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Research article

A numerical analysis of a semi-dry coupling configuration in photoacoustic computed tomography for infant brain imaging

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ABSTRACT

In the application of photoacoustic human infant brain imaging, debubbled ultrasound gel or water is commonly used as a couplant for ultrasonic transducers due to their acoustic properties. The main challenge in using such a couplant is its discomfort for the patient. In this study, we explore the feasibility of a semi-dry coupling configuration to be used in photoacoustic computed tomography (PACT) systems. The coupling system includes an inflatable container consisting of a thin layer of Aqualene with ultrasound gel or water inside of it. Finite element method (FEM) is used for static and dynamic structural analysis of the proposed configuration to be used in PACT for infant brain imaging. The outcome of the analysis is an optimum thickness of Aqualene in order to meet the weight tolerance requirement with the least attenuation and best impedance match to recommend for an experimental setting.

1. Introduction

The rate of growth of the brain during infancy, the most critical developmental period, is incomparable with that of any other developmental periods [1,2]. A better understanding of the infantile brain change helps early detection of abnormalities and provides ideal opportunities for prevention and reduction of neurological and mental disorders in the most modifiable stage of the central nervous system. Among different neuroimaging methods for studying the infant brain [3–10], photoacoustic (PA) imaging is a noninvasive modality that can potentially simultaneously provide high-resolution images of brain vasculatures and hemodynamics [11–16]. With this method, improving an infant or child's compliance during neuroimaging sessions within a clinical setting would be possible. The PA imaging methodology involves a pulsed laser light source, ultrasonic transducers and an acoustic couplant layer between the imaging target and transducers. Transmission from an ultrasonic sensor is best received with a couplant to minimize degradation and signal loss, such as gaps or air bubbles [17,18].

Acoustic couplants can be characterized in the following groups: liquids, gels, and dry couplants. Liquids and gels generally have lower acoustic impedances than dry couplant materials, and help reduce the large impedance mismatch between air and solid materials [19]. Water has a low acoustic attenuation and impedance which makes it a desirable PA coupling material, and is commonly used for PA imaging applications. However, due to the viscosities of liquids and gels, they tend to fall due to gravity, or dry out over a long period of time [20]. Liquid and gel couplants may sometimes lead to corrosion or a reduction in mechanical properties with the material being tested [21]. Coupling gels could also lead to potential bacterial growth if not cleaned properly [22]. These are some of the challenges that have led to studies exploring dry coupling materials as alternatives to avoid liquid/gel coupling in PA imaging. Dry coupling materials are desirable for applications in which the material would be needed for an extended period of time, such as daily usage for patients, and are generally preferred over liquid or gel couplants [23]. Reduced reflectance and low transmission loss of acoustic energy is needed for efficient dry coupling. Reduced reflectance is a result of the acoustic impedance of the couplant that needs to be close to that of the tissue [24], such that the acoustic energy is not lost due to high impedance mismatch between air and the couplant material [25].

Elastomers have been studied as the most popular dry couplant which have impedance values most similar to water. Additionally,

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they are most similar in overall performance to wet couplants [20]. There are several dry couplants that are polymeric materials, which are divided into three main categories: thermoplastics, thermosets, and elastomers. Crosslinked molecular chains are found in thermosets and elastomer materials, the major difference being that the molecular chains are not as heavily crosslinked in elastomers, and there is more freedom for the chains to relax after removal of a load [26]. Table 1 compares acoustic attenuation and impedance of water against several other polymeric materials [24,27–29].

Although the represented materials do not have an attenuation low enough to match water, Aqualene is a material that closely matches water in impedance compared to other materials.

Dry couplants are preferred for PA imaging, due to the stability and structural support that water cannot provide, while still obtaining water's acoustic characteristics, specifically low attenuation and impedance matching. In this study, we explore the feasibility of a semi-dry coupling system including an inflatable container which consists of a thin layer of Aqualene with US gel or water inside of it to be used in a PACT system for infant brain imaging. If a rigid membrane is used as the couplant, the gap between the membrane and the infant's head will significantly attenuate the signal. If the membrane is purely flexible, such as Aqualene, the transducers will not be placed in a fixed position, hence the image will not be correctly reconstructed. The semi-dry configuration proposed here is chosen to utilize the flexibility of the dry coupling material while incorporating water to minimize the air gap between the inner and outer layers to obtain the best acoustic signal. Finite element method (FEM) is used for static and dynamic structural analysis of the proposed configuration. The outcome of the analysis is an optimum thickness of Aqualene in order to meet the weight tolerance requirement with the least attenuation and impedance.

2. Materials and method

The analytical setup of the semi-dry coupling methodology mainly consists of a hemispherical cap designed for the head of an infant on which the US transducers are placed, the inflatable membrane, a pump and US gel/water. The cap comprises of two polymeric materials with two openings that allow water or US gel to flow between them, thus providing a semi-dry coupling set up. Fig. 1 represents the setup that was used for the theoretical analyses. In this cap, the outer layer and the inner layer were defined as a rigid layer and a deformable layer, respectively. The main purpose of the outer layer is to provide a closed space to contain the water surrounding the inner layer. Given that all the analyses were performed on the inner layer, the only criteria that was considered for the outer layer was that it needed to be rigid. Thus, the inner and outer layers chosen were Aqualene [29] and polyethylene [30], respectively. The specifications of these layers are presented in Tables 2 and 3. Table 2 lists the values cited from literature, and Table 3 lists the values that were determined experimentally for Aqualene. The only mechanical property information supported for Aqualene was the tensile strength and Young's modulus, which were listed as 3.3 MPa and 1580 MPa [31], respectively. Given the material was cited as an elastomer, and its incredibly high Young's Modulus that is not typical of elastomeric materials, five samples of Aqualene were tested at Wayne State University in the Department of Biomedical Engineering to obtain accurate mechanical property values. The samples were tested on a Mark-10 ESM301 from Wagner Instruments for tensile strength and strain at break, and the Young's Modulus was calculated from these values. The average Young's Modulus from the tested samples was 22.5 MPa. Fig. 2 shows the stress-strain curve of one of the samples with its experimental material properties listed in Table 3.

Additionally, the optical properties of Aqualene are also considered to prove its validity for this application. Simple optical properties characterization experiments were performed at Wayne State University in the Department of Biomedical Engineering. Observations showed that the very thin layer of Aqualene did not impact the light from scattering and absorption standpoints. The material is translucent, and only 0.2% light intensity reduction at a wavelength of 532 nm for 2 mm thickness was observed. No scattering effect on the light (comparing the beam size before and after the Aqualene layer) was observed during experimentation.

For the analysis, in order to displace the air between the inner layer of the cap and the head of the infant, the inner layer must be tangent to the surface of the infant's head with the least amount of pressure applied to prevent any damage to the head. Due to the lack of symmetry of the infant's head and to achieve more precise results, a three-dimensional model of a one month-old infant's head is used. The model was constructed from CT Scan slices using the Mimics and Geomagic software programs provided by Shahid Sadoughi University of Medical Sciences and Health Services, Yazd, Iran. Two models were designed for the analytical simulations using the Abaqus and CATIA software programs.

In the first model, the cap was designed with Abaqus in a hemispherical shape. The diameter of Aqualene (inner layer) for the cap was set to 19.4 cm and the distance between the forehead and the back of the head set to 18.6 cm. The range of the distance to the skin was 4–10 mm for Aqualene. In this model, since the geometrical characteristics such as the diameter and the shape of Aqualene were constant, the only variable factor was thickness; thus, the thicknesses of Aqualene were changed from 0.4 mm to 1 mm, leading to three modes to be evaluated in Model 1. In the

Table 1
Acoustic impedance and attenuation of polymeric materials in literature [24,27–29].

Material	Impedance (MRayl)	Attenuation (dB/cm @ 5 MHZ)
Sylgard 184 (Silicone Elastomer)	1.03	–
Aqualene	1.46	2.8
Water	1.48	0.054
Acrylic, Clear	2.32	11.3
UHMWP	2.33	8
Polyurethane	2.36	27.6–100
Polypropylene	2.40	5.1
Polystyrene	2.52	1.8
Polycarbonate	2.75	23.2
Polyester	2.86	10–20
Epoxy	2.86	15–20
Nylon 6-6	2.90	12.9
Teflon	3.00	3.9