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Research paper

Evaluation of the friction coefficient, the radial stress, and the damage work during needle insertions into agarose gels

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ABSTRACT

Agarose hydrogels have been extensively used as a phantom material to mimic the mechanical behavior of soft biological tissues, e.g. in studies aimed to analyze needle insertions into the organs producing tissue damage. To better predict the radial stress and damage during needle insertions, this study was aimed to determine the friction coefficient between the material of commercial catheters and hydrogels. The friction coefficient, the tissue damage and the radial stress were evaluated at 0.2, 1.8, and 10 mm/s velocities for 28, 30, and 32 gauge needles of outer diameters equal to 0.36, 0.31, and 0.23 mm, respectively. Force measurements during needle insertions and retractions on agarose gel samples were used to analyze damage and radial stress. The static friction coefficient (0.295 ± 0.056) was significantly higher than the dynamic (0.255 ± 0.086). The static and dynamic friction coefficients were significantly smaller for the 0.2 mm/s velocity compared to those for the other two velocities, and there was no significant difference between the friction coefficients for 1.8 and 10 mm/s. Radial stress averages were 131.2 ± 54.1, 248.3 ± 64.2, and 804.9 ± 164.3 Pa for the insertion velocity of 0.2, 1.8, and 10 mm/s, respectively. The radial stress presented a tendency to increase at higher insertion velocities and needle size, which is consistent with other studies. However, the damage work did not show to be a good predictor of tissue damage, which appears to be due to simplifications in the analytical model. Differently to other approaches, the method proposed here based on radial stress may be extended in future studies to quantity tissue damage in vivo along the entire needle track.

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1. Introduction

Agarose hydrogels have been extensively used in tissue engineering to repair or substitute biological tissues or organs (Caló and Khutoryanskiy, 2015). Examples of applications of agarose hydrogels are found in wound-healing (Pal et al., 2009), intervertebral disc therapies (Hudson et al., 2013; Cloyd et al., 2007), cartilage tissue engineering when combined with poly (ethylene glycol) diacrylate (Rennerfeldt et al., 2013), and even in bone regeneration when combined with biphasic calcium phosphate (Puértolas et al., 2011). In addition, agarose gels have been extensively used as a phantom material to mimic the mechanical behavior of soft biological tissues such as the larynx (Choo et al., 2010), the breast (Pleijhuis et al., 2011), the lungs (Wielputz et al., 2015), and the brain (Chen et al., 2004). Moreover, clinical protocols like imaging (Chen et al., 2008), drug delivery (Raghavan et al., 2006), indentation (Lee et al., 2011), and needle insertion (Casanova et al., 2014a, 2014b) have been studied using agarose hydrogel.

Currently, several clinical techniques needed to diagnose or treat diseases include needle insertion into the organs producing tissue damage. This damage is detrimental in procedures such as convection-enhanced delivery (CED) into the brain since it increases backflow, which is produced by the infusion pressure that separates the tissue from the needle and creates a channel, in which the infusate can easily flow, causing undesirable drug distributions (Sampson et al., 2008; Vogelbaum et al., 2007). Hence, a significant amount of drug may be transported into the tissue from the lateral surface formed around the needle rather than from the infusion cavity formed around the catheter tip. Infusions during CED have shown that the radial stress generated during the insertion, called pre-stress in the CED literature (Raghavan et al., 2010), is an important factor to reduce backflow, since the infusate has to overcome this radial stress to separate the tissue from the needle (Casanova et al., 2014b). Hence, some studies have been aimed to assess the variables that affect both, tissue damage and radial stress.

Damage due to needle insertion has been evaluated by histology (White et al., 2011; Casanova et al., 2014) and by imaging the hole left by the needle after retraction (Casanova et al., 2012; Shergold and Fleck, 2005). Force measurements during needle insertion and retraction have also been used to analyze damage in agarose hydrogels (Casanova et al., 2012; Chen et al., 2004). High insertion forces are generally associated with larger damage across tissue types (Andrei et al., 2012; Welkenhuysen et al., 2011; Peidong et al., 2012; Van Gerwen et al., 2012; Mahvash and Dupont, 2010; Sharp et al., 2009; Casanova et al., 2014a).

Radial stress has been calculated based on a simplified hyper-elastic mechanical model and measurements of the hole left by the needle after retraction (Casanova et al., 2014b, 2012). Under this approximation, the radial stress depends on the model and the constitutive parameters chosen for the material. A novel digital imaging correlation method has also been developed (Oldfield et al., 2014) to measure the strain distribution during needle insertion, which may be used to calculate the radial stress, but again, it would be dependent on the constitutive parameters of the model. The needle insertion and retraction forces have been used to evaluate damage and friction stress in the rat brain tissue in vivo (Casanova et al., 2014a). However, the radial stress was not quantified since the friction coefficient between the needle and the tissue was unknown.

To the best of our knowledge, only the study by Baykal et al. (Baykal et al., 2013) reports the coefficient of friction between hydrogel and ceramic. Some other studies have considered the friction behavior of needles on substrates (Lee et al., 2015; Ramkumar et al., 2004; Ramkumar and Roedel, 2003). However, the friction coefficient between the A304 stainless steel, used to manufacture commercial catheters, and agarose gels have not yet been determined. This coefficient is an important parameter for a more accurate analysis of tissue damage and radial stress. Hence, the objective of this study was to quantify the friction coefficient between the material of the needles and agarose hydrogels. Additionally, damage and radial stress were also evaluated by using the force–time curves during insertion and retraction. Lastly, we assessed the influence of needle insertion speed and needle gauge in the development of damage and radial stress.

2. Material and methods

Experiments were conducted with specimens made of agarose gel powder (A6013, Type 1, low EEO, Sigma Aldrich, USA) and water. The solution, which was composed of 0.48 g of powder and 80 ml of water (0.6% w/v), was mixed up, boiled, and cast into PVC pipes of 36.4 mm internal diameter and 25 mm length. Next, the product was allowed to cool down until solidification. The experiments were performed at room temperature (22 °C).

2.1. *Determination of the friction coefficient between agarose hydrogel and A304 stainless steel*

To the best of our knowledge, there is no direct method to measure the radial stress caused during needle insertion, since a use of a pressure sensor would disrupt the stress field around the needle. Hence, we measured the friction coefficient between the gel and plates made of the stainless steel A304 that is the material generally used to manufacture the medical needles (Hamilton, Reno, NV, USA).

As the material roughness may affect the friction coefficient, the roughness of the 28, 30, and 32 gauge needles was first determined as follows. A portable surface roughness tester (Surftest SJ-210, Mitutoyo, Aurora, IL) with 0.01 μm resolution was used. Each needle and the roughness tester were positioned as presented in Fig. 1, taking care to

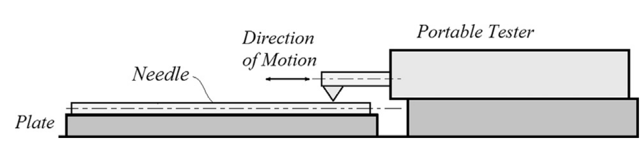

Fig. 1 – Schematic of the needle arrangement and roughness tester.