

Histological Evaluation of Tissue Damage Caused by Rotational Needle Insertion*

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Abstract—Needles used in percutaneous insertion must be as thin as possible to minimize invasiveness. However, using extra-thin needles with a diameter less than 25G (0.53 mm diameter) can cause needle deflection. Needle deflection can be minimized by insertion with axial rotation along the needle shaft; this rotation is also useful for steering the insertion direction of the needle tip. However, although high rotation speeds may decrease needle deflection, this may increase tissue damage. Therefore, the purpose of this study was to histologically evaluate tissue damage caused by the rotational needle-insertion method, and to verify the needle-tip deflection caused by tissue damage. In this paper, we evaluated tissue damage and needle deflection caused by needle insertion with no rotation, unidirectional rotation, and bidirectional rotation. The results suggest that percutaneous needle insertion under unidirectional rotation is potentially risky in humans, as this causes wound-up tissue and expansion of the area of the hole created by the needle path. In contrast, needle insertion under bidirectional rotation appeared to minimize deflection, and prevented winding of tissue and expansion of the hole created by the needle path.

I. INTRODUCTION

Percutaneous needle insertion is used in minimally invasive medical applications such as tissue biopsy, blood sampling, brachytherapy, radio frequency ablation, and regional anesthesia. The injection of dendritic cell vaccines via percutaneous needle insertion directly into tumors has also recently been proposed as an immune therapy against cancer [1].

The needle must be as thin as possible to minimize the invasiveness of the procedure. However, using extra-thin needles with a diameter smaller than that of the 25G (approx. 0.5 mm diameter) may cause increased needle deflection. Curvature of the needle path can be controlled using duty-cycled spinning algorithms [2]; the needle path is relatively straight during high duty-cycled spinning, and curved during low duty-cycled spinning. Bidirectional rotation has been used to steer flexible needles under duty-cycled spinning to avoid winding up wired sensors [3].

This rotational needle steering technique requires real-time information on needle-tip and tumor positions from ultrasonic images [4, 5]. However, real-time tracking is difficult because

of intestinal gas effects in the lower abdomen. Images from inside the body are usually obtained with computed tomography, which can provide clear images at intervals. Needle insertion with high duty-cycled spinning, ideally on a straight path, allows for accurate insertion under these conditions.

Observation of the path taken by needles inserted with axial rotation into a gel indicates that high needle rotation speeds may increase tissue damage [6]. Moreover, connective tissue was wound up when rotational needle insertion was tested in rats, and the force was increased as the needle was pulled out [7]. Tissue winding and needle deflection may occur more markedly when using an extra-thin needle. However, few studies have focused on histological evaluation of tissue damage caused by rotational needle insertion, and the effects of the needle-tip deflection caused by tissue damage are not well understood.

Therefore, the purpose of this study was to histologically evaluate tissue damage caused by the rotational needle-insertion method, and to verify the effect of the needle-tip deflection caused by tissue damage. We evaluated tissue damage and needle deflection caused by needle insertion with no rotation, unidirectional rotation, and bidirectional rotation.

II. TISSUE DAMAGE CAUSED BY NEEDLE INSERTION WITH ROTATION

A. Effect of Needle Rotational Direction

Needle insertion with unidirectional rotation is expected to minimize needle-tip deflection. However, when a needle is inserted with unidirectional rotation into biological tissue, the needle winds up the tissue due to viscous friction between the needle and tissue (Fig. 1); connective tissues such as fascia are particularly easily wound up [7]. We therefore considered needle-insertion methods that could minimize needle deflection while also preventing tissue damage; this could potentially be achieved by switching rotation directions, with rotation of 180° clockwise or counterclockwise (bidirectional rotation).

B. Robotic Needle-Insertion System

We used a robotic needle-insertion system to insert needles with axial rotation in the insertion direction. The axial rotation was achieved with a 24V stepping motor (BE231DJ-KLCN; Parker, USA) connected by gears. Needle insertion was performed by uniaxial movement of the ball screw (003-3891-53, Parker). In addition, a 6-axis force and torque sensor (Nano17A SI-12-0.12; ATI, USA) was attached to the needle-holding part, connected with a slip ring

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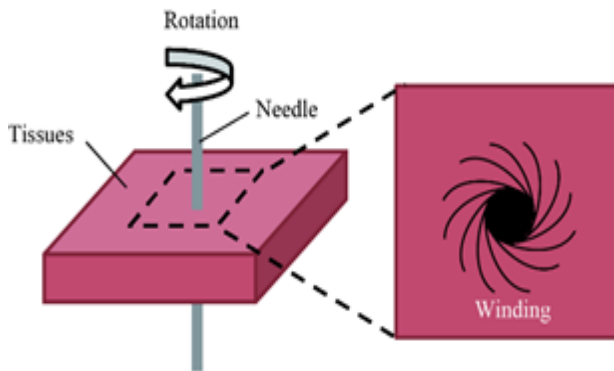


Figure 1 Wind-up of tissue caused by unidirectional rotation during needle insertion.

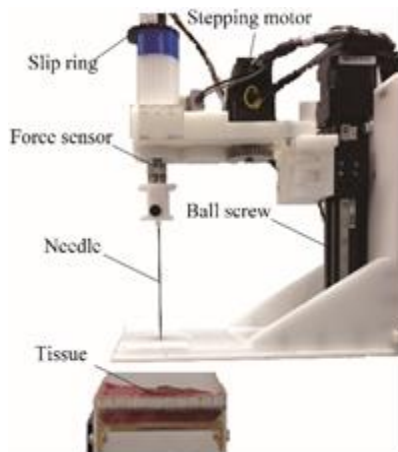


Figure 2 Experimental setup.

(322M1-1200-HS1; Orbex Group, USA) that allowed infinite unidirectional rotation between the controller and transducer.

C. Experimental Protocol

We evaluated the needle-tip deflection and tissue damage caused by different rotation parameters. The needle was inserted with uni- or bi-directional rotation parameters as follows: 0 rpm (both conditions), 100 rpm (both conditions) or 1,000 rpm (unidirectional). All experiments were performed using a bevel-tipped 25G disposable needle (diameter: 0.53 mm, length: 100 mm). Each needle was only used once to avoid dulling of the needle tip. We also measured needle insertion force in all experiments.

In the verification of needle-tip deflection, 100 mm $\times$ 100 mm $\times$ 20 mm rounds of beef containing little fat were used as the insertion target. The needle insertion speed was 5 mm/s, and the insertion distance was 80 mm. Experimental trials were performed eight times under each rotational condition. The needle-tip deflection was measured and calculated using the number of image pixels on a video imagery screenshot (HDR-PJ; Sony, Japan).

D. Results

Figure 3 shows the results of the needle-tip deflection experiments. Some of the unidirectional rotation trials had to be discontinued because the needle wound up the tissue and

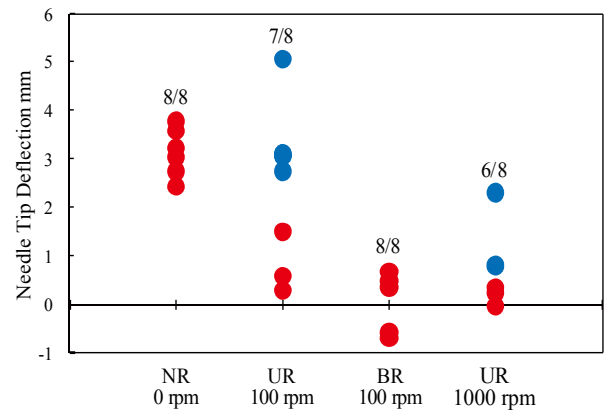


Figure 3 Needle tip deflection for all insertion methods.

NR: no rotation, UR: unidirectional rotation, BR: bidirectional rotation. The numbers above each set of data indicate the number of successful trials per number of attempted trials (some trials failed because of extreme tissue wind-up). The blue points indicate results with tissue attached to the needle tip, and the red points indicate results with no attached tissue.



Figure 4 Photograph of tissue attached to needle tip

TABLE I Trials in which tissue attached to the needle tip and trials that failed

Rotation condition	0 rpm	100 rpm (Unidirectional)	100 rpm (Bidirectional)	1,000 rpm
Attached tissue	0	3	0	2
Failure	0	1	0	2

became extremely bent. The number of times that the needle was inserted completely is shown on the graph (Fig. 3). In some trials there was wound-up tissue attached to the needle even though the needles were inserted completely (Fig. 4). The number of trials that were discontinued, and the number of trials in which tissue was found attached to the needle tip are shown in Table I.

The needle-tip deflection in four of seven successful trials with unidirectional rotation at 100 rpm was significantly less than in the trials with no rotation; however, the deflection in the other three trials with unidirectional rotation at 100 rpm was equal to or greater than in the trials with no rotation. The needle deflection in all trials using bidirectional rotation at 100 rpm was significantly decreased compared with trials using unidirectional or no rotation. The needle deflection with unidirectional rotation at 1,000 rpm was significantly decreased in five of six successful trials, but was not decreased in one trial.

There was no failure of needle insertion and no tissue attached to the needle tip in the trials with no rotation or bidirectional rotation. In contrast, needle insertion failures occurred in trials in which the needle was rotated unidirectionally at both 100 rpm and 1,000 rpm; although the needle was inserted successfully, wound-up tissue was

sometimes observed, and the needle-tip tended to be deflected by large distances.

Needle insertion force was markedly increased in trials that were confirmed to have tissue attached to the needle, while the force was not increased in trials that had no attached tissue. Figure 5 shows the force measured in a case where tissue was attached to the needle compared with the force measured in a case where no tissue was attached under unidirectional rotation at 100 rpm.

E. Discussion

There was variation in needle deflection in each trial using unidirectional rotation; hence, the larger deflection may be attributed to enlargement of the insertion resistance force due to attachment of tissue to the needle. The attached tissue often covered the sharpened edge of the needle tip, and would presumably have provided resistance during insertion. We focused on the force data of the 100-rpm trials and confirmed that the insertion force was markedly increased in cases where tissue was attached to the needle (Fig. 5).

III. OBSERVATION OF TISSUE SECTION

A. Histological Observation of Tissue Damage

In Section II, we confirmed that tissue became wound up by needle insertion with rotation. We hypothesized that the wound-up tissue corresponded to an increase in the area of the hole created by the needle path. Tissue fractures and deformations have previously been histologically evaluated by fixing tissue (with the needle still inserted) in formalin and creating tissue sections along several directions [8]. We used this method to measure the area of the hole created by the needle path in tissue sections in order to quantitatively evaluate the tissue damage caused by needle insertion.

B. Experimental Protocol

We histologically evaluated the area of the hole created by the needle path caused by insertion with no rotation, uni- and bi-directional rotation. Four rotational parameters were used: 0 rpm, 100 rpm (both rotational conditions), and 1,000 rpm (unidirectional rotation). All experiments were performed using bevel-tipped disposable 25G needles (diameter: 0.53 mm, length: 100 mm). The insertion speed was 1 mm/s, and the insertion distance was 50 mm. Experimental trials were

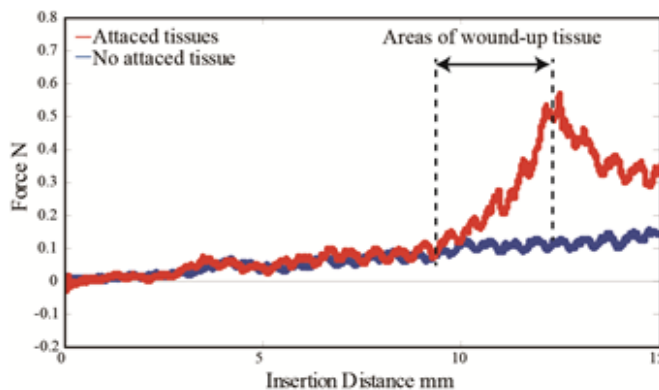


Figure 5 Comparison of force measured in a case where tissue was attached to the needle and a case where no tissue was attached under unidirectional rotation at 100 rpm.

performed three times under each rotational condition. We also examined the needle tips to determine whether tissue was attached after needle was completely inserted.

We used 50 mm × 50 mm × 20 mm rounds of beef as the insertion target. The tissue in which the needle remained was immediately fixed after needle insertion in 10% neutral-buffered formalin and left for approximate 24 hours. After fixation, the needle was removed, and a small piece of fixed tissue was cut 5 mm from the bottom along the direction of the needle radius (Fig. 6a). If tissue was attached to the needle, fixed tissue was cut from the position at which the needle insertion force was markedly increased (Fig. 5 and Fig. 6b). The tissue was dehydrated (ASP300; Leica Microsystems, Germany) and embedded in paraffin (EG1160; Leica Microsystems). The paraffin block was sliced with a microtome into sections 10-μm thick along the radial direction of the needle. In the case of attached tissue, the sliced area was taken from around the distance at which the peak insertion force appeared. In the cases without any attached tissue, the sliced area was taken from the bottom of the tissue. Tissue sections were stained with hematoxylin and eosin, and examined under an optical microscope (ECLIPSE E600; Nikon, Japan). Tissue section images were recorded by a camera connected to the microscope (DP70 Digital Camera; Olympus, Japan).

We used the method devised by Chan *et al.* [9] to detect the contour of the hole area created by the needle path, and measured and calculated this area. We made the binary image corresponding to the needle section in advance. The binary image was transformed by 200 repetitions of the method described by Chan *et al.* [9].

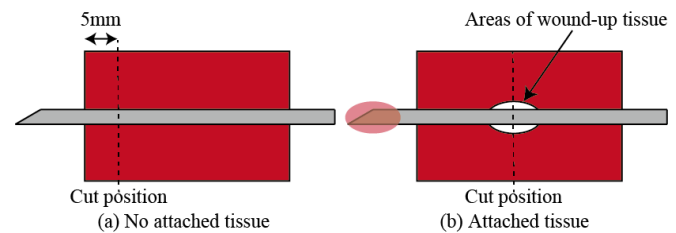


Figure 6 Cut position of tissue section.

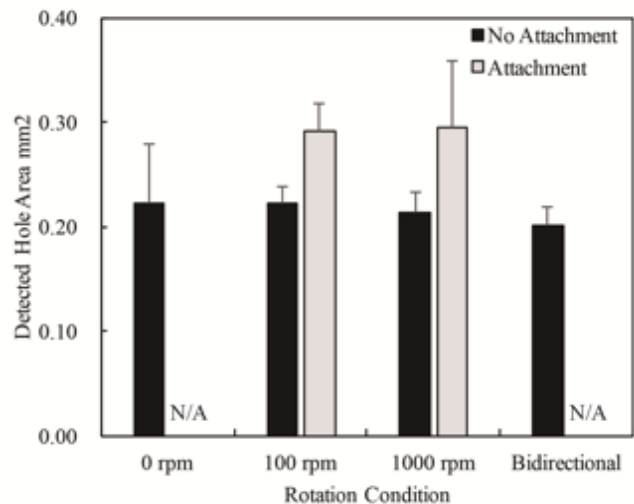


Figure 7 Comparison of the area of the hole created by the needle path under different rotational conditions (Needle cross section is 0.22 mm²).

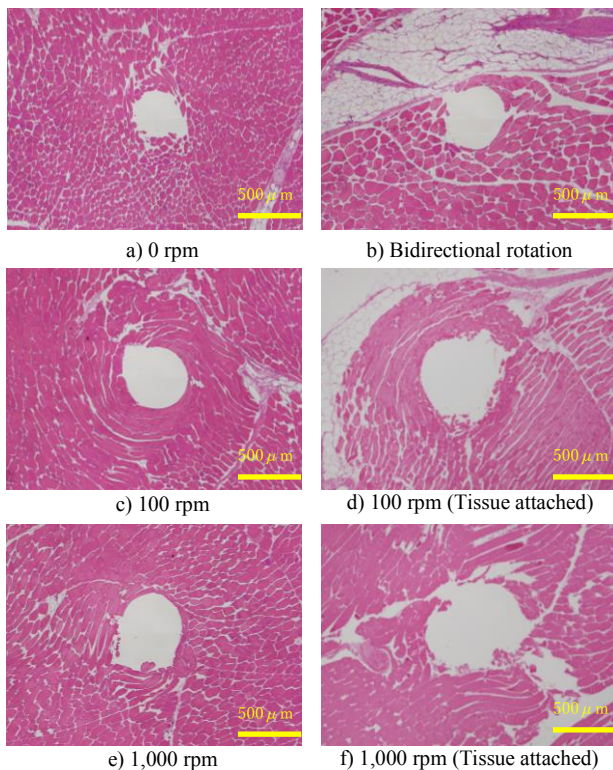


Figure 8 Magnified view of cross-sections of stained tissue sections.

C. Results

Figure 7 graphically shows the comparison of the hole areas of the needle path created by each rotational condition. Figure 8 shows examples of microscopic tissue cross-section images. The differences in area were statistically analyzed with two-way analysis of variance (Fisher's method).

Under unidirectional rotation (at both 100 and 1,000 rpm), the area of the hole made in cases where tissue was attached to the needle was significantly increased significantly compared to no attached tissues ($p < 0.01$). Also, there was no significant difference between no rotation, 100 rpm (no attached), 1,000 rpm (no attached) and bidirectional rotation, respectively.

D. Discussion

In the condition of unidirectional rotation, it was confirmed that the hole areas of needle path in the case of attached tissue were increased compared with the case of no attached tissue. On the other hand, it was confirmed that the hole areas of resulting from bidirectional rotation was almost equal to that created by needle insertion with no rotation. Therefore, it is reasonable to assume that the area of the hole is increased due to wound-up tissue. The attached tissue (Fig. 4) was identified as connective tissue, as the tissue was composed of muscle fibers, fatty tissue and collagen fibers (Fig. 9).

Needle insertion with unidirectional rotation into human bodies might be dangerous, as it is likely that the area of the hole left by the needle path will be enlarged because of the winding of tissues.

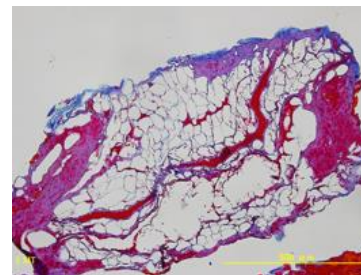


Figure 9 Specimens of attached tissue were stained with hematoxylin-eosin and Masson's trichrome. The blue area is connective tissue, the red area is muscle fiber, and the netlike area is adipocytes.

IV. CONCLUSION

We histologically evaluated tissue damage due to needle insertion with rotation, and verified the needle-tip deflection caused by tissue damage.

The results suggest that percutaneous needle insertion under unidirectional rotation is potentially risky in humans, as this causes wound-up tissue and expansion of the area of the hole created by the needle path. In contrast, needle insertion under bidirectional rotation appeared to minimize deflection, and prevented winding of tissue and expansion of the hole created by the needle path.

In future research, the authors will ascertain whether bidirectional rotation can robustly reduce needle-tip deflection and tissue damage in cases with different tissue such as multiple layer tissue including fat and muscle.

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REFERENCES

- [1] K. Hasumi, Y. Aoki, R. Wantanabe, and D. L. Mann, "Clinical response of advanced cancer patients to cellular immunotherapy and intensity-modulated radiation therapy," *Oncoimmunology*, vol. 2, no. 10, p. e26381, 2013.
- [2] D. S. Minhas, J. a. Engh, M. M. Fenske, and C. N. Riviere, "Modeling of needle steering via duty-cycled spinning," in *Annual International Conference of the IEEE Engineering in Medicine and Biology - Proceedings*, 2007, pp. 2756–2759.
- [3] A. Majewicz, J. J. Siegel, A. a Stanley, and A. M. Okamura, "Design and Evaluation of Duty-Cycling Steering Algorithms for Robotically-Driven Steerable Needles," *2014 IEEE Int. Conf. Robot. Autom.*, pp. 5883–5888, 2014.
- [4] M. Abayazid, R. J. Roesthuis, R. Reilink, and S. Misra, "Integrating deflection models and image feedback for real-time flexible needle steering," *IEEE Trans. Robot.*, vol. 29, no. 2, pp. 542–553, 2013.
- [5] G. Vrolijk and M. Abayazid, "Needle path planning and steering in a three-dimensional non-static environment using two-dimensional ultrasound images," *Int. J. Rob. Res.*, vol. 33, no. 10, pp. 1361–1374, 2014.
- [6] M. a Meltsner, N. J. Ferrier, and B. R. Thomadsen, "Observations on rotating needle insertions using a brachytherapy robot," *Phys. Med. Biol.*, vol. 52, no. 19, pp. 6027–6037, 2007.
- [7] H. M. Langevin, D. L. Churchill, J. Wu, G. J. Badger, J. A. Yandow, J. R. Fox, and M. Krag, "Evidence of connective tissue involvement in acupuncture," *FASEB J.*, vol. 16, pp. 872–874, 2002.
- [8] Y. Nakagawa and Y. Koseki, "Histological observation for needle-tissue interactions," in *Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society, EMBS*, 2013, pp. 6691–6694.
- [9] T. F. Chan and L. a. Vese, "Active contours without edges," *IEEE Trans. Image Process.*, vol. 10, no. 2, pp. 266–277, 2001.