ROBOTIC NEEDLE INSERTION IN SOFT MATERIAL PHANTOMS: AN EVALUATION OF THE PROPERTY OF COMMONLY USED MATERIALS

T.K. Podder[1], D.P. Clark[1], J. Sherman[1], D. Fuller[1], D.J. Rubens[2,4,5], W.S. Ng[4], E.M. Messing[3,4], W. O'Dell[1], J.G. Strang[3], Y.D. Zhang[1], and Y. Yu[1]

Departments of [1]Radiation Oncology, [2]Radiology, [3]Urology, and [4]Surgery
University of Rochester Medical Center, Rochester, NY 14642, USA.

[5]Department of Biomedical Engineering,
University of Rochester, Rochester, NY 14642, USA.

[6]Department of Mechanical and Aerospace Engineering,
Nanyang Technological University, Singapore 639798.

tarun_podder@urmc.rochester.edu

Abstract: Accurate placement of surgical needles is very important in a variety of medical procedures. However, precise interstitial intervention is quite challenging due to the heterogeneous nature of biological tissue. In order to better understand the force acting upon the needle during insertion procedure, different types of soft material phantoms have been experimented upon in the recent years. In this paper, we have performed a comprehensive study on surgical needle insertion force into soft materials (agar, gelatin, silicon rubber, and polyvinylchloride). Experimental results include insertion force as well as a Young's modulus analysis. Additionally, the effects of temperature, and amount of time between phantom preparation and experimentation have been investigated. Initial results show that depending upon the material used, material properties will vary significantly due to both temperature as well as elapsed time. These variations can greatly change experimental results causing erroneous conclusions.

Introduction

Precise placement and steering of needle are very important for percutaneous intervention, which is an essential part of many medical diagnostic and therapeutic procedures. But accurate steering and placement of surgical needle in soft tissue are challenging because of several reasons. Some of them are: inhomogeneity and elastic stiffness of the tissue, needle bending, inadequate sensing, deformation and displacement of soft tissue, unfavorable anatomic structure, and poor maneuverability. Researchers have performed different types of experiments and developed various models for needle insertion forces [1-3]. Needle deflection and positional accuracy during the insertion have also been investigated by several researchers [4-6] Most of the researchers, in the initial stage, perform their experiments using mainly soft material phantoms for several reasons: (1) unlike biological tissues, soft materials like agar, gelatin, silicon rubber, polyvinylchloride (PVC) etc. are isotropic and homogeneous (or near homogeneous), (2) property of soft material phantoms can be easily manipulated, (3) soft material phantoms can be stored easily for future experiments, and (4) these materials are easily available and less expensive.

In [1], O'Leary *et al*. have used silicon rubber phantoms for their experiments to investigate the effects of friction and needle geometry for robotic needle insertion. Schneider *et al*. [2] have used PVC phantoms to test their robotic system for transrectal needle insertion into the prostate. DiMaio *et al*. [3] have developed some analytical models for estimating needle forces and soft tissue deformation using Finite Element Method (FEM). These models have been verified by experimentations with PVC phantoms. In [4], Ebrahimi *et al*. have tested their hand-held steerable needle device using PVC phantoms with three different concentrations of hardener and reported constant Young's modulus. L. Hiemenz *et al.* [5] have studied the effects of change in concentrations of gelatin on puncture resistance and modulus of compression. In [6], Wang *et al.* have validated their hypothesis of needle insertion accuracy improvement using agar phantoms.

In the currently available literatures, little information is available regarding the physical properties of the soft material phantoms and the property change with composition/ concentration, time elapsed, temperature; and sometimes it is difficult to recreate or compare the results. In this study we have investigated the change in physical properties (needle insertion force, and Young's modulus) of the commonly used soft materials such as agar, gelatin, PVC, and silicon rubber with change in composition, temperature and mount of time elapsed.

Materials and Methods

In these experiments, commercially available and commonly used 17-gauge (1.47mm diameter & 200mm long) brachytherapy needles (Mick Radio-Nuclear Instruments, Inc., NY) were used. Needle insertion forces were measured during penetration in a variety of phantoms prepared from three commonly used materials: (a) agar (Bacto™ from

Becton Dickinson & Co., MD) and water, (b) gelatin and water, (c) polyvinylchloride (PVC) – a liquid plasticizer and a softener (Super Soft Liquid Plastic, from M-F Manufacturer, TX), and (d) silicon rubber (TC-5005 A/B-C, BJB Enterprises, Inc., CA). A wide range of elastic properties can be achieved by varying the ratio of gelatin to water, agar to water, softener/hardener to plasticizer, and TC-5005C to TC-5005A/B. We prepared several phantoms for each of the aforementioned materials. The cylindrical phantom dimensions used for (1) needle insertion were 15cm in length and 7.62cm in diameter, (2) compression tests (Young's modulus tests) were 6cm in length and 7.62cm in diameter, and (3) time elapse experiments were 7.5cm in length and 8cm in diameter.

Figure 1: Test setup

The needle was inserted in the phantom vertically from the top by a 6 degree-of-freedom (DOF) robotic system (Figure 1). A 6 DOF force/torque (F/T) sensor (Nano17®, ATI industrial automations, NC) was mounted at the proximal end of the needle. A 5mm thick plexiglas compression plate was held against the F/T sensor during compression test. The robotic system was kinematically controlled; commands were sent using LabVIEW™ (version 7.1 from National Instruments). The software was executed on Windows XP in a Pentium® 4, 1.6GHz computer with graphical user interface (GUI), which we developed. The time, position and force on the needle were recorded at a frequency of 100Hz. Here we presented data that were smoothed using a running average with a 50-point window. All the data were averaged from five insertions for each type of needles, each type of phantoms, and at each insertion/rotation speed.

Results and Discussions

In all the experiments we used trapezoidal velocity profile for the needle. Both the acceleration and deceleration of the needle was 508 mm/s^2. The velocity we used was 5mm/s, which the robot can attain in 0.01s with only 0.025mm of movement.

Experiment 1: PVC concentration

In this experiment we prepared three PVC phantoms with different percentage of plasticizer and softener: (1) 50% PVC (50% plasticizer and 50% softener by vol.), (2) 75% PVC (75% plasticizer and 25% softener by vol.), and (3) 100% PVC (100% plasticizer and 0% softener by vol.). Like softener, a hardener is also available to prepare harder phantom. However, for these experiments we found PVC without hardener to be too strong as compared to the strongest agar (3% agar and 97% water by weight) or gelatin (20% gelatin and 80% water by weight) phantoms. The actual penetration distance of the needle into the phantom was 13.24cm. The needle insertion forces for penetration as well as withdrawal (in loop form) all three phantoms are plotted in Figure 2 and the percentage change is presented in Table 1.

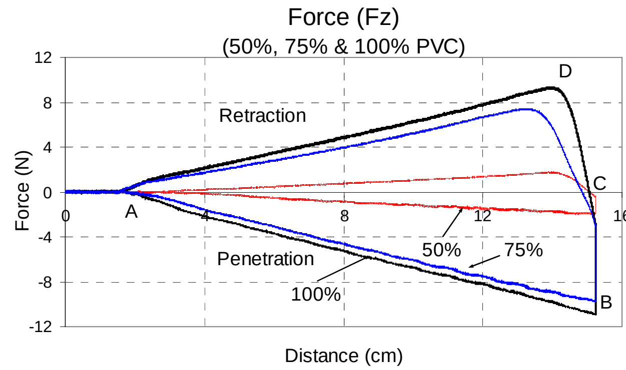

Figure 2: Forces in z-direction while inserting needle in polyvinylchloride (PVC) with different percentages of plasticizer (50%, 75%, and 100%).

Table 1: Changes in penetration force exerted on needle along z-axis for different concentrations of PVC.

PVC Concentration (%)	Force (N)	% Change
50	1.93	
75	9.69	402.3
100	10.86	12.1

From these plots (in Figure 2) it is observed that the force profiles for all the samples are similar, but the amounts of force experienced by the needle are different. Although the PVC concentrations were equally spaced (50%, 75% & 100%), the forces changed differently, i.e. force difference between 50% and 75% PVC is remarkably high (403.3%) as compared to that of between 75% and 100% PVC (12.1%) (Table 1). The main force (z-force) is the summation of stiffness force, friction force, and cutting force. Initial zero force for 2cm distance (up to point A) indicates the needle did not reach/touch the phantom. Once the needle tip touches the phantom, the needle force starts developing with mainly stiffness force and puncture force, then friction force grows gradually. The friction force, which is a combination of mainly the coulomb friction, and viscous friction, is linear and directly proportional to length of needle in the material. This linearity continues almost up to the end of the penetration, i.e. till 15.24cm (point B). Then the needle motion was stopped for 5s during which period the material relaxed (from point B to point C). During this time the force changes to about -2.9N from –10.9N for 100% PVC. The –2.9N compressive stiffness force which could not be released, requiring more time to relax. After 5s of pause (note that after full penetration, there was a pause of 5s before retraction of the needle), the needle starts retracting and the load changes from compressive to tensile, i.e. the material starts pulling back the needle. The stiffness force and the friction force increase to a critical value (9.3N for 100% PVC, up to point D), then material no longer can hold back the needle, and the force starts decreasing linearly as the portion of needle in the material gradually reduced. Up to point D the whole length of needle was in the material, x_t is the elongational deformation of the material, x_c is the residual compression recovery. During retraction, there is no cutting force on the needle. If we assume that the stiffness behavior of the PVC is the same in both compression and elongation, then the difference of absolute force at point B and point D is the cutting force (1.6N for 100% PCV).

Experiment 2: Gelatin concentration

In this experiment we prepared three gelatin samples with 5%, 10% and 20% gelatin concentrations (by weight) in water. We tried to make gelatin phantoms, which could provide comparable force that is experienced with PVC, but could not add more than 20% gelatin. The needle traveled for 13.2cm with 11.2cm penetration in the material, because the mold length/depth was limited due to shrinkage during solidification. From F_z force plots (Figure 3) it is observed that the 5% and 10% gelatin samples impart quite close forces and 20% gelatin sample exerts higher force on the needle. However, the nature of the forces is identical. We do not observe much elongational deformation, which was prominent with PVC (F_z plots slanting left during retraction). Thus, gelatin is less rubbery (or sticky) when compared to PVC. The bulging shape at the beginning of the needle insertion into the material indicates higher piercing force requirement.

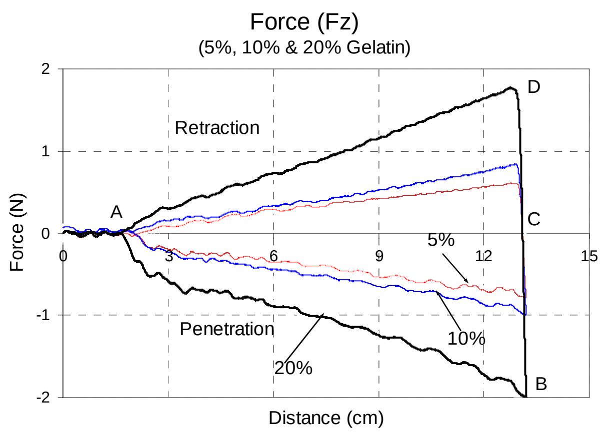

Figure 3: Forces in z-direction while inserting needle in gelatin phantom with 5%, 10%, and 20% concentrations.

Table 2: Changes in force exerted on needle along z-axis for different concentrations of Gelatin.

Gelatin Concentration (%)	Force (N)	% Change
5	0.79	
10	1.0	27.1
20	2.01	100.8

Experiment 3: Agar concentration

In this experiment we used three agar (Bacto™) samples with 1%, 2%, and 3% (by weight) of agar concentrations in water. In agar the needle traversed a total of 13.2cm with 11.2cm penetration into the material phantoms. The maximum concentration (3%) sample can exert about 1N force on the needle (see Figure 4). The F_z force profile is similar to gelatin samples where the force increases with penetration length and during 5s elapse the force relaxes quickly and during retraction the force picks up instantly as compared to that of in PVC. Percentage change of the insertion force is presented in Table 3, here we observe more change between 1% and 2% as compared to that between 2% and 3%.

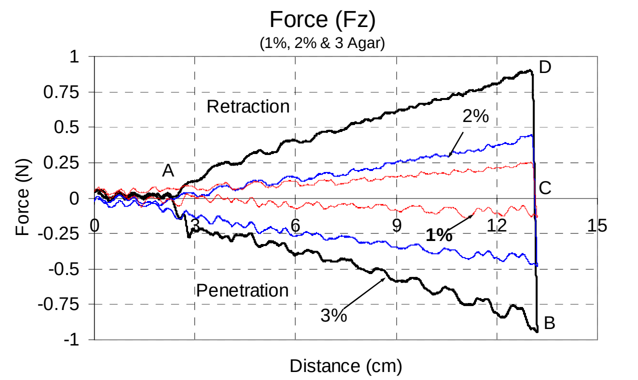

Figure 4: Forces in z-direction while inserting needle in agar phantom with 1%, 2%, and 3% concentrations.

Table 3: Changes in force exerted on needle along Z-axis for different concentrations of Agar.

Agar Concentration (%)	Force (N)	% Change
1	0.14	
2	0.48	238.4
3	0.94	96.1

Experiment 4: Change in insertion force over time

In this experiment, we have stored two sets of phantoms (PVC, gelatin, agar and silicon rubber) at different temperatures: one set was refrigerated at 6^0C (Figure 5), and the other set was kept on the shelf at room temperature (about 24^0C) (Figure 6).

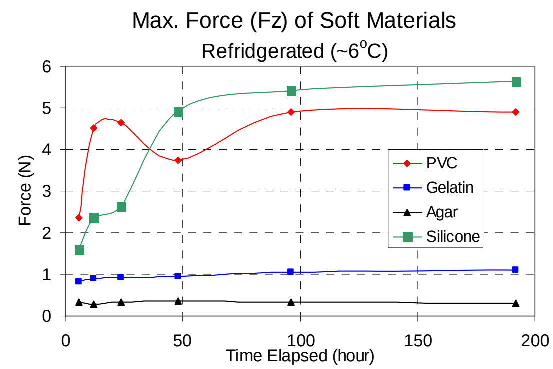

Figure 5: Change in insertion forces, i.e. resistances over time (at 6hr, 12hr, 24hr, 48hr, 96hr, & 192hr intervals) when the phantoms (PVC, gelatin, agar, & silicon rubber) are kept refrigerated at 6^0C temperature.

Needle insertion data were collected at six different time intervals (6hr, 12hr, 24hr, 48hr, 96hr, and 192hr) to study the effects of temperature and time elapse. From these plots it is observed that there are some significant changes in force during initial stages. This is mainly due to time required for the material to cure. It appears that the gelatin and agar phantoms are more consistent in the refrigerated condition. The PVC and silicon phantoms show more consistency at the initial stage if stored at room temperature. However, for a long time elapsed (more than 100hr) the refrigerated phantoms are exhibiting very consistent resistance during needle insertion.

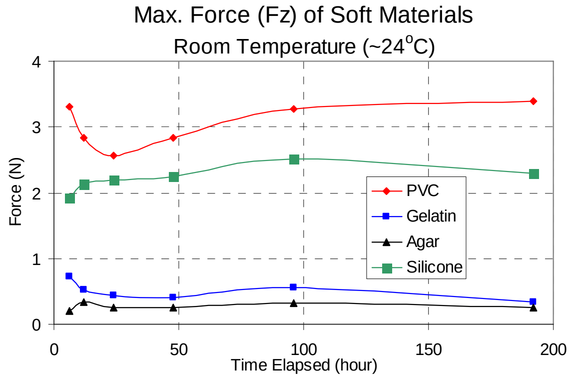

Figure 6: Change in insertion forces, i.e. resistances over time (at 6hr, 12hr, 24hr, 48hr, 96hr, & 192hr intervals) when the phantoms (PVC, gelatin, agar, & silicon rubber) are kept on the shelf at room temperature at about 24^{0}C.

Experiment 5: Elastic Modulus (Young's Modulus)

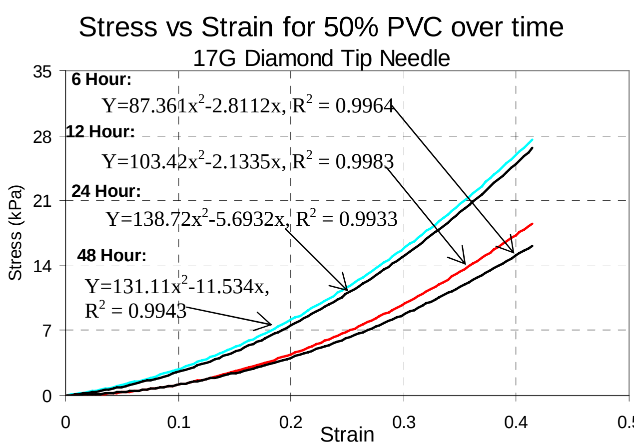

Figure 7: stress vs. strain plots of 50% PVC material at different time intervals (6hr, 12hr, 24hr, & 48hr).

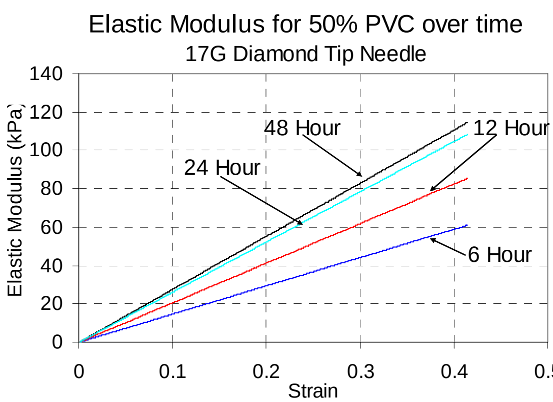

Figure 8: Change in Young's modulus of 50% PVC material at different time intervals (6hr, 12hr, 24hr, & 48hr).

In this experiment, 50% PVC phantoms (50% softener with 50% plasticizer) were used for compression test to determine the elastic modulus. These samples were compressed between 5mm thick plexiglas plates, and the force versus displacement data was collected; and then the stress and strain were calculated from force and deformation data. The stress vs. strain plots were approximated by best-fit second order polynomial (Figure 7). The derivatives (differentiations with respect to strains) of these polynomials were the elastic modulus of the material at different time elapsed (6hr, 12hr, 24hr & 48hr) (Figure 8). From these plots we observed significant change in elastic modulus with strain as well as with time elapse.

Remarks and Future work

We have performed five sets of experiments and observed some interesting performances of the most commonly used soft materials (agar, gelatin, PVC, and silicon rubber). We observe one of the main difficulties in experimenting with these soft material phantoms is the variation of property with time, temperature, and composition. It appears that more consistent results can be obtained if the phantoms are refrigerated for a longer period (more that 100hr). Therefore, care must be taken when experimenting with these soft material phantoms; an appropriate time-window should be utilized or temperature must be controlled carefully. In future, we plan to develop multi-layer soft material phantoms, which can mimic the various human tissues that the needle encounters during perineal insertion into the prostate during brachytherapy and other surgical procedures.

Acknowledgement

This work is supported by the National Cancer Institute, under grant R01 CA091763.

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