PAA phantom for use in thermal ablation of high intensity focused ultrasound: Phantom fabrication and acoustic parameters measurements

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Abstract: Objective An optically transparent phantom used for thermal ablation of HIFU has been developed with acoustic parameters measured. Methods The color and transparency of different concentration phantoms were observed. Properties including density, acoustic speed and acoustic attenuation of PAA gel phantom were measured. Results (1) PAA gel phantom was amber and transparent. The color became heavier and transparency decreased with the egg-white concentration increasing. (2) The density of PAA gel phantom was similar to water, which was from 1.0250g/cm³ to 1.0617g/cm³. There was a significant correlation between sound speed and phantom concentration. The acoustic attenuation was from 0.125dB/cm to 0.329dB/cm, increased with the phantom density and transducer frequency increasing. Conclusions PAA gel phantom was homogeneous and a good mimicking phantom for HIFU thermal ablation. The experiment results had a satisfied reproducibility.

Key words: polyacrylamide (PAA); phantom; high intensity focused ultrasound (HIFU); therma ablation; acoustic parameters

用于高强度聚焦超声热消融的 PAA 模块：模块的制作及声学参数的测量

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摘要：目的 研制一种透明的用于高强度聚焦超声热消融的 PAA 模块，并对其声学参数进行测量。 方法 观察模块浓度的不同所致颜色与透明度的变化，并对 PAA 模块的声学特性包括密度、声速及声衰减进行测量。 结果 (1) PAA 模块为透明的琥珀色，蛋白浓度越高，颜色越深，透明度越低。(2) PAA 模块的密度与水相近，为 1.0250g/cm³ 至 1.0617g/cm³。声速与模块浓度之间有明显的相关性。声衰减从 0.125dB/cm 至 0.329dB/cm，随着模块密度与探头频率的增加而增加。 结论 PAA 模块是一种较好的用于高强度聚焦超声热消融的均质仿体，实验结果有较好的重复性。

关键词：聚丙烯酰胺(PAA)；模块；高强度聚焦超声(HIFU)；热消融；声学参数

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1 INTRODUCTION

High intensity focused ultrasound (HIFU) is one of therapeutic methods of solid tumors. Though this new thermal ablation technology is developed very rapidly, are were still lots of non-resolved problems in the research aspects including temperature and acoustic field, the relationship between lesion volume and radiation dosage. Because most of the human tissues are not transparent, it is difficult to measure the temperature and thermal field accurately. So it requires us to produce a transparent phantom with properties similar to human or animal soft tissues to perform the study. A kind of PAA gel phantom was developed and used in the preliminary experiments of thermal ablation. The results as followed were finished in our laboratory from March to July in 2005.

2 MATERIALS AND METHODS

2.1 Apparatuses and materials

2.1.1 Materials

Acrylamide (AMRESCO, 500g), bis-acrylamide (AMRESCO, 50g), ammonium persulfate (AP) (AMRESCO, 100g), N, N, N', N'-Tetramethylethylenediamine (TEMED) (AMRESCO, 50ml), degassed water, egg white.

2.1.2 Ingredients

This tissue-mimicking phantom gel is based on a polyacrylamide gel mixed with egg white used here as a temperature-sensitive indicator. The acrylamide concentration used in this study was 40% weight in volume (w/v), calculated by dividing the mass of total acrylamide in grams by the volume of pre-polymerized solution.

The mixed solution was consisted of 44.5% volume in volume (v/v) degassed water, 30% (v/v) egg white, 24.8% (v/v) acrylamide (diluted with 40% w/v aqueous solution), 0.5% (v/v) ammonium persulfate (diluted with 10% solution) and 0.2% (v/v) TEMED. The volume of egg white was changed with the volume of degassed water to keep concentrations of egg white ranging from 20% to 60%. Afterwards, the mixed solution was transferred into a suitable mold to polymerize for 10 to 20 min.

2.1.3 Directions

All preparation takes place at room temperature without any additional heating. First, stir fresh egg white and degassed water together until mixture appears homogeneous in color and consistency and remove bubbles or foam from the top of the liquid with a pipette. Second, add acrylamide into the mixture and stir gently and thoroughly. After removing additional bubbles, add AP and TEMED to catalyze acrylamide polymerization. Third, pour mixture into a suitable mold and allow the phantom to polymerize for 10-20 minutes.

10% AP: Put 1.0 g Ammonium persulfate into 10ml degassed water and stir gently until AP solid dissolved. Best freshly-dissolved (prepare AP the same day when it is to be used) and keep it covered and refrigerated.

2.2 Experimental procedures of acoustic properties measurements

2.2.1 The gel density is obtained as the mass divided by the volume of a tested sample.

2.2.2 Acoustic attenuation and sound velocity: Lead zirconate-titanate (PZT) transducers were used to measure acoustic attenuation and sound velocity. The approach was to make an acoustic signal transmitted through a test sample and compare the received signal with one transmitted through a reference path such as water with the same geometry. All the experiments were performed at room temperature or in water bath of 25 ℃.

2.2.3 The sound attenuation was measured with transducers of 0.85MHz and 1.5MHz. Data were presented as mean ±SD. The correlation between the concentration of egg white and sound speed was analyzed by Pearson's regular correlation and a p value <0.01 was considered to be significant.

3 RESULTS

3.1 The PAA gel phantom

The PAA gel phantom was amber and transparent. It had a heavier color and became less transparent with egg-white concentration increasing. Too much egg white results in an opaque gel, while too little results in low sensitivity and low optical contrast (Fig1). An optimal egg white concentration of 30% (by mass) is satisfied for visualization of HIFU exposure (Fig2).

3.2 The acoustic properties

The acoustic properties of our PAA phantom with different egg white concentrations were summarized in Table 1. The density of the gel ranged from 1.0250g/cm^3 to 1.0617g/cm^3 with concentration from 20% to 60%, which were almost the same with that of water (Fig.3). The sound speed of the gel ranged from 1537m/s to 1570m/s. Gels with higher concentrations of egg white had higher sound speeds (Fig.4), and there was a significant correlation be-

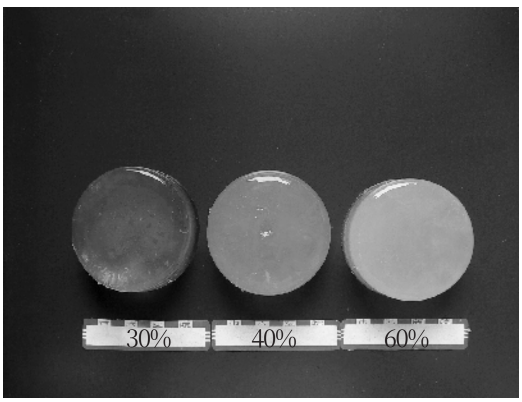

Fig.1 PAA phantom with different concentrations egg white (30%, 40% and 60% respectively from left to right).

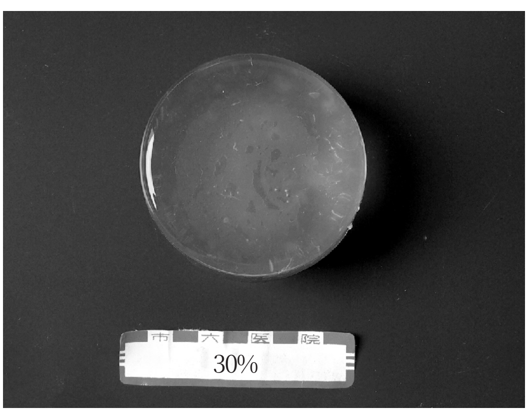

Fig.2 PAA phantom with 30% egg white, it was transparent and amber.

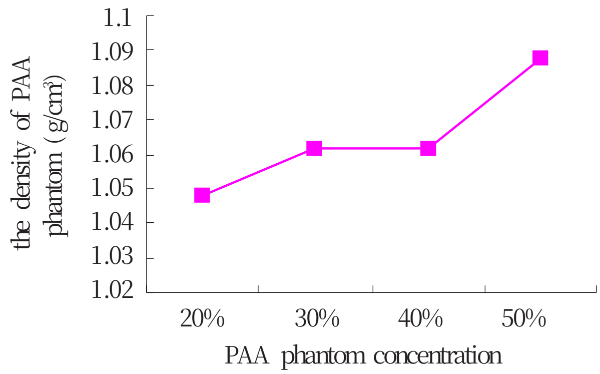

Fig.3 Relation of density and concentration of PAA phantom

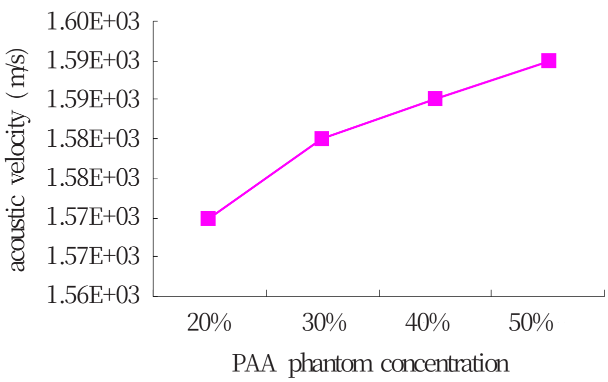

Fig.4 Relation of acoustic velocity and concentration of PAA phantom

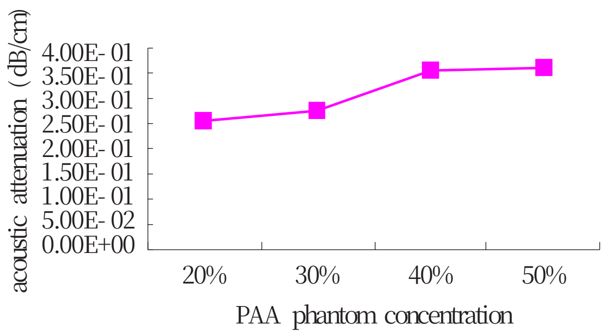

Fig.5 Relation of acoustic attenuation and concentration of PAA phantom with transducer of 1.5MHz frequency

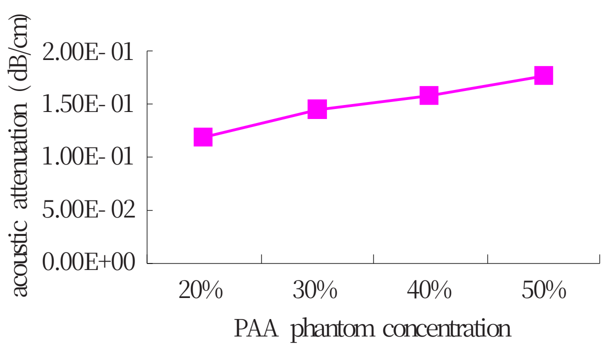

Fig.6 Relation of acoustic attenuation and concentration of PAA phantom with transducer of 0.85MHz frequency

Table 1 Acoustic properties of PAA gel with different egg white concentrations (Values are expressed as mean ±SD.)

Egg white concentration	Density (g/cm³)	Sound speed (m/s)	Acoustic attenuation 0.85MHz	Acoustic attenuation 1.5MHz
20%	1.0250±0.005	1537±1	0.125±0.003	0.147±0.004
30%	1.0480±0.006	1540±1	0.256±0.002	0.283±0.003
40%	1.0613±0.008	1550±1	0.278±0.003	0.305±0.002
60%	1.0617±0.006	1570±1	0.309±0.004	0.329±0.003

tween the sound speed and egg white concentration ($r=0.996$, $p<0.01$). The acoustic attenuation varied linearly with egg white concentrations from 20% to 60% during the studied frequency domain. The magnitude of the attenuation coefficient was between 0.125dB/cm to 0.329dB/cm (Fig5-6).

4 DISCUSSION AND SUMMARY

High intensity focused ultrasound (HIFU) is one of new therapeutic methods of solid tumors. Researchers have done a lot of work with the standard phantoms in HIFU ablation experiments. It is well known that the phantom material with tissue-mimicking thermal properties is essential for the development and characterization of thermal therapy devices, and for clinically related activities such as quality assurance, device comparisons and treatment verification[1]. The key requirements to this material are (1) heat absorption and conduction properties similar to those of tissue; (2) stability over the entire range of temperatures experienced in thermal therapy (up to 100 ℃); (3) accurate delineation of the volume that is thermally coagulated and (4) a coagulation temperature similar to that of tissue. Additional desirable characteristics are homogeneity to ensure reproducibility of results, and a simple and inexpensive fabrication process. To facilitate MR imaging of the coagulated volume, the thermal therapy phantom material should (unlike tissue) undergo a large, non-reversible change in MR parameters (T1 or T2) upon reaching a threshold temperature for thermal coagulation[2].

Several other phantom materials for thermal therapy have been developed but none meets all these requirements. Previously, Bouchard and Bronskill reported a polyacrylamide-based material with bovine serum albumin (BSA) added as a temperature sensitive protein. The advantage of a polyacrylamide base was its stability at the high temperatures experienced in thermal therapy, unlike other gel materials (such as agar, gelatin) which have lower melting temperatures. The dissolved protein in this material underwent thermal coagulation (i.e. den-aturation) above approximately 70℃, resulting in a region of irreversible thermal damage and, therefore, a permanent record of the volume where the temperature exceeded 70℃[3].

Our study demonstrated the feasibility of PAA phantom as a thermal therapy phantom. PAA gel phantom was amber, transparent and homogeneous. It became heavier color and less transparent with the egg-white concentration increasing. The density of PAA gel phantom was similar to water, which was from 1.0250 to 1.0617g/cm³. There was a significant correlation between sound speed and phantom concentration. The acoustic attenuation was from 0.125 to 0.329dB/cm, increased with the phantom density and transducer frequency increasing. The acoustic velocity and attenuation of 30% PAA gel phantom were similar to liver and muscle in vitro. But there were apparent differences between PAA phantom and vivo liver and muscle.

The experiment results have a satisfied reproducibility. The phantom can reduce the quantity of experiment materials and provide an effective method in HIFU evaluation. It is a good mimicking phantom for HIFU thermal ablation.

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