064 nm of polyvinyl chloride-plastisol for use as a tissue phantom in biomedical optoacoustics *Phys. Med. Biol.* **50** N141–53

Takegami K, Kaneko Y, Watanabe T, Maruyama T, Matsumoto Y and Nagawa H 2004 Polyacrylamide gel containing egg white as new model for irradiation experiments using focused ultrasound *Ultrasound Med. Biol.* **30** 1419–22

Viator J A and Prahl S A 1999 Photoacoustic imaging of gelatin phantoms using matched field processing *Proc. SPIE* **3601** 276–83

White D R and Wambersie A 1998 *Tissue Substitutes, Phantoms and Computational Modelling in Medical Ultrasound* (Bethesda, MD: ICRU)