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Mechanics of anesthetic needle penetration into human sciatic nerve

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ABSTRACT

Nerve blocks are frequently performed by anesthesiologists to control pain. For sciatic nerve blocks, the optimal placement of the needle tip between its paraneural sheath and epineurial covering is challenging, even under ultrasound guidance, and frequently results in nerve puncture. We performed needle penetration tests on cadaveric isolated paraneural sheath (IPS), isolated nerve (IN), and the nerve with overlying paraneural sheath (NPS), and quantified puncture force requirement and fracture toughness of these specimens to assess their role in determining the clinical risk of nerve puncture. We found that puncture force (123 ± 17 mN) and fracture toughness (45.48 ± 9.72 J m^{-2}) of IPS was significantly lower than those for NPS (1440 ± 161 mN and 1317.46 ± 212.45 Jm^{-2}, respectively), suggesting that it is not possible to push the tip of the block needle through the paraneural sheath only, without pushing it into the nerve directly, when the sheath is lying directly over the nerve. Results of this study provide a physical basis for tangential placement of the needle as the ideal situation for local anesthetic deposition, as it allows for the penetration of the sheath along the edge of the nerve without entering the epineurium.

1. Introduction

Anesthesiologists frequently inject local anesthetic agents in close proximity to peripheral nerves, termed nerve blocks, in order to interrupt nerve transmission and provide pain control related to surgical procedures. In the lower extremities, for example in surgery for knee or foot disorders or trauma, the sciatic nerve is often targeted for such injections (Wegener et al., 2011; Perlas et al., 2013). The sciatic nerve is unique in its architecture in the body, being comprised of two nerves, each with its own outer epineurial lining, held together by an outer paraneural sheath which encapsulates the entire nerve (Vloka et al., 1997) (Fig. 1). To optimize the onset and effectiveness of a sciatic nerve block, anesthesiologists attempt to inject the local anesthetic between the paraneural sheath and the outer epineurial covering of the nerves within. Currently, ultrasound is usually utilized to guide needle placement for nerve blocks (Chin et al., 2008; Gadsden et al., 2014; Missair et al., 2012; Tran et al., 2011). However, the sciatic nerve lies relatively deep in the posterior thigh (3–5 cm), and ultrasound cannot provide the accuracy required for precise needle tip placement between the sheath and the epineurium, making it difficult to consistently avoid penetration of the nerve with the needle. Such penetration may occur in as many as 17% of sciatic blocks (Liu et al., 2011), increasing the risk of physical and chemical nerve injury.

The cause of the high incidence of nerve penetration in sciatic blockade has not been investigated. The relative differences in biomechanical failure properties and associated forces required to puncture the outer sheath versus those required to puncture the epineurium of the nerves within may influence this risk. We investigated these relative forces in an ex vivo model in order to determine how they might affect the clinical risk of nerve puncture; understanding these mechanisms may help anesthesiologists to place blocks with a higher degree of safety. In addition, we studied the biomechanical nature of the puncture event when the paraneural sheath is directly overlying the nerve, to assess whether it is practical to manually puncture the tissue of the sheath but avoid puncturing the nerve directly deep to it.

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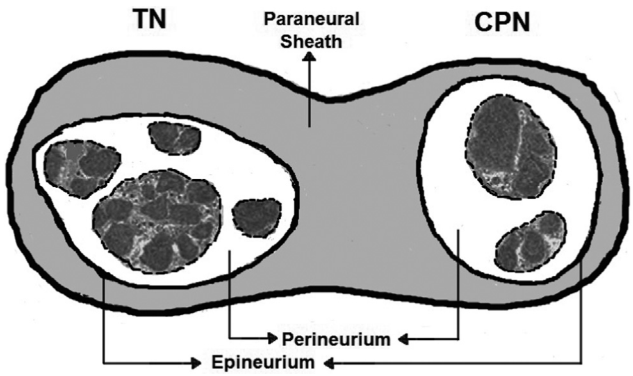

Fig. 1. Schematic diagram of histological architecture of the sciatic nerve demonstrating outer paraneural sheath holding together the tibial (TN) and the peroneal (PN) nerve components. The epineurium is a connective tissue lining the TN and CPN individually enclosing perineurium.

2. Methods

2.1. Sciatic nerve tissue harvest

Segments of sciatic nerve were harvested from six human cadavers and stored in saline at 4 °C. Three specimens were dissected from each nerve sample, and were defined as the isolated paraneural sheath (IPS), isolated nerve (IN), and nerve with overlying paraneural sheath (NPS) as seen in Fig. 1. Paraneural sheath isolation was performed by inserting scissors beneath the sheath and cutting down the midline of the sheath. The sheath was then detached from the underlying nerve via blunt dissection. Successful puncture tests were then performed as described below and the tests were averaged per cadaver resulting in the reported n = 6, 5, and 5 for IPS, IN, and NPS, respectively (one sample each for IN and NPS were of insufficient size to be affixed to the stage of the micro-indentation system and therefore could not be tested).

2.2. Needle penetration test

Specimens were stretched onto the mounting stage of an ASTM standard calibrated micro indentation system and were held securely by sutures (Fig. 2) so that it was in a no-slip and drag-free condition. This holding technique ensured that the specimens did not undergo any overall vertical displacement (except elastic deformation) during the indentation process. Testing of the IPS was performed with a 50 g load cell (GSO-50 Transducer Techniques, Temecula, CA), as it was determined to be sufficient to capture the puncture force. A 500 g load cell (GSO-500 Transducer Techniques, Temecula, CA), was used to test the IN & NPS as the 50 g load cell did not allow for proper recording of the larger puncture force needed for these tissues. Testing was performed with a Stimuplex A, 21 gauge, 10 cm steel block needle. This is the most commonly used peripheral nerve block needle, with a diameter of 0.819 mm, and a "dull" tip with a 30 degree bevel. As noted in Fig. 2D, this results in an ovoid aperture at the tip, with a leading edge that is relatively sharp, but not does not have the same shearing capacity as typical "cutting" needles for vascular puncture. Clinicians prefer this type needle for peripheral nerve blockade because it is less likely to inadvertently enter and damage a nerve. A single needle was used for all penetration tests on each specimen so that there was no variability in the needle properties between the tests. The needle was replaced after each specimen was tested to compensate for dullness that may have occurred due to repeated use. Although no clinical data exists on the rate of insertion, lower rates are preferred to avoid nerve trauma. To simulate careful

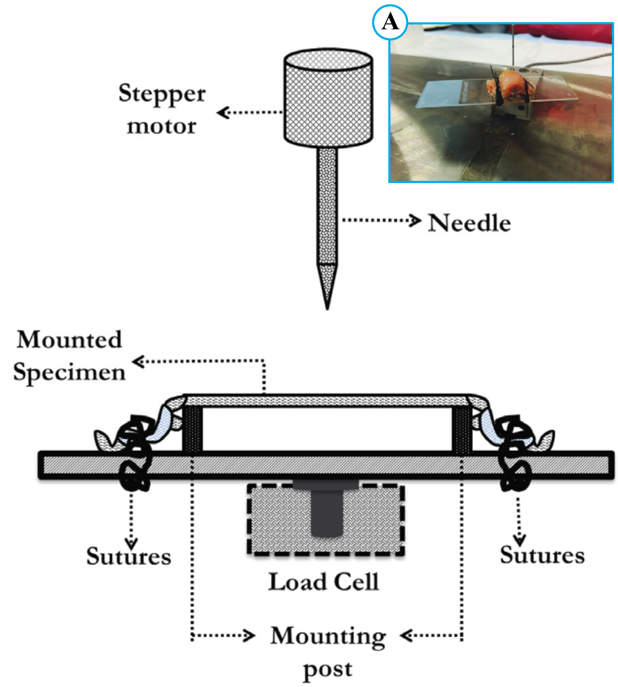

Fig. 2. Schematic diagram of micro-indentation system and mounted specimen. The micro-indentation system contains a stepper motor that is controlled by the user via LabView software. The motor derives the advancement of the needle towards the specimen. The nerve specimen is mounted on the mounting post and held securely by sutures. Detail A shows a photograph of the mounted nerve specimen with the paraneural sheath.

insertion of the needle, the needle was driven at a slow speed of 0.1 mm/sec into the specimen. The force from the load cell remained at the same value until the needle tip touched the surface of the mounted specimen. This force was considered as the baseline dead load value and represented the weight of the mounted nerve sample; this baseline value was then subtracted from the experimental force measurements for that sample. From the instant the needle tip touched the surface of the specimen, the needle tip force gradually increased due to advancing of the needle through the specimen. The sudden drop in the force while advancing the needle into the specimen was noted as the puncture event. The puncture force was calculated as the maximum value of the needle force observed during the first penetration event. After the initial puncture was performed, the indenter was retracted and subsequently the insertion-retraction of the needle was performed two more times at the same location of the specimen. Data from three insertions in the same location was gathered to determine energy spent to initiate puncture. For each specimen, three different locations at least 5 mm apart on the tissue were chosen as puncture sites in order to maximize the amount of puncture force data gathered for each specimen. The needle tip force and displacement data was continuously recorded with a sampling rate of 50 Hz using LabView software (National instruments, Austin, TX) and calculation of puncture force and energy released during each insertion was performed in MATLAB.

2.3. Fracture toughness assessment

Needle penetration test data was post-processed to assess the fracture toughness J, the intrinsic resistance of the tissue against mechanical failure, of IPS, IN and NPS. We used the fact that J equals the energy release rate G during steady state crack propagation (Irwin, 1956), and measured G from the penetration