EFFECTS OF TIP GEOMETRY OF SURGICAL NEEDLES: AN ASSESSMENT OF FORCE AND DEFLECTION

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Abstract: Precise placement and steering of surgical needles is very important for many medical diagnostic and therapeutic procedures. But accurate steering and placement of needles in soft tissue is challenging because of a variety of reasons. In this study we focused on the effects of tip geometry (bevel tip, diamond tip, and conical tip) of brachytherapy needles while inserted in soft material phantoms. We have validated our hypothesis that rotation of needle can reduce deflection significantly.

Introduction

Accurate intervention of surgical needles is very important in various medical diagnostic and therapeutic procedures like tissue biopsy, brachytherapy, anaesthesia, vaccinations, blood/fluid sampling, abscess drainage, catheter insertion, cryogenic ablation, electrolytic ablation, neurosurgery, deep brain biopsy,, etc. But precise placement of needle is challenging because of several reasons such as tissue heterogeneity and elastic stiffness, tissue deformation and movement, unfavorable anatomic structures, needle bending, inadequate sensing, and poor maneuverability. Some of the factors such as needle bending, tissue deformation and movement are directly proportional to the forces experienced by the needle during interstitial intervention. A portion of these forces depends on the needle tip geometry. For example, bevel tip (BT) needle experiences more transverse force as compared to diamond tip (DT) needle or conical tip (CT) needle and thereby the BT needle bends more. Deflection of a needle from the desired target is critical in percutaneous procedures because it may create complications such as vital tissue damage, misdiagnosis, under/over dosing with radiation, tumor seeding, etc. Thus, the reduction of force or change in orientation of the needle may reduce the needle deflection and target movement resulting in enhanced surgical interventions. Therefore, understanding the complex mechanism of needle interaction with soft tissue is an area of active research. Several researchers have performed different types of experiments and developed various models for needle insertion forces in order to understand and predict the interaction between needle and soft materials or tissues [1-8]. Researchers have emphasized thorough testing and in-depth analysis, development of new testing and modeling methodologies, and multiple model (e.g. deformation, friction, and optimal speed) integration for better understanding and re-generating the complex *in vivo* soft tissue environment during various percutaneous interventions [2-6, 9-10].

In this study we have investigated deflection of brachytherapy needles with different tip geometry and validated our hypothesis that continuous rotation of needle can reduce the deflection significantly.

Materials and Methods

We have used polyvinylchloride (PVC) – a liquid plasticizer (Super Soft Liquid Plastic, M-F Manufacturer, TX) as phantom material. Both liquid softener and hardener can be added to the plasticizer to achieve a wide range of material property. We prepared phantoms with three different concentrations of softener and hardener (25% & 40% softener, and 25% hardener). The phantoms were 7.5cm in diameter and 10.8cm & 6cm in length (Figure 1). Two types of phantoms (phantoms 3 & 4 in Figures 1(b) & 1(c)) were supported peripherally by a solid PVC tube whereas the phantoms (phantom 1 & 2) as shown in Figure 1(a) were not supported by any tube; they were supported at the base only. Cylindrical phantoms were placed on syntactic foam blocks on which graph papers were pasted. The reference point on the graph paper was the first insertion when there was no phantom on the paper; subsequently five insertions were

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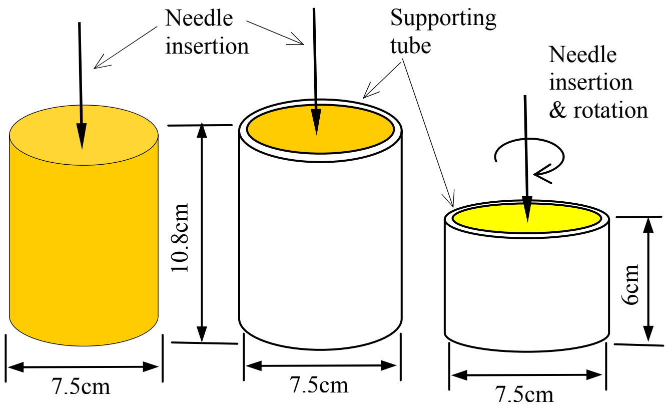
made through the phantom and the distances from the reference position were measured and then averaged to get the needle deflection.

Brachytherapy needles (18gauge, i.e. 1.27mm in diameter and 200mm in length) with different tip geometries, i.e. bevel tip (BT), conical tip (CT), and diamond tip (DT) were inserted in the phantoms vertically from the top by a 6 degree-of-freedom (DOF) robotic system. A 6 DOF force/torque sensor (Nano25®, ATI) was mounted at the proximal end of the needle. The time, position, and force data were recorded at a frequency of 100Hz. All the data were averaged from five insertions for each type of needle, each type of phantom, and at each insertion/rotation speed.



(a) Phantom 1 &2
25% softener
25% hardener

(b) Phantom 3
in solid tube
25% softener

(c) Phantom 4
in solid tube
40% softener

Figure 1: Shape and size of polyvinyl chloride (PVC) phantoms with different concentration of softener and hardener; and different needle insertion modes.

Results and Discussions

Experiment 1:

The phantoms (as shown in Figure 1(a)) used in this experiment were supported at the base only. The needles (BT (with 10^0 bevel angle), DT, & CT) were inserted vertically downward along the perimeter of a 3cm diameter circle around the center of the 7.5cm in diameter phantom. Since there were no tubes around these phantoms, they had flexibility (to some extent) to move laterally; one can imagine some sort of similarity of mounting of internal organ (like prostate) in human body. The needles were inserted at 5mm/s constant velocity.

Needle deflections and force profiles are presented in Figure 2 through Figure 6. From Figure 2, it is observed that the BT needle deflected the most and the DT deflected the least. The CT needle deflected almost the same amount (5mm) as the DT needle in the softer phantom, but deflected about 10mm in the harder phantom (Figure 2). From Figures 3 & 5, it is observed that needle penetration force on the CT needle is the most and that on the BT needle is the least. This difference is attributed to poor cutting capability of the CT needle. However, the resultant transverse force on BT needle is the most for the softer phantom (Figures 4 & 6). But in the case of harder phantom, the transverse force on CT needle is quite significant (Figure 6); this again may be due to the poor cutting capability and associated phantom deformation/ dynamics caused by the lack of lateral supports.

From these experimental results we observed that support of the phantom is critical; needles deflect more in harder phantom; although a bevel tip needle experiences less axial force (insertion force), it deflects the most.

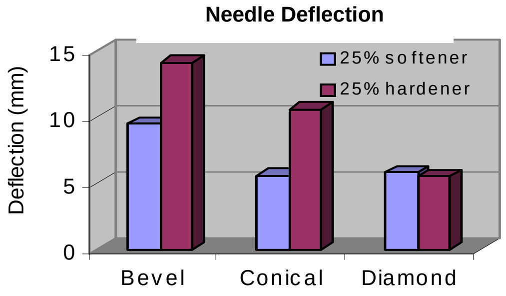


Figure 2: Final deflection of needle tips.

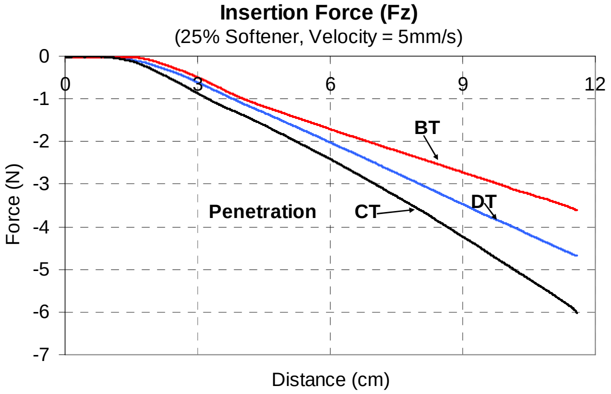


Figure 3: Penetration forces (F_z) for 25% softener.

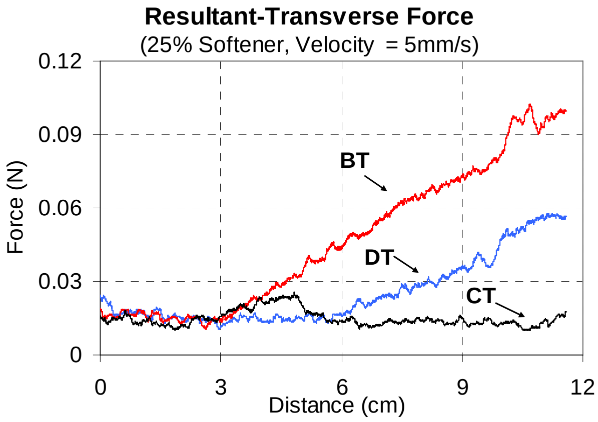


Figure 4: Resultant transverse forces ($F_{x,y}$) for 25% softener.

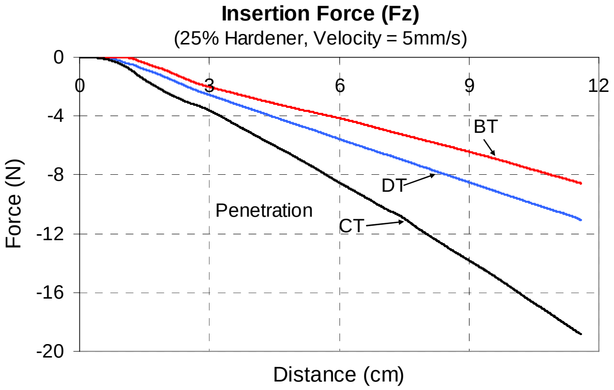


Figure 5: Penetration forces (F_z) for PVC with 25% hardener.

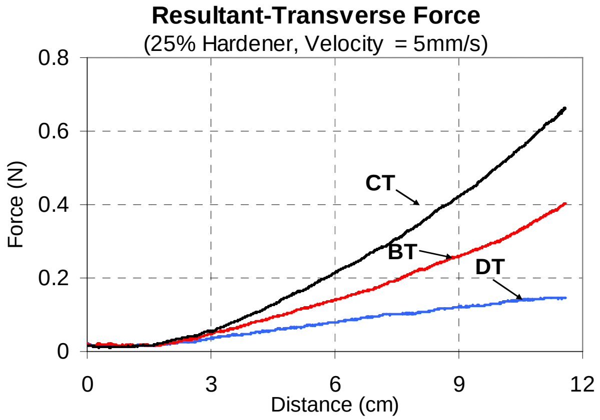


Figure 6: Resultant transverse forces ($F_{x,y}$) for PVC 25% hardener .

Experiment 2:

The cutting force on any BT needle can be resolved into axial and transverse components (Figure 7) as follows:

$$F_{cz} = F_c \ \sin(\theta) \qquad (1)$$

$$F_t = F_c \ \cos(\theta) \qquad (2)$$

where, F_c is the total cutting force, θ is the bevel angle, F_{cz} is the axial component of F_c and F_t is the transverse component of F_c. From equation (1) it is obvious that the axial force (F_{cz}) increases with increase in cutting force (F_c) and with an increase in bevel angle (θ). However, the main contributing factors of an increase in total axial force F_z are the friction and stiffness change due to the change in phantom composition. From equation (2) we observe that transverse force on BT needle increases with decrease in bevel angle (θ) and with increase in cutting force (F_c). This transverse force is mainly responsible for large deflection of BT needles.

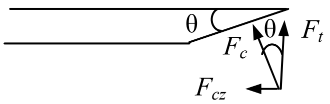


Figure 7: Axial and transverse components of cutting force on bevel tip (BT) needle.

The phantom used for this experiment was supported peripherally by a solid tube (the liquid PVC was solidified in a rigid tube; Figure 1(b)). Three types of needles (BT needles with two different angles (10^0 and 20^0), DT and CT) were inserted vertically downward while the phantoms were kept on graph papers pasted on foam blocks. Average of five insertions for each of the 2cm, 4cm, 6cm, 8cm & 10cm long phantoms are plotted in Figure 8 (at 5mm/s insertion speed) and in Figure 9 (at 50mm/s insertion speed).

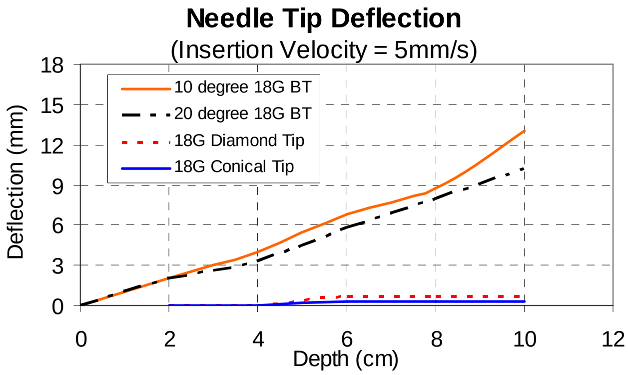


Figure 8: Needle deflection vs. depth of penetration at 5mm/s into PVC phantom with 25% softener.

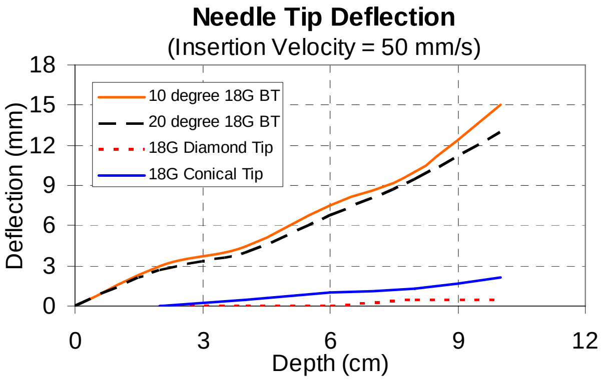


Figure 9: Needle deflection vs. depth of penetration at 50mm/s into PVC phantom with 25% softener.

From theses plots (Figures 8 & 9) it is observed that the velocity has a significant effect on needle deflection, with increase in insertion speed the deflection increases. It is also noticed that the BT needle deflects the most; at a lower speed (5mm/s) deflections of the DT needle and the CT needle are insignificant; but at a relatively higher speed (50mm/s) their deflections are prominent and the DT needle tends to deflects more than that of CT needle.

Experiment 3:

In this experiment we have prepared PVC phantom with 40% softener; stiffness of this phantom was close to bovine liver. Here we have validated our hypothesis that rotation can decrease the deflection of a BT needle. The needle was rotated at 60rpm, 600rpm, 1800rpm and 4200rpm while it was inserted at 5mm/s. The deflection at each speed was averaged from five insertions. The results are shown in Figure 10. It is observed that needle deflection was reduced significantly (more than 50%) even at 60rpm rotation; at 600rpm and 1800rpm there was a steady decrease in deflection, however, at 4200rpm deflection was a little more than that of 600rpm or 1800rpm. From these results it appears that needle deflection can be reduced by rotating the needles during insertion.

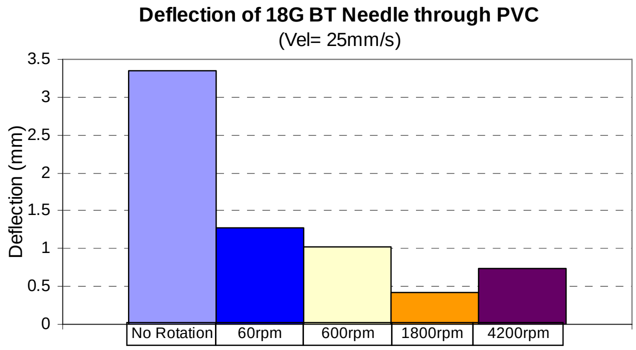


Figure 10: Reduction of needle deflection by rotating the needle at different speeds while inserted at 25mm/s into PVC phantom with 40% softener.

Conclusions

From our experimental results, it appeared that in all cases the BT needle deflected the most. With poor support, the DT needle was even more accurate as compared to the CT needle. With proper support of the phantom, the accuracy of DT and CT needles was comparable and the deflection was insignificant (at lower speed) as compared to that of for BT needle. The penetration force of the CT needle was the most because of its poor cutting capability, which increases the frictional force due to the small opening in the materials. We noticed that the deflection of the needle increased with increase in penetration depth. It has been observed that rotation can reduce deflection of bevel tip needle significantly. It may be argued that this type of drilling effect will remove a significant amount of material from the phantom or the biological organ. However, we did not observe any significant material removal during our experiments with PVC phantom; moreover, at relatively slow rotational speed, the 18G or 17G needles may not remove a significant (or any at all) amount of tissue. Therefore, needle rotation during percutaneous intervention may enhance accuracy of needle placement with minimal tissue damage. We are working on this aspect of the needle rotation with biological tissue phantoms.

Acknowledgement

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