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Review

Tissue mimicking materials in image-guided needle-based interventions: A review

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ABSTRACT

Image-guided interventions are widely employed in clinical medicine, which brings significant revolution in healthcare in recent years. However, it is impossible for medical trainees to experience the image-guided interventions physically in patients due to the lack of certificated skills. Therefore, training phantoms, which are normally tissue mimicking materials, are widely used in medical research, training, and quality assurance. This review focuses on the tissue mimicking materials used in image-guided needle-based interventions. In this case, we need to investigate the microstructure characteristics and mechanical properties (for needle intervention), optical properties and acoustical properties (for imaging) of these training phantoms to compare with the related properties of human real tissues. The widely used base materials, additives and the corresponding concentrations of the training phantoms are summarized from the literatures in recent ten years. The microstructure characteristics, mechanical behavior, optical properties and acoustical properties of the tissue mimicking materials are investigated, accompanied with the common experimental methods, apparatus and theoretical algorithm. The influence of the concentrations of the base materials and additives on these characteristics are compared and classified. In this review, we assess a comprehensive overview of the existing techniques with the main accomplishments, and limitations as well as recommendations for tissue mimicking materials used in image-guided needle-based interventions.

1. Introduction

In recent years, the magnetic resonance (MR) images and computerized tomography (CT) images are widely employed in clinical test and treatment, due to the higher resolution of the medical images, while ultrasound images (US) are used extensively in intraoperative navigation owing to the good quality of real-time imaging and non-radiation to medical staffs. Thus, image guidance has become a popular technique in minimally invasive surgery, which includes techniques such as localization and tracking of the position of surgical tools or therapeutic devices, registration of the patient to the preoperative data, and assessment of any difference between the preoperative data and the intraoperative reality [1]. The rapid increase in computing power and the improvements in imaging modalities in 1990s allow concomitant growth in the field of computer-aided surgery. Virtual planning in the computer equipment allows better visualization of tissue morphology prior to the target positioning, and the user group utilize the software packages which are shared or operated via the cloud-base to jointly improve the treatment planning according to the results of the image segmentation and reconstruction [2]. Since then, several computer-aided systems became available and soon evolved into the standard of care for image-guided interventions, including but not limited to image guided surgery in the kidney, liver and prostate [3–5], the image guided neurosurgery [6], cardiac interventions [7], and vascular interventions [8], or the image guided brachytherapy [9,10]. In computer-aided image-guided interventions, some flexible needle-like instruments are more likely to be used to perform the interventions, as the researchers reported in their work [11–15]. Because the flexible steerable instruments have the potential to allow the physician to reach targets that located behind some vital organ/tissues and should not be passed through by rigid straight instruments, which can avoid some unexpected surgical complications and improve the surgical safety [16,17].

However, it is impossible for some trainees to experience the image-guided interventions physically in patients using the flexible needles due to the lack of certificated skills. Therefore, tissue-mimicking materials are necessary and widely used in medical research, training, and quality assurance [18]. Many literatures have demonstrated that residents who experienced the training or education by using the tissue mimicking material model have increased confidence and skill in their

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use of ultrasound to guide percutaneous needle positioning or other clinical operations than that who have no chance to experience the phantom training [19–21]. At the clinic, tissue-mimicking materials would be significantly useful for training medical residents in gynecologic brachytherapy or biopsy, which requires image-guided insertion of needles into soft tissues. To present the similar properties to human organs or tissues, the tissue mimicking materials should meet the criteria of micro-structure characteristics, mechanical properties, optical properties and acoustical properties, for using in multi imaging modality. Tissue mimicking materials will be used as substitutions in image-guided needle-based interventions for medical trainees as long as they meet the requirements of the similar microstructure characteristics, imaging performance, and mechanical properties to that of the human soft tissues. Thus, many researchers are focused on developing tissue-mimicking materials by selecting appropriate base materials and filters as well as the corresponding concentration. The developed materials are employed in the training process to simulate different human tissues, for example, brain [22–25], liver [26,27], kidney [28], prostate [29–31], breast [32,33], vessel [34] or human hollow organs [35], and any groups of the human tissues [36–38].

However, a kind of appropriate phantom, which can meet all of the experimental conditions, is not easy to be selected. Thus, in this review, we summarized most kinds of the tissue mimicking materials and investigated the imaging properties and mechanical properties to provide a reliable guide for choosing the most appropriate training phantom used in image-guided needle-based interventions. Even though there are several reviews listing the training phantoms used for tissue engineering [18], this review will focus on the properties of the tissue mimicking materials that are used in image-guided needle-based interventions. We provide a figure here (see Fig. 1) to explain the connection and framework of the microstructure characteristics, mechanical properties, optical properties, and acoustical properties of the tissue mimicking materials in image-guide needle-based intervention.

This review is organized as follows: Section 2 is the preparation of the tissue mimicking materials, representing the preliminary preparation approach of kinds of base tissue mimicking materials. Section 3 is listing the additives and related concentrations, which is used to improve the material properties, in tissue mimicking materials. Section 4 is demonstrating the material property requirement of needle-based intervention including the microstructure characteristics and the mechanical characterization. Section 5 is aiming to investigate the material property requirement of imaging, which includes the optical properties and the acoustical properties. The limitations and recommendations are proposed in the Discussion, followed by the main accomplishments in Conclusion.

2. Preparation of the base tissue mimicking materials

Currently, the widely used base materials include but are not limited to polyvinyl alcohol (PVA) [39–42], polyvinyl chloride (PVC) [43,44], gelatin [45–47], silicone [48–50], agar [51,52], agarose. The preliminary preparation of these base tissue mimicking materials are shown in the following subsections.

2.1. Polyvinyl alcohol (PVA)

PVA is a non-toxic, hydrophilic and synthetic polymer developed in the recent years in tissue engineering due to its repeatability and biocompatibility [53]. Kumar and Han [18] have reviewed PVA-based hydrogels for tissue engineering from aspects of PVA-natural, PVA-synthetic polymers, PVA bio-ceramics and other combinations. Here we focus on the PVA-based tissue mimicking materials especially in terms of simulating needle-tissue interaction. PVA polymer solution is obtained by adding a certain amount of PVA powder into water or deionized water and then magnetically stirring. To fully resolve the PVA powder, the solution was heated to 93 °C with constantly stir. This temperature was maintained for about 30 min, after which the solution was transferred into a storage container and allowed to cool down to room temperature. The flask was weighed, and any loss in mass was replaced with de-ionized water, in order to ensure an initial planned concentration of PVA solution. Human tissues have different microstructure characteristics, imaging performance and different mechanical properties, thus the characteristics of the PVA hydrogel should be controllable by tuning the ratio of the additive raw materials or

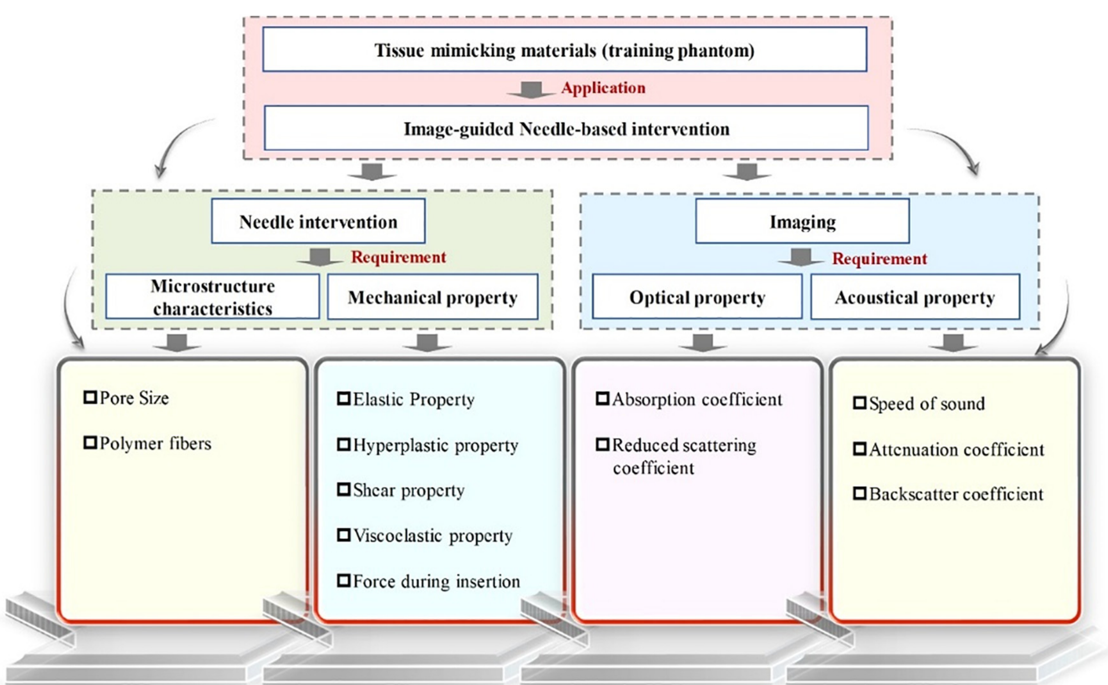

Fig. 1. The framework of the review content showing the connection of the microstructure characteristics, mechanical properties, optical properties, and acoustical properties of the tissue mimicking materials in image-guided needle-based intervention.