A Short Study Report For Phantom Investigation

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In order to make a brain phantom for ultrasound imaging, certain materials and construction method need to be investigated. In this report, the materials used for this project are broken into two parts: one for the inner part of the brain, the other for the skull.

I. The inner part of the brain:

1. Polyvinyl Alcohol Phantoms (Polyvinyl alcohol gels)
   Polyvinyl alcohol cryogel (PVA-C) is a typical tissue-mimicking material for ultrasound imaging. It is formed from PVA solution undergoing some freeze-thaw (F/T) cycles. As the optical and mechanical properties change with the number of F/T cycle, certain requirements, like the scattering coefficient and absorption coefficient, for the phantom can be achieved. This phantom can be used in a permanent way under humidity-controlled conditions. PVA can be obtained from Sigma-Aldrich (catalog number 36 314-6) [5], Acros organics (Geel, Belgium) [2] or Airvol Grade 165 PVA powder (Air Products and Chemicals, Inc; Allentown, PA) [6].
   Detailed construction process is discussed in [2]. The brief idea is shown below:
   1) 5% or 8% by weight PVA are dissolved in distilled water. And this solution is heated for about 7 hours at the temperature of 93 to 95 degree Celsius.
   2) The PVA solution is cooled to -25 to -20 degree Celsius for about 12 hours. Then, the solution will warm back to room temperature in a continuous way for another 12 hours. If needed, this F/T cycle can be repeated for several times. Without the addition of dimethyl sufoxide (DMSO), the scattering coefficient will increase with each cycle and the phantom will be stiffer, too.
   3) Brain Mold is prepared using Colin27 data set.
   4) Approximating the live Brain Texture. (Useful data from [2]: 6% PVA solution at 1 FTC is similar to palpating the surface of a live brain and 4% PVA at 3FTC as being similar to palpating a low-grade gliomas.)
   5) Implants for registration and image guidance are included.

2. Ref. [3] provides an easily made, low-cost, tissue-like material for ultrasound phantom.
   The ingredients are for this material is as followed: 250mL boiling water, 20g of unflavored gelatin (3 packets of Know brand gelatin), and 10g of sugar-free psyllium hydrophilic mucilloid fiber (brand name: sugar-free Metamucil).
   The construction process is easy: poured the mixture into the container and cooled until firm. It takes about 1 to 2 hours to congeal in a refrigerator at 6 degree Celsius. “cysts” or masses can also be created in a simple way.
   The second choice can provide a fast and low cost phantom. However, the optical, the acoustic and the mechanical properties need to be determined. Otherwise, we cannot guarantee the phantom do not affect the experiment results.

3. To learn whether the phantom we will build is suitable, certain properties should be compared with the real brain. Also, the data will play as a guide for the phantom construction. In this report, certain properties, such as absorption coefficients, the scattering coefficients and the anisotropy factors, are studied and concluded from some previous researches.

   As the brain shunt surgeries are performed on children at a high percentage, the data from children age of 3 and age of 8 are listed here respectively from [4]. This measurement is done in vivo.

Table 1. Optical Properties of Normal and Malignant Human Brain Tissue, Case 1

Type of Tissue	Wavelength (nm)	Probe Measurements γ	Probe Measurements μ_s' (mm^{-1})	Probe Measurements μ_a (mm^{-1})	FDPM[a] μ_s' (mm^{-1})	FDPM[a] μ_a (mm^{-1})
Cortex (frontal lobe)	674	1.9 ± 0.2	1.00 ± 0.05	<0.02 ± 0.01	1.12	0.0173
	811	1.9 ± 0.2	0.91 ± 0.05	<0.01 ± 0.01	0.74	0.0182
	849	1.9 ± 0.2	0.92 ± 0.05	<0.01 ± 0.01	0.74	0.0185
	956	1.9 ± 0.2	0.89 ± 0.05	0.015 ± 0.01	0.80	0.0206
Cortex (temporal lobe)	674	1.9 ± 0.2	1.00 ± 0.05	0.02 ± 0.01	0.99	0.0179
	811	1.9 ± 0.2	0.82 ± 0.05	0.02 ± 0.01	0.48	0.0190
	849	1.9 ± 0.2	0.82 ± 0.05	<0.01 ± 0.01	0.45	0.0179
	956	1.9 ± 0.2	0.82 ± 0.05	0.025 ± 0.01	0.42	0.0218
Astrocytoma of optic nerve	674	1.7 ± 0.2	1.25 ± 0.10	0.14 ± 0.03	0.92	0.0165
	811	1.7 ± 0.2	0.95 ± 0.10	0.12 ± 0.03	0.55	0.0190
	849	1.7 ± 0.2	0.76 ± 0.10	0.09 ± 0.03	0.59	0.0191
	956	1.7 ± 0.2	0.73 ± 0.10	0.15 ± 0.03	0.58	0.0323
Normal optic nerve	674	1.7 ± 0.2	1.75 ± 0.20	0.06 ± 0.03	N/A	N/A
	811	1.7 ± 0.2	N/A	N/A	N/A	N/A
	849	1.7 ± 0.2	1.60 ± 0.20	0.08 ± 0.03	N/A	N/A
	956	1.7 ± 0.2	1.52 ± 0.20	0.07 ± 0.03	N/A	N/A

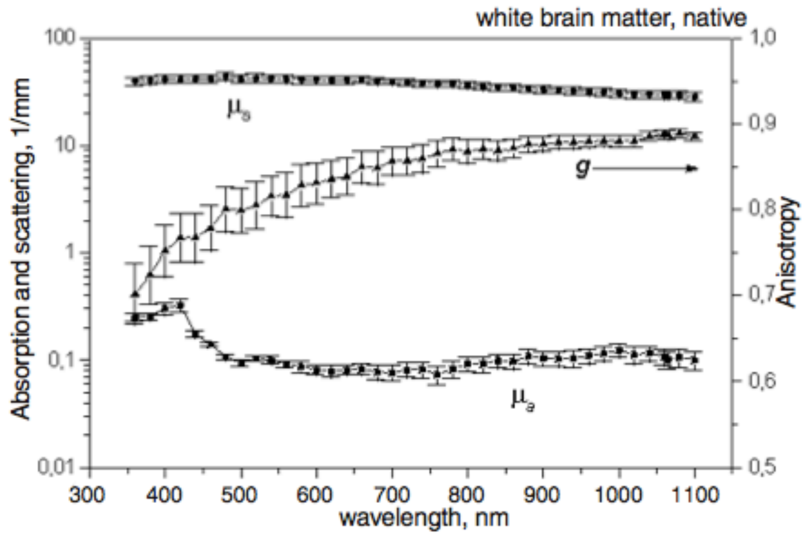
[a]The uncertainty of the FDPM values, given by the fitting procedure (see Refs. 2 and 3), is typically 2%.

Table 2. Optical Properties of Normal and Malignant Human Brain Tissue, Case 2

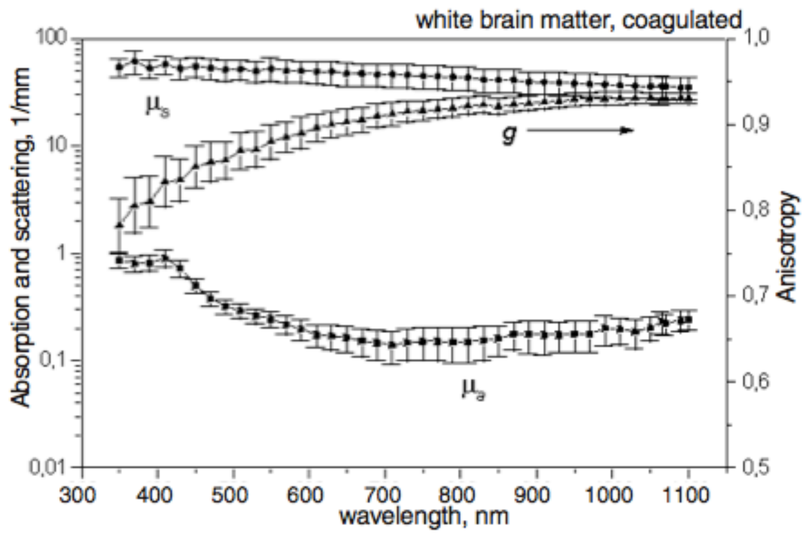
Type of Tissues	Wavelength (nm)	Probe Measurements γ	Probe Measurements μ_s' (mm^{-1})	Probe Measurements μ_a (mm^{-1})	FDPM* μ_s' (mm^{-1})	FDPM* μ_a (mm^{-1})
Skull	674	1.9 ± 0.2	0.9 ± 0.1	0.05 ± 0.02	1.19	0.0208
	849	1.9 ± 0.2	0.9 ± 0.1	0.05 ± 0.02	0.91	0.0215
	956	1.9 ± 0.2	0.85 ± 0.1	0.05 ± 0.02	0.77	0.0355
Cerebellar white matter	674	1.9 ± 0.2	1.35 ± 0.1	0.25 ± 0.05	1.34	0.0165
	849	1.9 ± 0.2	0.85 ± 0.1	0.095 ± 0.02	0.98	0.0132
	956	1.9 ± 0.2	0.78 ± 0.1	0.090 ± 0.02	0.84	0.0299
Medulloblastoma	674	1.9 ± 0.2	1.40 ± 0.1	0.26 ± 0.05	1.05	0.0120
	849	1.9 ± 0.2	1.07 ± 0.1	0.10 ± 0.02	0.66	0.0079
	956	1.9 ± 0.2	0.4 ± 0.1	0.075 ± 0.02	0.54	0.0239
Cerebellar white matter with scar tissues	674	2.2 ± 0.2	0.65 ± 0.05	<0.02	N/A	N/A
	849	2.2 ± 0.2	0.80 ± 0.05	<0.02	N/A	N/A
	956	2.2 ± 0.2	0.65 ± 0.05	<0.02	N/A	N/A

[a]The uncertainty of the FDPM values, given by the fitting procedure (see Refs. 2 and 3), is typically 2.5%.

   In [6], the optical properties of selected native and coagulated human brain structures were determined in vitro. The method and the sample are not specified here. But the figures are pasted below.

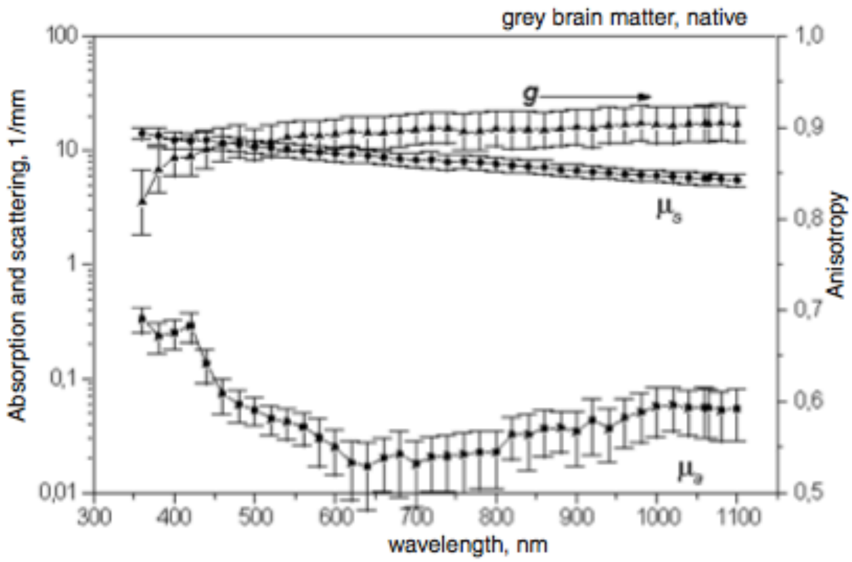


(a)



(b)

Figure 2. Optical properties of human white brain matter. Average of seven samples. Squares: absorption coefficient, circles: scattering coefficient, triangles: anisotropy factors and bars: standard errors. (a) Native samples and (b) coagulated samples.



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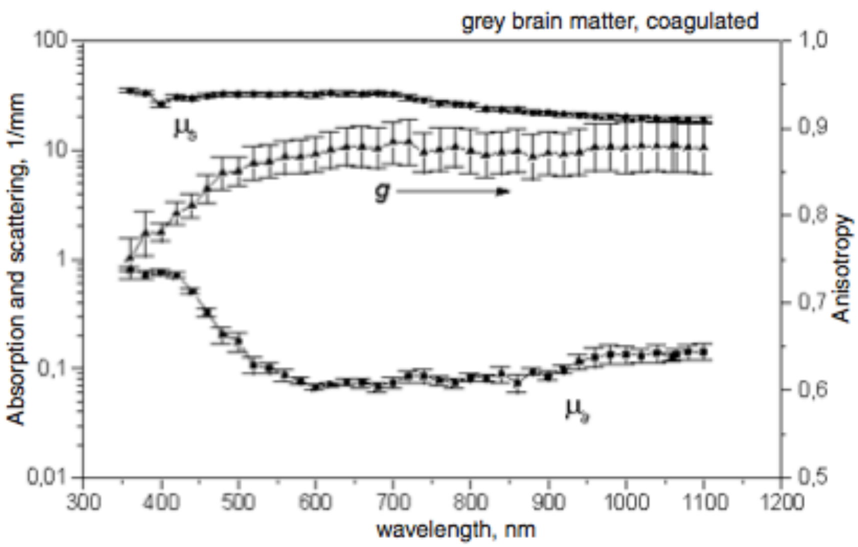
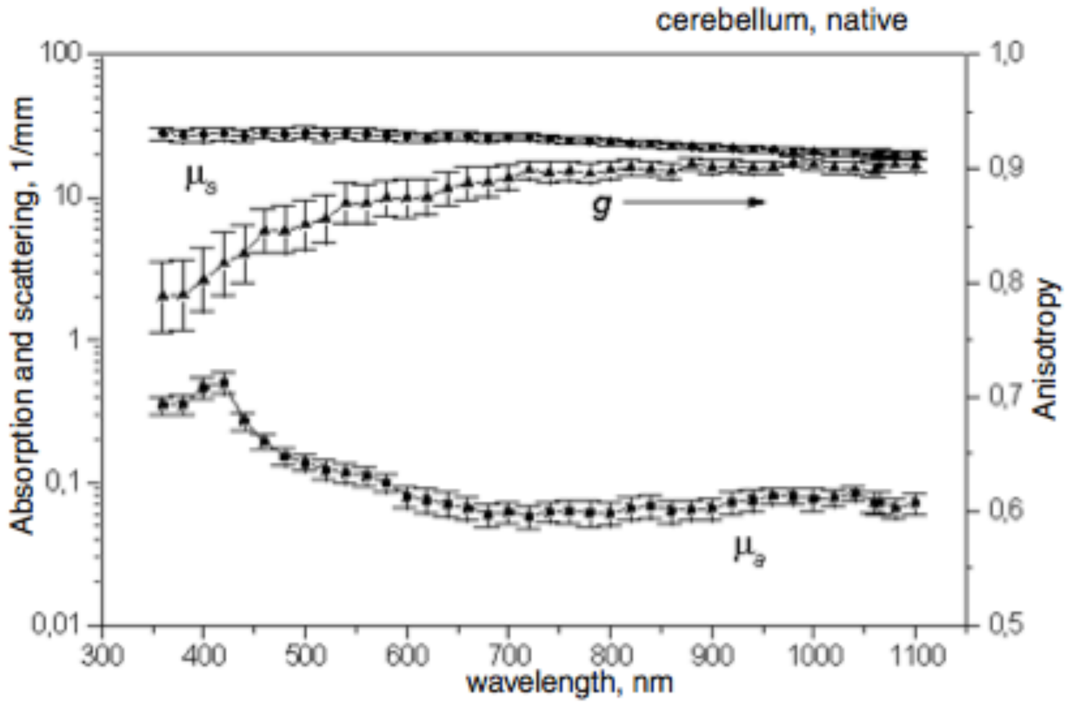
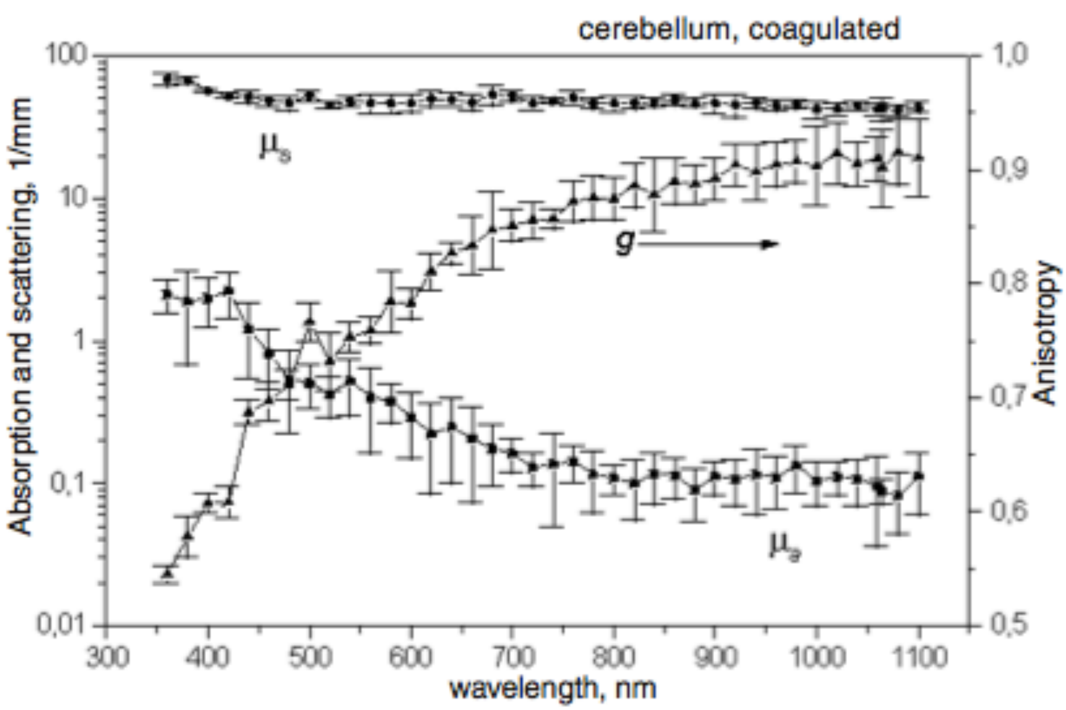


(b)

Figure 3. Optical properties of human grey brain matter. Average of seven samples. Squares: absorption coefficient, circles: scattering coefficient, triangles: anisotropy factors and bars: standard errors. (a) Native samples and (b) coagulated samples.

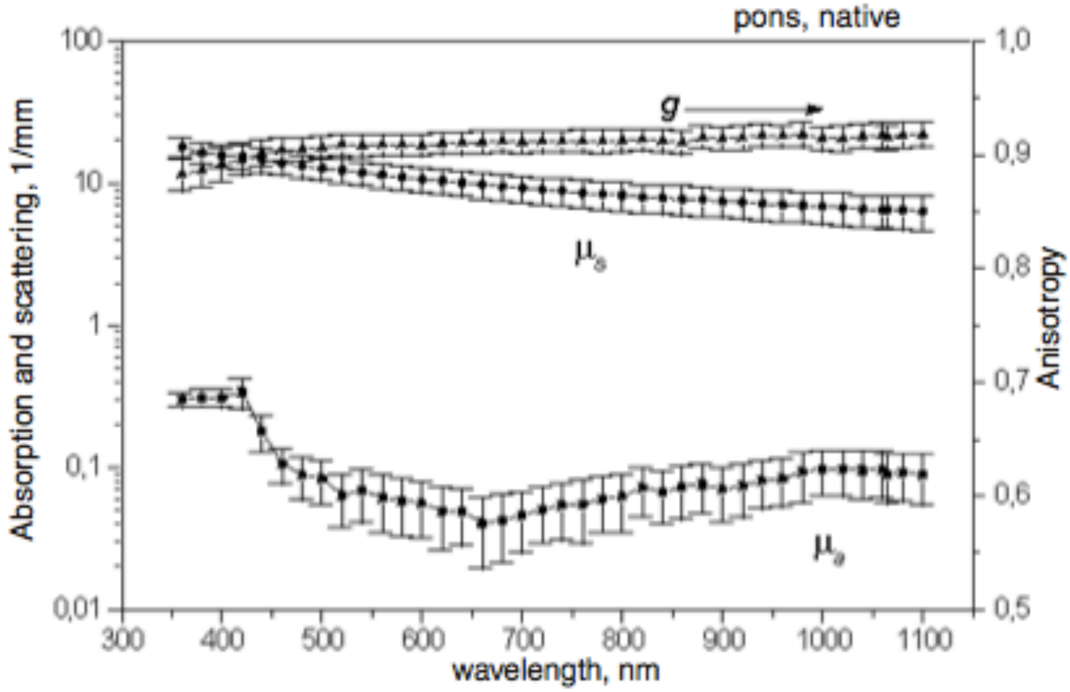


(a)



(b)

Figure 4. Optical properties of human cerebellum. Average of seven samples. Squares: absorption coefficient, circles: scattering coefficient, triangles: anisotropy factors and bars: standard errors. (a) Native samples and (b) coagulated samples.



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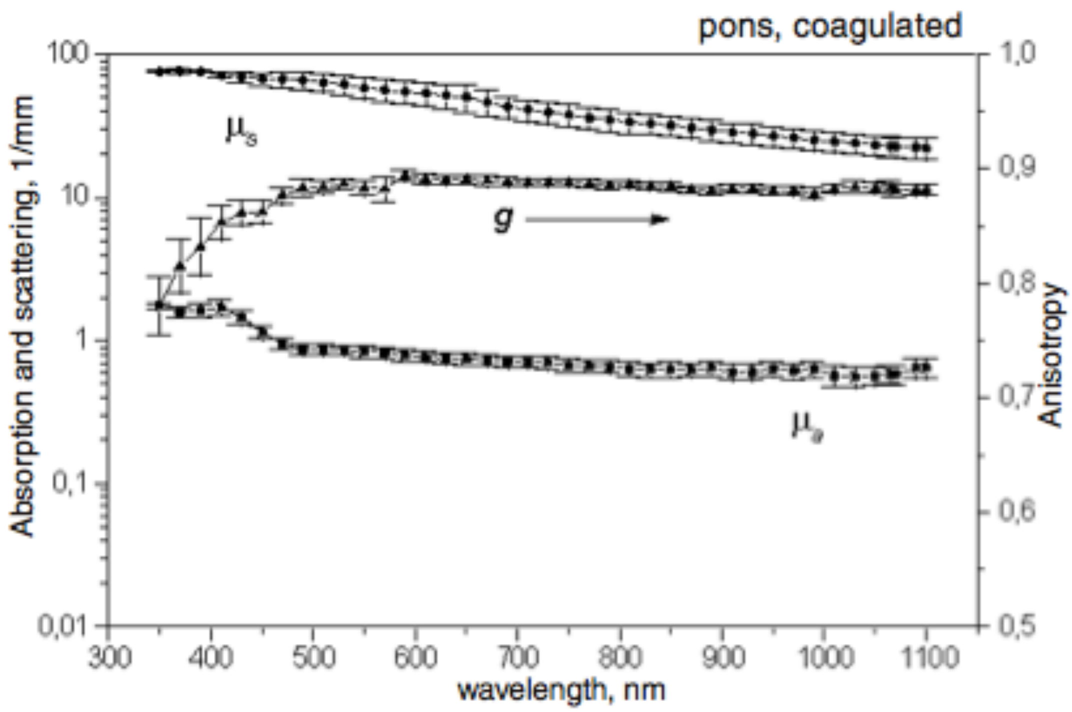
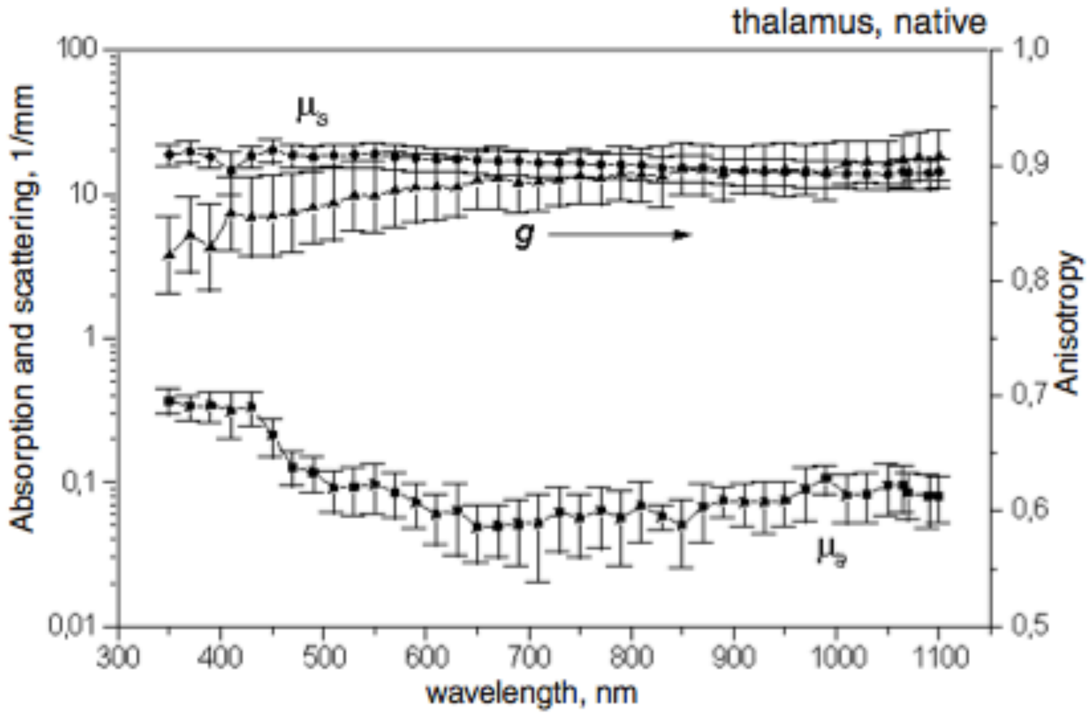
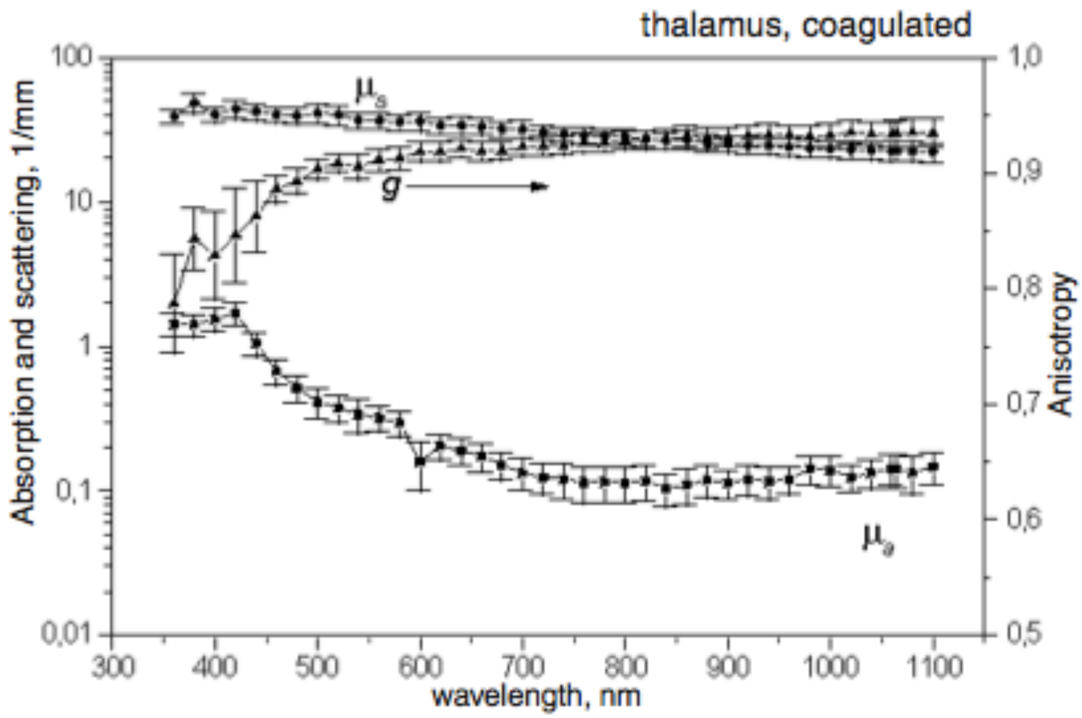


(b)

Figure 5. Optical properties of human pons. Average of seven samples. Squares: absorption coefficient, circles: scattering coefficient, triangles: anisotropy factors and bars: standard errors. (a) Native samples and (b) coagulated samples.



(a)



(b)

Figure 6. Optical properties of human thalamus. Average of seven samples. Squares: absorption coefficient, circles: scattering coefficient, triangles: anisotropy factors and bars: standard errors. (a) Native samples and (b) coagulated samples.

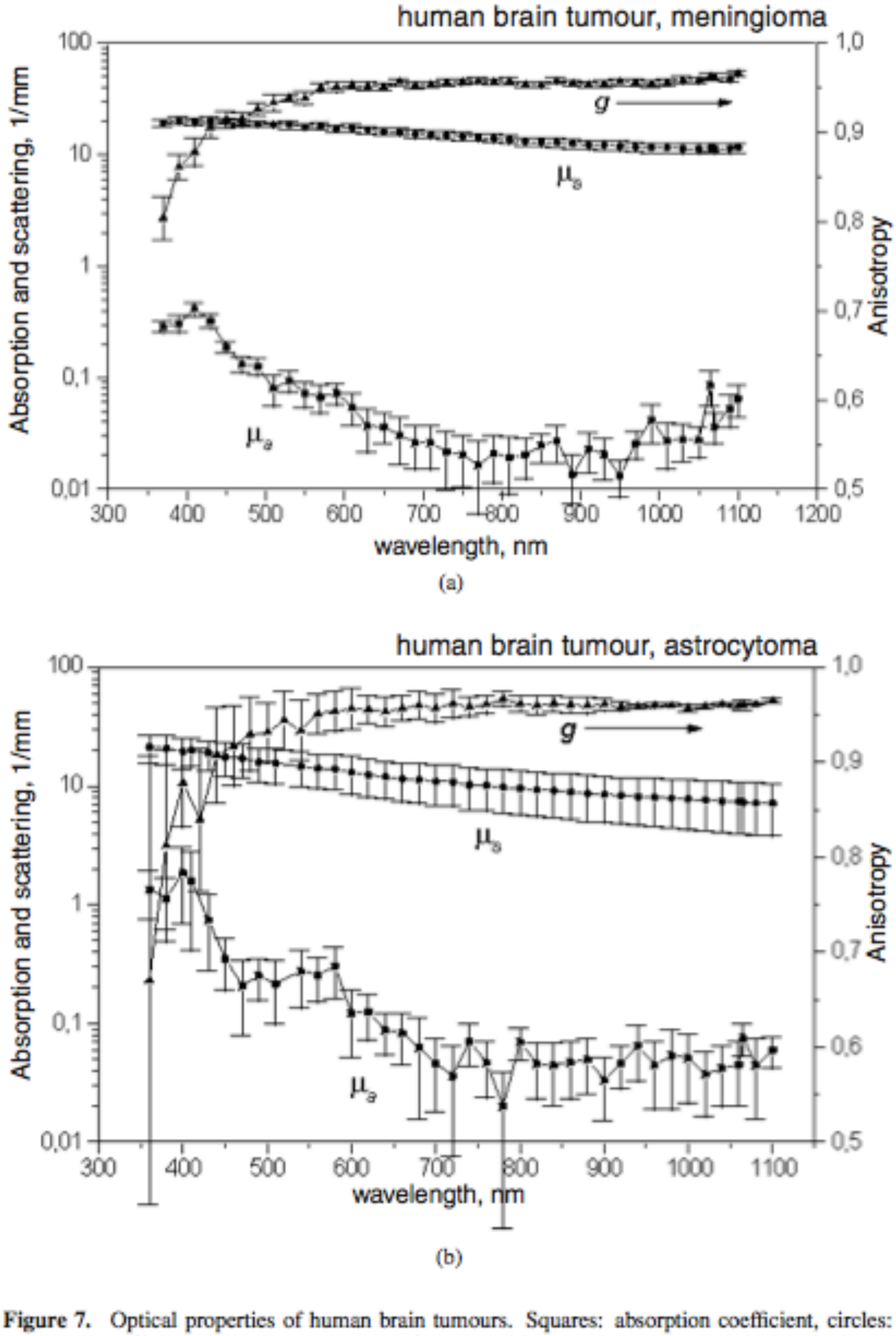


Figure 7. Optical properties of human brain tumours. Squares: absorption coefficient, circles: scattering coefficient, triangles: anisotropy factors and bars: standard errors. (a) Meningioma. Average of six samples. (b) Astrocytoma. Average of four samples.

White brain and grey brain properties with specific values from [6] are also listed here.

Table 1. Optical properties of native human brain tissues, obtained in this work (∗) and known from the literature.

Biotissue	λ (nm)	μ_a (mm^{-1})	μ_s (mm^{-1})	g	μ_s' (mm^{-1})	δ_{eff} (mm)	Reference
White brain matter	456	0.81	92.3	0.92	7.384	0.22	Gottschalk (1992)
	450	0.14	42.0	0.78	9.24	0.5	∗
	514	0.5	104.5	0.93	7.315	0.29	Gottschalk (1992)
	510	0.1	42.6	0.81	8.094	0.64	∗
	630	0.15	38.6	0.86	5.404	0.63	Gottschalk (1992)
	630	0.08	40.9	0.84	6.544	0.79	∗
	675	0.07	43.6	0.87	5.668	0.83	Gottschalk (1992)
	670	0.07	40.1	0.85	6.015	0.83	∗
	850	0.08	14	0.95	0.7	2.3	Roggan *et al* (1994)
	850	0.1	34.2	0.88	4.1	0.9	∗
	1064	0.16	51.3	0.95	2.565	0.88	Gottschalk (1992)
	1064	0.04	11	0.95	0.55	3.76	Roggan *et al* (1994)
	1064	0.1	29.6	0.89	3.256	1.0	∗
Grey brain matter	456	0.9	68.6	0.95	3.43	0.29	Gottschalk (1992)
	450	0.07	11.7	0.88	1.404	1.84	∗
	514	1.17	57.8	0.97	1.734	0.31	Gottschalk (1992)
	510	0.04	10.6	0.88	1.272	2.52	∗
	630	0.14	47.3	0.93	3.311	0.83	Gottschalk (1992)
	630	0.02	9.0	0.89	0.99	4.06	∗
	675	0.06	36.4	0.91	3.276	1.29	Gottschalk (1992)
	670	0.02	8.4	0.9	0.84	4.4	∗
	1064	0.19	26.7	0.96	1.07	1.18	Gottschalk (1992)
	1064	0.05	5.7	0.9	0.57	3.28	∗

Table 2. Optical properties of coagulated human brain tissues, obtained in this work (∗) and known from the literature.

Biotissue	λ (nm)	μ_a (mm^{-1})	μ_s (mm^{-1})	g	μ_s' (mm^{-1})	δ_{eff} (mm)	Reference
White brain matter	850	0.09	17	0.94	1.02	1.83	Roggan *et al* (1994)
	850	0.09	30	0.88	3.6	1.01	∗
	1064	0.05	13	0.93	0.91	2.6	Roggan *et al* (1994)
	1064	0.1	27	0.89	2.97	1.06	∗

As mentioned in this paper, optical properties determined in vitro can provide information adequate for in vivo use. Thus, we can use this data as a reference to find whether the phantom is suitable.

As I preferred to use PAV-C to build the phantom not only because it can last very long time which is enough for this project but also the good properties for US, certain properties about PAV-C are studied from [7]. This would be useful if we finally decide to use this method. The experiment results are listed below:

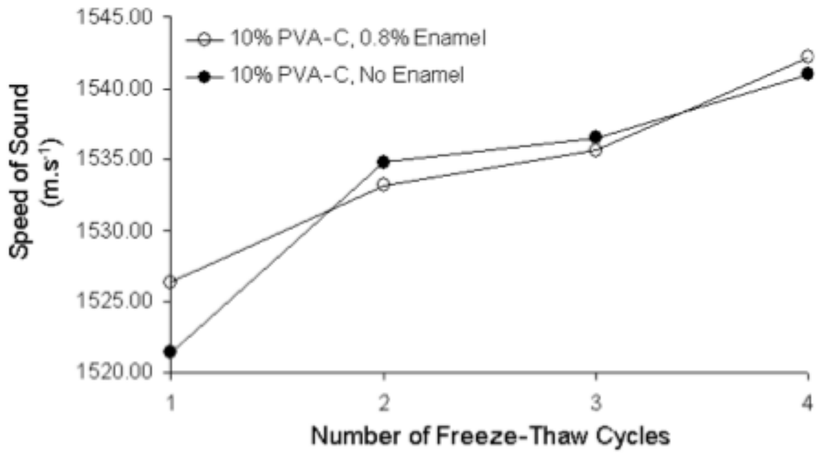


Figure 5. The speed of sound in 10% PVA-C, with and without 0.8% enamel paint added, as it changes with the number of freeze–thaw cycles.

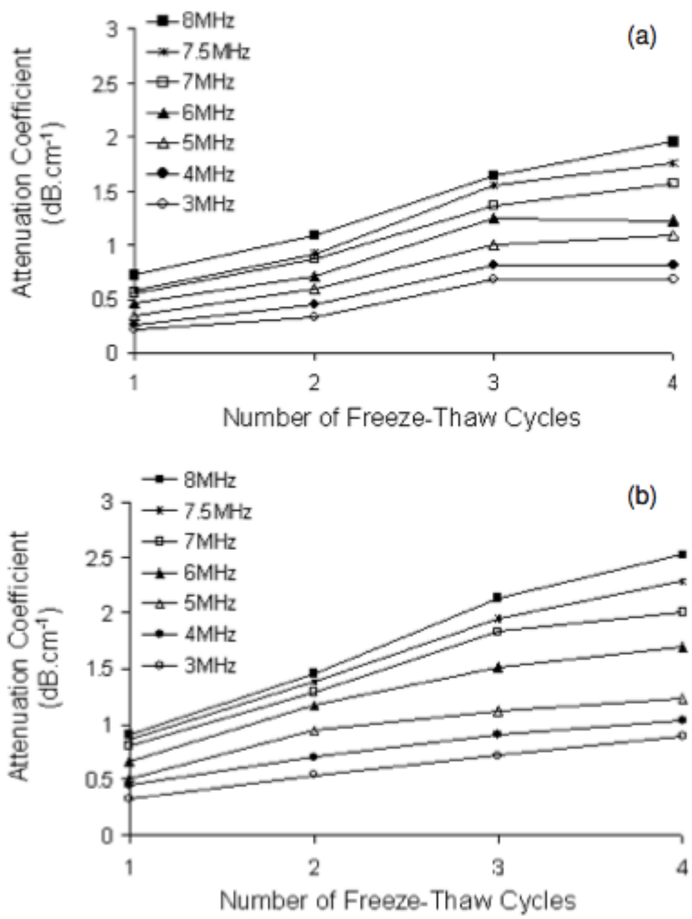


Figure 6. The attenuation coefficients for 10% PVA-C, (a) with and (b) without 0.8% enamel paint. The coefficients are quoted in dB cm^{-1}, for each frequency, for clarity.

According to the results of figure 5 in [7], samples with four times F/T cycles have the closest speed of sound values with the clinical ultrasound scanners (1540 m/s). And from figure 6 (a) in [7], the frequency-independent attenuation coefficients were significantly lower than human tissue, which plays the most negative factor in US imaging. However, this negative factor can be greatly improved by adding enamel into the PAV-C solution.

II. The skull part of the brain phantom:

This project is to use the external probe to do the ultrasound imaging. Its main significance is to use eliminate or counteract the effects from the skull. Thus, the skull of the brain phantom plays an important role in this project. Its properties must meet the real brain skull at a very high accuracy. Of course the best solution is to use the real brain skull. But in this stage, we cannot guarantee the availability. A study for the skull is made here.

The question here is it's hard to model the complex structure of the brain, and three-dimensional printing (3DP) provides a good solution. [8] proposed a good method to do this.

A typical procedure to produce the model for medical application is described here:

1) Use CT/MRI to get the medical image
2) 3D model reconstruction in the medical software
3) Computer Aided Design (CAD)
4) STL file generation
5) Prototyping (3DP)
6) Post-processing: cleaning, support removal, infiltration, etc.

Materials used in [8] are listed in tables below:

Table 1
Components for the standard mix for the tissue-mimicking material in IEC 60601-2-37.

Component	Weight %
Water	82.95
Glycerol	11.21
Agar	3.02
Aluminium oxide (3 μm)	0.94
Aluminium oxide (0.3 μm)	0.88
Silicon carbide (400 mesh)	0.53
Benzalkonium chloride	0.47

Table 4
Summary of acoustic properties of 3 variations of brain mimic compared to target values. Speed of sound values have an uncertainty of 0.5%, attenuation coefficients of 10%.

Conc. of Al_2O_3 (g/l)	Speed of sound (m/s)	Attenuation coefficient [dB cm^{-1}] (at 1 MHz)
0.91	1528	0.264
1.82	1531	0.437
2.73	1537	0.571
Target value	1528 at 28 weeks; increasing with age	0.16–0.3

Table 1 in [8] is the standard mix for the tissue-mimicking gel, which gives an attenuation coefficient of 0.5 dB cm^{-1} approximately, which is greatly higher than typical value of 0.16 to 0.3 dB cm^{-1}. And table 4 shows the properties for modified ingredients within the range of target values. Thus, we can use these two tables as the guide for the skull material.

It should be noted that this is only for the neonatal brain. The brain material meet the requirements of adults should be studied later if necessary.

Reference:

[1]. Parastoo Farnia, Alireza Ahmadian, Alireza Khoshnevisan, AmirHossein Jaberzadeh, Nasim Dadashi Serej, Anahita F. Kazerooni: An efficient Point Based Registration of Intra-operative Ultrasound images with MR images for computation of brain shift; a Phantom Study. 33rd Annual International Conference of the IEEE EMBS Boston, Massachusetts USA, August 30 - September 3, 2011

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[3]. Ronald O. Bude, Ronald S. Adler: An Easily Made, Low-Cost, Tissue-Like Ultrasound Phantom Material. J Clin Ultrasound 23:271 – 273, May 1995.

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