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Noninvasive Assessment of Visco-Elasticity in the Presence of Accumulated Soft Tissue Fluid

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Background. **The diagnosis of compartment syndrome is made by clinical examination, but direct compartmental measurements are important and serve an adjunctive role in establishing the diagnosis. This study examines a noninvasive screening method for differentiating compartmental syndrome from edema without elevated internal pressure.**

Materials and methods. **The study groups consisted of 16 normals, 22 subjects with edema, and 2 subjects with compartmental syndrome. Force-displacement curves on the posterior and anterior surface of the extremity at mid-calf of each extremity were recorded using a noninvasive mechanical tester. A cyclic force peaking at 120 N was applied over a skin area of 1.5 cm^2. In a uniform applied force environment, the peak force would be comparable to an applied pressure of 60 mm Hg. Mechanical parameters associated with tissue softness (SOFT), degree of hysteresis, and departure from linear elastic behavior were calculated. In seven subjects, direct intracompartment pressure readings were obtained by the Stryker method.**

Results. **Posterior SOFT was significantly larger than anterior SOFT, as expected, for all study groups, except those with compartmental syndrome. SOFT for subjects with compartment syndrome fell below the 99% confidence interval of all other groups in the affected compartment(s). Departure from linear elastic behavior values were also depressed in the posterior compartment for subjects with compartment syndrome as compared with the other groups. Degree of hysteresis was significantly increased for pitting edema. Extremities with nonpitting edema were not distinguishable from normal extremities for the levels of applied pressure used in this study.**

Conclusion. **Noninvasively measured mechanical properties were significantly different between normal tissues and tissues with pitting and nonpitting edema. The mechanical properties of the extremity with compartmental syndrome were different than those with edema as well as normal extremities. A noninvasive mechanical tester is seen as a possible clinical tool to diagnose and monitor compartmental syndrome.**

Key Words: **compartment syndrome; tissue softness; edema.**

INTRODUCTION

Biological tissue has been referred to in general terms as quasi-viscoelastic [1, 2]. Clinical signs in which the "feel" of the tissue is judged by palpation provide clues about changes in mechanical properties but are subjective and not reliable. Changes in mechanical properties with fluid accumulation are not accurately documented [3]. When the fluid accumulation is suspected to represent a compartment syndrome, invasive measurements by needle are taken. The needle manometer technique was introduced in 1884 [4]. Intracompartment pressures of 30 mm Hg or higher raise suspicion of a compartmental syndrome, and pressures in excess of 45 mm Hg are usually considered diagnostic [3]. Criticisms of the needle technique are that nonequilibrium conditions occur during measurement and further that continuous long-term measurements are problematic due to the invasive nature of the test and the risk of infection. Variants of the basic procedure have been described [5–7] that serve to increase the surface area for fluid equilibrium and that help to maintain patency in the catheter. A search for other quantitative measures to more accurately reflect the presence of compartment syndrome is warranted [8].

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Fisher developed a handheld tissue compliance meter to measure changes in soft-tissue consistency [9]. Criticisms of mechanical testing are that the measurement can be affected by the direction of applied forces, the area over which the force is applied, and the time course of the application. In these circumstances, usefulness requires that the observed differences with disease entities be significantly different relative to intersubject differences. An improved means of obtaining quantitative hardness measurements is reported. The handheld noninvasive compartment syndrome evaluator device formulates a quantitative hardness curve of force *versus* depth of indentation by applying a 5.0-mm-diameter indenter to a limb muscle compartment [10]. Study evaluated a prototype handheld, digital, fluid pressure monitor used for the measurement of compartment pressure in the exercising athlete [11]. The noninvasive mechanical tester used in this study is a quantitative analogue of hands-on extremity palpation. It was found that there was a close correlation between the direct measurement of intracompartmental interstitial pressure with the quantitative hardness in compartment syndrome models in dog and anatomical specimen limbs, and in patients suspected of having compartment syndromes. The determination of surface hardness of limb compartments might be suitable for longer term assessments of intracompartmental interstitial pressure [12]. It was found that sensitivity of noninvasive near-infrared spectroscopy is clinically equivalent to that of invasive intracompartmental pressure measurements, and in the cadaveric tests, the ultrasonic device uses a pulsed phase locked loop as a noninvasive method for diagnosing acute compartment syndrome [13, 14].

The present study examined the question as to whether noninvasive mechanical tester is sensitive and specific to compartmental syndrome, among the groups tested. Since different pathologies alter tissue mechanics, it would be important to determine quantitative differences in soft-tissue mechanical properties that are specific to the compartmental syndrome. The present study examined whether the compartmental syndrome was differentiable from edema, as well as from the mechanical condition of the normal extremity. The comparison is of interest since both edema and compartment syndrome involves accumulation of fluid in tissues. Selected parameters from the force-displacement curves generated by the noninvasive mechanical tester were evaluated as to their potential in distinguishing the compartmental syndrome from edema, both pitting and nonpitting, and from clinically normal extremities. The inclusion of pitting edema allows a comparison of noninvasive mechanical tester with the physically observable symptomatology of the "pit" left in the tissue for several seconds after indentation.

MATERIALS AND METHODS

Noninvasive Mechanical Tester

The noninvasive mechanical tester (Raenselea Polytechnic Institute, Troy, NY) consisted of an instrumented handheld sensor, an electronic interface unit, and an x-y plotter for data display. The handheld sensor has a center indenter that is mounted at the end of force transducer. Three linear variable displacement transducers are located symmetrically around the force transducer and are connected to a stable platform that rests lightly upon the surface of the skin about the indenter. There is an opening in the platform for the indenter (Fig. 1). The indenter area is 1.5 cm^2 with a domed surface, although other indenter sizes were evaluated in preparation for the tests. It should be noted that the area over which measurements are acquired is limited by the size of the indenter and not by the size of the platform that provides the reference position information.

Prior to use, the sensor is first calibrated with known displacement and force. The devise was calibrated using standard weight and displacement shims reading from 0.60 to 2.06 mm in thickness. In use, indentation was produced by pressing the sensor perpendicularly against the surface of the skin. First, the sensor is placed at rest on the surface of the skin, with an applied force under 10 N. This provides a reference position for subsequent indentation. The motion of the indenter relative to the platform measures the displacement with indentation. When multiplied by the surface area, the displacement provides approximate measurements for change in tissue volume (neglecting edge effects). The force divided by surface area provides an approximate indication of pressure under the indenter. Tissue force-displacement curves were recorded for forces applied cyclically up to 120 N. The cycle period was 15 s. The response curves (e.g., see Fig. 2) were of a shape similar to those reported by Fung for force-displacement of rabbit mesentery [1]. During cycling between a minimum and a maximum indentation force, the force-displacement curves remain within an envelope curve. Other patterns of indentation force application fall within the same envelope. The data reported below are taken from the force-displacement envelope, when the force is cycled monotonically back and forth between minimum and maximum. Duplicate curves were recorded to establish repeatability of the data.

Extraction of Study Parameters

Calculation of tissue mechanical parameters is illustrated in Fig. 2B. Softness (SOFT) is the maximum excursion of tissue displacement divided by the force of the indenter. It is calculated by refer-

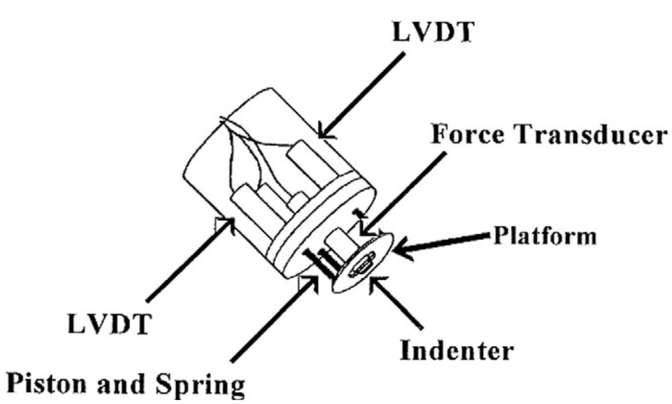

FIG. 1. Schematic diagram of the noninvasive mechanical tester sensor. Three linear variable displacement transducers (LVDTs) are located symmetrically around the force transducer and connected to a stable platform that rests lightly upon the surface of the skin about the indenter.