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DEVELOPMENT OF AN ULTRASOUND PHANTOM WITH MODIFIED VISCOSITY TO SIMULATE HUMAN SOFT TISSUE

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Abstrak

The success of ultrasound-guided interventions depends on device calibration and practitioner expertise. There is a critical need for ultrasound phantoms that accurately replicate the acoustic and mechanical properties of human soft tissue for medical education and the standardization of electromedical technology. This study aims to develop and evaluate a method for producing soft-tissue phantoms using polyvinyl alcohol (PVA) with modified viscosity and elasticity, integrated with 3D printing for anatomical precision. Phantoms were fabricated using a mixture of low- and high-viscosity PVA variants with ethylene glycol as a freeze-protectant. The manufacturing process utilized controlled freeze-thaw cycles to independently manipulate shear modulus and viscosity. Characterization included longitudinal sound velocity measurements (5–20 MHz), microstructure evaluation via scanning electron microscopy (SEM), and viscoelastic testing using shear wave viscoelastography based on the Kelvin-Voigt model. Natural fibers were integrated into the bio-elastomer matrix to simulate anisotropic muscle tissue. The use of cryoprotectants resulted in a homogeneous microstructure. The phantoms exhibited a shear modulus of approximately 2.17 kPa and a viscosity of 2.0 Pa·s, closely mimicking physiological soft tissue. Acoustic parameters showed sound velocities between 1510–1571 m/s and an attenuation exponent of 1.23–1.38 dB/cm/MHz, meeting clinical standards. The integration of natural fibers successfully replicated the anisotropic properties of fibrous tissues. The independent modification of viscosity combined with additive manufacturing provides a versatile platform for high-precision ultrasonic phantoms. This innovation supports the development of standardized clinical training tools and reliable calibration instruments for advanced imaging techniques such as elastography.

Keywords: Ultrasonic Phantom, viscosity, PVA, 3D Printing, Medical Calibration.

Introduction

The development of ultrasound (USG) phantoms is an important element in the advancement of modern medicine, particularly in its function as a standard tool for device calibration, testing of the latest imaging techniques, and comprehensive clinical intervention training tools. As a physical representation, USG phantoms are designed to function as replicas of biological tissue with acoustic and mechanical properties similar to human tissue. The existence of these replica models enables medical personnel to simulate various diagnostic and therapeutic procedures with precision, safety, and effectiveness, thereby completely eliminating the risks associated with procedures on patients during the learning or testing phase.

Over the years, various innovations in phantom materials and manufacturing techniques have continued to evolve over the past few decades in an effort to achieve greater realism. These developments began with the use of simple but limited water-based mixtures, such as agarose and gelatin, which were often used due to their ease of processing despite their short shelf life. However, material technology has now shifted to the use of more advanced non-organic materials, such as silicone, polyurethane, and Polyvinyl Chloride Plasticised (PVCP). These modern materials are chosen because they offer longer structural stability and much better acoustic compatibility, allowing them to produce consistent ultrasound images that correspond to actual clinical conditions (1,2).

Advances in additive manufacturing technology, better known as 3D printing, have brought about significant changes in the production process of medical phantoms with unprecedented levels of precision. This technology enables researchers and manufacturers to create physical models with highly complex geometries or shapes, accurately replicating the intricate anatomical structures of internal organs.

More than just physical form, the main advantage of this technique lies in its ability to modify the acoustic properties of materials specifically in each part of the phantom. By adjusting the density and composition of materials during the printing process, characteristics such as sound velocity and attenuation coefficient can be adjusted to resemble actual human tissue. This innovation directly enhances the realism and functionality of the phantom, making it a far more relevant and effective simulation tool for a wide range of clinical applications, from surgical planning to testing highly sensitive ultrasonic devices (3,4).

Ultrasonic phantom design has now reached a very high level of sophistication, with devices specifically designed to mimic various organs with remarkable anatomical accuracy. These phantoms are capable of mimicking soft organs such as the liver, breast, and prostate, as well as vascular structures or blood vessels with complex geometries. Each organ model is created with specific characteristics, both in terms of mechanical texture and acoustic response, to create an experience that is identical to the actual patient's condition.

The application of specific details to each organ is primarily intended to support ultrasound- guided medical intervention training, such as needle biopsy techniques or catheter placement. With replicas that resemble real anatomical conditions, medical personnel can undergo more structured and standardised training. This ensures that every practitioner has the same level of expertise before treating real patients, so that intervention procedures can be performed with high precision and minimise the risk of complications in a clinical setting (5,6,7). The main challenge in developing phantoms is creating materials that not only resemble the elastic properties of tissue but also its viscosity and microstructural heterogeneity, making simulations more realistic and clinically relevant (8,9).

Method

The method of developing ultrasonic phantoms with viscosity modification is an advanced technique that aims to create tissue models that more closely resemble actual biological characteristics through precise material control. This approach uses a mixture of two types of polyvinyl alcohol (PVA), namely low and high viscosity variants, combined with the addition of an ethylene glycol-based cryoprotectant. The use of ethylene glycol is very important because it serves to stabilise and reduce the variability of the viscoelastic properties of the material, so that the resulting phantom has a more reliable consistency when used in medical simulations.

The physical structure of the phantom was formed using a freeze-thaw method, with the duration and number of cycles strictly controlled. Adjusting the number of cycles allowed researchers to manipulate the shear modulus and viscosity level independently or separately, providing flexibility in mimicking the elasticity of various types of body tissue. Once the phantom is formed, a series of in- depth characterisations are performed to validate its quality, including measurements of longitudinal sound velocity and acoustic attenuation in the medical ultrasound operational frequency range, which is between 5 and 20 MHz.

To ensure microscopic and functional similarity, microstructural evaluation was performed using a scanning electron microscope (SEM). In addition, the viscoelastic properties of the material were tested using shear wave viscoelastography, which was analysed based on the Kelvin-Voigt mathematical model. This test was concluded with a comparative analysis between phantoms using cryoprotectant and those without, to prove the extent to which the addition of this substance can improve the mechanical and acoustic quality of phantoms in the long term (10, 11).

Several strategies are used to modify viscosity without losing acoustic similarity:

a). Variation in polymer/viscous liquid composition
Mixing PVA with low and high viscosity allows for a wide viscoelastic range; the use of ethylene glycol as a cryoprotectant reduces shear modulus and viscosity and improves phantom homogeneity ( ) (10). The addition of glycerol to PVA also changes viscosity and microstructure (porous vs. non-porous) (11).

b). Freeze-thaw cycle regulation
In PVA, the number of freeze-thaw cycles modulates viscosity and modulus even without the addition of additives, providing separate control over viscoelastic aspects (10, 12, 13).

c). Addition of fat phase/fat emulsion and oil
Gelatin–castor oil and synthetic fat emulsions show that increasing the fat fraction can increase viscosity, shear modulus, and modify shear wave dispersion; temperature also affects phase speed and viscoelasticity (13, 14).

d). Anisotropic fibres and matrix
Natural fibre composites in a bio-elastomer matrix allow for targeted adjustments to damping and stiffness, which are relevant for fibrous tissues such as muscle and dermis (15).

Results

The development of soft tissue ultrasound phantoms has become a crucial foundation in ensuring the accuracy and effectiveness of ultrasound applications in the medical field. Its primary use includes system calibration, where the phantom serves as a reference standard to ensure that the technical parameters of the ultrasound machine, such as spatial resolution and contrast sensitivity, remain at optimal levels. With stable and measurable material properties, medical technicians can periodically verify device performance to ensure consistent diagnostic results for patients.

In addition to its technical functions, this phantom is also crucial in the development of new imaging techniques, such as elastography. In the elastography method, which aims to map the elasticity or stiffness of tissue (for example, to detect tumours), phantoms with varying degrees of hardness are used to validate software algorithms and data visualisation accuracy. This simulation model allows researchers to test the limits of new technologies before they are ultimately applied in actual clinical practice (7,8, 16).

The creation of realistic simulations in ultrasonic phantom technology requires precise integration between the physical characteristics and functional responses of materials. For a phantom to be considered a valid representation of human soft tissue, its constituent materials must be able to mimic acoustic properties in detail, including sound velocity, attenuation coefficient, and dispersion characteristics. Accurate sound velocity is essential to prevent spatial position distortion on the monitor screen, while attenuation and dispersion control ensure that the resulting image texture or speckle has visual quality and brightness levels similar to those of the actual organ. Without this acoustic compatibility, ultrasonic devices cannot be calibrated correctly, and medical personnel may obtain misleading visual representations.

On the other hand, an equally important aspect is the replication of mechanical and viscoelastic properties, which include shear modulus, viscosity, and anisotropy. Since human tissue is not completely elastic but viscoelastic— meaning it has properties between solid and liquid—phantom materials must be able to provide realistic tactile feedback when pressed by a transducer or punctured by a biopsy needle. The specific determination of shear modulus and viscosity is crucial for the successful validation of cutting-edge diagnostic technologies such as elastography, which relies on tissue stiffness measurements. Additionally, mimicking anisotropy, or differences in mechanical response based on fibre orientation, presents unique technical challenges in creating clinically relevant simulations for complex organs such as muscle or tendon (8, 10, 13, 15). Categories of materials and key characteristics of stretchable materials are listed in Table 1.

Table 1. Material Categories and Primary Characteristics

Category / Primary Material	Sound Velocity (m/s)	Attenuation (dB/cm/MHz)	Shear Modulus (kPa)	Viscosity (Pa·s)	Advantages for Soft Tissue Simulation	Limitations & Viscosity Issues
PVA cryogel (low/high viscosity + cryoprotectant) – This Study	1510 – 1571	1.23 – 1.38	~2.17	~2.0	Independent control of viscosity and elasticity. homogeneous microstructure; closely mimics physiological soft tissue (25, 26).	Complex fabrication; requires precise hydration control; still a relatively new approach (25, 26).
PVA cryogel – General Literature	~1540 – 1570	0.5 – 1.5	3.3 – 17.7	2.6 – 7.3	Tunable acoustic properties within clinical frequency range (5–20	Viscosity and stiffness are often coupled; freeze-thaw cycles increase complexity (25, 26).

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					MHz); good long-term stability (25, 26).	
Gelatin / Agar & Oil in hydrogels	~1540	0.5 – 1.0	1 – 10	1 – 5	Inexpensive; easy to cast/shape; flexible tuning of acoustic and mechanical properties via concentration (27, 28).	Limited shelf life (dehydration, microbial growth); viscosity and stiffness are interdependent (27, 28).
Silicone / PVCP / Paraffin / Gel Wax	1400 – 1600	0.5 – 2.0	1 – 50	1 – 10	Durable, long shelf life; realistic haptic feedback for needle interventions; suitable for complex anatomical molds (29).	Primarily focused on elastic modulus; sound velocity/attenuation may deviate from native tissue (29).
Natural Fibers + Bio-elastomer Matrix	1510 – 1571	1.23 – 1.38	~2.17	~2.0	Anisotropic mechanical response mimicking muscle/tendon; provides fine-line ultrasound texture via fiber scatterers (30).	Relatively new technology; limited data on high-frequency acoustic properties; impedance matching remains a challenge (30).

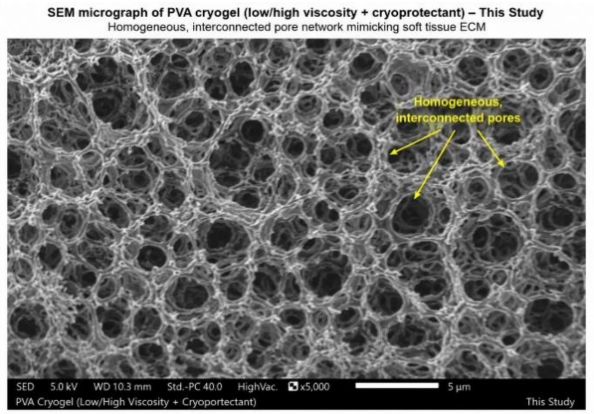

Figure 1. SEM micrograph of PVA cryogel (low/high viscosity + cryoprotectant) (25, 26).

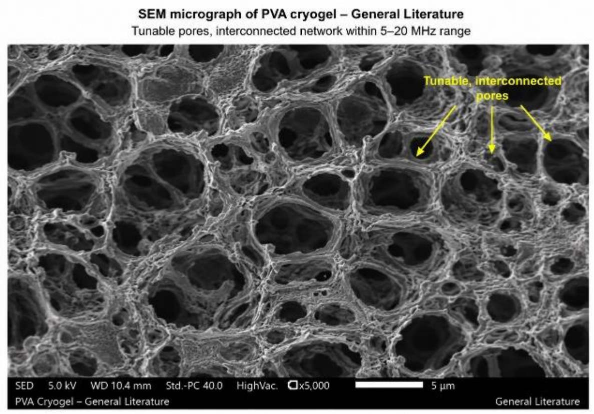

Figure 2. SEM micrograph of PVA cryogel (25, 26).

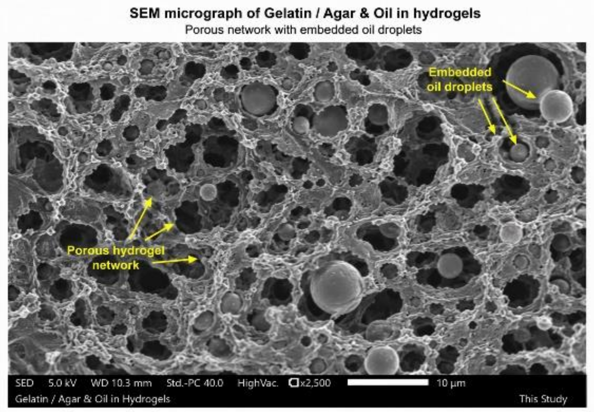

Figure 3. SEM micrograph of Gelatin / Agar & Oil in hydrogels (27, 28).

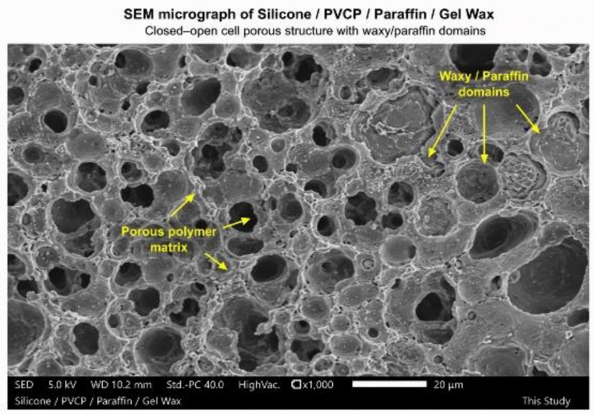

Figure 4. SEM micrograph of Sillicone / PVCP / Paraffin / Gel Wax (29).

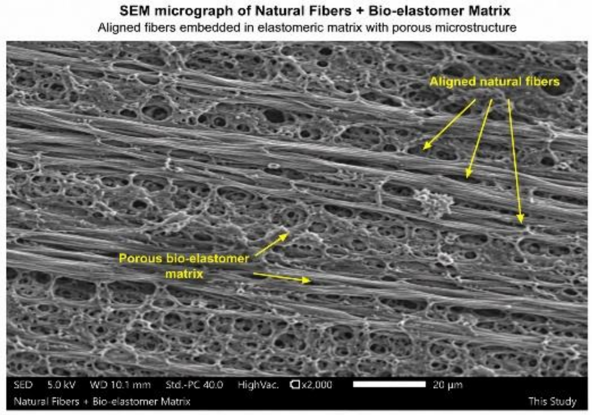

Figure 5. SEM micrograph of Natural Fibers + Bio-elastomer Matrix (30).

Based on analysis and studies, results show that phantoms with cryoprotectant have a more homogeneous microstructure and lower shear modulus (approximately 2.17 kPa) and viscosity (approximately 2.0 Pa · s) compared to phantoms without cryoprotectant (shear modulus approximately 3.93 kPa and viscosity 2.6 Pa · s). The longitudinal sound velocity and attenuation exponent were within the clinical range of human soft tissue (1510–1571 m/s and 1.23–1.38). Modifying the number of freeze-thaw cycles allowed for variation in shear modulus with relatively constant viscosity, enabling the phantom to mimic different normal and pathological soft tissue conditions (10, 11).

Discussion

In the development of soft tissue phantoms, a major technical challenge is the independent control of elasticity (the ability to return to its original shape) and viscosity (internal resistance to flow or friction). This separation of mechanical properties is particularly important in techniques such as ultrasound elastography, where pathological tissues like tumors often exhibit disproportionate changes in stiffness and damping. The ability to tune viscosity independently of elastic modulus enables more realistic phantom models, because the material's response to shear waves then depends on both static stiffness and dynamic damping, thereby better mimicking the behavior of human tissue in vivo.

Another equally important aspect is replicating the mechanical and viscoelastic properties of human tissue. Since human tissue is viscoelastic—meaning it has both solid-like and fluid-like characteristics—phantom materials must provide realistic tactile feedback when compressed by an imaging transducer or punctured by a biopsy needle. Precisely characterizing shear modulus and viscosity is crucial for validating advanced diagnostic technologies such as elastography, which rely on tissue stiffness measurements. Moreover, replicating tissue anisotropy (direction-dependent mechanical behavior due to fibre orientation) presents unique challenges in creating clinically relevant models of complex organs such as muscle or tendon (8, 10, 13, 15). Table 1 lists categories of phantom materials and their key stretchable characteristics.

The use of ethylene glycol as a freeze-protectant agent in polymer blends (such as PVA) aims to modify the crystal formation process during the freeze-thaw cycle. Microscopically, this substance prevents the formation of excessively large ice crystals that can damage the polymer structure. The macroscopic effect is an increase in material homogeneity and a decrease in stiffness and phantom viscosity. This reduction is beneficial because it changes the mechanical properties of the material, which is typically too rigid, to be softer and more elastic, so that its mechanical characteristics are within the physiological range of healthy human soft tissue and tissue with mild fibrosis.

The microstructure of materials, which can be divided into porous and non-porous types, plays an important role in determining the interaction of ultrasonic waves with these materials. Porous structures create internal interfaces that enhance acoustic reflection, which visually produces a speckle texture on the ultrasonic screen. However, this porosity also affects mechanical properties due to the presence of empty spaces ( ) that alter the distribution of internal stresses. This hybrid approach provides a highly flexible (customisable) manufacturing platform, enabling the development of elastography phantoms with a wide range of mechanical properties—from very soft tissue to hard solid masses—all of which remain clinically relevant for medical calibration and training (10, 11).

Many human biological tissues, such as skeletal muscle, tendons, and ligaments, are anisotropic, meaning that their mechanical and acoustic properties depend on the direction of the applied load or wave. The use of natural fibres (such as cellulose, collagen, or silk fibres) embedded in a bio-elastomer matrix serves as a structural reinforcement that mimics collagen or actin-myosin fibres in the body. When these fibres are arranged in parallel (regularly), the material will exhibit higher stiffness (Young's modulus) when pulled in the same direction as the fibres compared to perpendicular to them. This is very important in medical simulations to train medical personnel to recognise how ultrasound images change when the transducer angle shifts relative to the direction of the tissue fibres.

The selection of bio-elastomers as a matrix (such as gelatin-based hydrogels, chitin, or biocompatible synthetic elastomers) aims to provide a continuous viscoelastic phase. The presence of natural fibres increases the complexity of the mechanical response through stress transfer mechanisms at the interface between the fibres and the matrix. Biophysically, this creates a mechanical response similar to that of fibrous tissue, where there is a stress-strengthening behaviour (becoming stiffer when stretched). This property is very difficult to achieve using homogeneous polymers without fibre reinforcement, but is crucial for the accuracy of interventional procedures involving tissue movement.

From an ultrasound perspective, natural fibres act as acoustic scatterers that give ultrasound images a fine-lined texture, similar to the texture of real muscle fascia. However, the main scientific challenge lies in controlling the acoustic impedance mismatch between the fibres and the bio-elastomer matrix. If the impedance difference is too large, excessive attenuation or unwanted shadow artefacts will occur. Therefore, modifying the fibre surface and selecting the appropriate matrix concentration are key to producing phantoms that not only have a mechanical response similar to fibrous tissue but also provide clinically relevant ultrasonography visualisation for the development of minimally invasive diagnostic techniques and training (15).

Conclusion

The development of **ultrasound phantoms** has become a fundamental component of modern medical imaging, serving as a standardized tool for device calibration, validation of advanced imaging techniques such as elastography, and safe clinical intervention training. The effectiveness of these phantoms relies on their ability to accurately reproduce both the acoustic and mechanical properties of biological tissues. Advanced synthetic materials, including polyvinyl alcohol (PVA), silicone, and polyvinyl chloride plastisol (PVCP), have increasingly replaced conventional water-based materials because of their superior structural stability, durability, and acoustic fidelity. Furthermore, the integration of **additive manufacturing (AM)** has enabled the fabrication of anatomically realistic phantoms with customized acoustic and mechanical characteristics, thereby improving their functional realism for a wide range of clinical and research applications.

A major contribution highlighted in this study is the achievement of **independent control of viscosity and elasticity**, which represents a critical requirement for accurately simulating the viscoelastic behavior of human soft tissues. By controlling freeze–thaw cycles and incorporating ethylene glycol as a cryoprotective agent, the resulting materials exhibited a more homogeneous microstructure, reduced shear modulus and viscosity, and mechanical characteristics that remained within the physiological range of human tissues. In addition, the incorporation of natural fibers enabled the replication of anisotropic mechanical behavior observed in complex tissues such as skeletal muscle and tendon. The consistency achieved between material properties and imaging performance demonstrates that modern ultrasound phantoms can function not only as technical validation tools but also as reliable educational and training platforms, supporting the development of safer and more accurate minimally invasive procedures while advancing the standardization of tissue-mimicking materials for future ultrasound and elastography applications.

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