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Robotic Cytology Using Extra-Fine Needles -Derivation of Suction Conditions for Collecting the Necessary Amount While Reducing Specimen Contamination with Blood-

Shotaro Tamura, Keisuke Oi, Ryusuke Hamano, and Hiroyasu Iwata, *Member, IEEE*

Abstract— **Fine-needle aspiration cytology (FNAC) is an inexpensive, quick, and minimally invasive diagnostic method for cancer. Physicians need to be highly skilled to perform FNAC as they are required to collect the appropriate quality and quantity of specimens. Many research have reported the robotic needle insertion method for improving the accuracy of needle placement using fine needles. These methods can expand the applicability of FNAC to organs deeper in the body, enabling less-invasive FNAC. However, there is little research focusing on the suction conditions and quality and quantity of specimens with extra-fine needles. In this study, we analyzed the suction conditions for reducing blood contamination and securing the necessary collection amount. The magnitude and duration of suction were chosen as the suction condition parameters. The effect of these parameters on collection amount and blood contamination was experimentally analyzed using pig organs. Blood contamination was evaluated by injecting ink into the organs to simulate blood and measuring the mass ratio of the liquid components of the specimen. The results showed that a long suction duration was effective in increasing the collection amount, and the collection amount reached saturation. Conversely, a small magnitude of suction was effective in reducing blood contamination in the specimens.**

I. Introduction

Fine-needle aspiration cytology (FNAC) is a diagnostic method for cancer [1] [2]. In FNAC, fine needles, such as a 22-gauge (ϕ0.71 mm), are inserted into the lesion; thereafter, negative pressure is applied using syringes, and cells are aspirated. The aspirated cells are observed by pathologists under a microscope for morphology analysis and diagnosis. FNAC is often used in the diagnosis of thyroid and breast cancer [2] [3]. This method is inexpensive, quick, and minimally invasive. Therefore, it is significantly beneficial for patients. To make accurate diagnoses with FNAC, it is important to accurately insert needles into lesions to collect specimens and collect cells of sufficient quantity and quality. Thus, physicians need to have the skills and experience to control the needle properly and carry out aspiration. Therefore, percutaneous FNAC is performed by physicians while checking the position of the needle tip using ultrasound images. However, percutaneous FNAC only applies to organs close to the body surface, which facilitates the accurate insertion of needles.

To accurately insert fine needles into the body, many robotic needle insertion systems have been developed [4] [5]. We proposed methods to control needles, as well as a preoperative path planning method using extra-fine 25-gauge (ϕ0.53 mm) needles, for lower abdomen organs [6] [7] [8]. These methods will enable less - invasive FNAC using extra-fine needles and may expand the scope of application to organs deeper in the body.

However, most previous research about robotic needle insertion systems have focused on insertion accuracy in the target organs, and less research have focused on the FNAC specimen’s appropriateness. FNAC is a minimally invasive diagnostic method. However, if sufficient quality and quantity of specimen cannot be obtained, the procedure must be repeated until meeting the requirements, resulting in tissue damage. When extra-fine needles (e.g., 25-gauge needles) are used in FNAC, they are less invasive; however, it is more difficult to obtain specimens of sufficient quality and quality [3]. Therefore, a method for FNAC that is minimally invasive and can provide specimens of sufficient quality and quality using extra-fine needles is required. We developed a needle insertion method to increase the aspiration cell amount in FNAC using 25-gauge needles [9]. We experimentally analyzed the relationship between the needle insertion motion and the specimen amount. Further, we proposed a method to increase the specimen amount by combining the needle’s reciprocating motion and rotation using the shape of the needle tip. The aspirated amount equivalent to that from a physician’s procedure using 22-gauge needles was obtained by that proposed method using 25-gauge needles. However, this previous study focused on only the relationship between the needle movement and specimen quantity but did not consider the aspiration conditions or specimen quality.

Studies have been conducted on the relationship between aspiration suction and specimen quality or quantity [10] [11] [12]. These studies suggested that reducing negative pressure improved specimen quality but reduced quantity. In these studies, the specimen quality was evaluated using a method called The Mair scoring system, in which pathologists examine the specimens under microscopes. However, 21-gauge or 22-gauge needles were used; no study has used extra-fine 25-gauge needles. Furthermore, no quantitative evaluation of the quality of specimens has been performed using physical quantities.

This study aims to analyze the relationship between aspiration conditions and the specimens’ quantity or quality

*Resrach supported by Hasumi International Research Foundation.
S. Tamura, K. Oi, and R. Hamano are with the Graduate School of Creative Science and Engineering at Waseda University, 27 Waseda-cho, Shinjuku-ku, Tokyo, 162-0042, Japan (email: 0kz462739345@asagi.waseda.jp).
H. Iwata is with the Faculty of Science and Engineering at Waseda University.

using 25-gauge extra-fine needles. One of the criteria for evaluating the quality of specimens is the quantity of blood contamination in specimens. If blood contaminates the specimens a lot, the cell morphology cannot be observed, and diagnoses cannot be made. In this study, we focus on the low level of blood contamination as a quality of the specimens. The analysis was carried out experimentally using pig organs.

II. ANALYSIS OF THE COLLECTED AMOUNT

Reducing the negative pressure or shortening the suction time can prevent blood contamination; however, this may reduce the collected amount of specimen. Therefore, we experimentally analyzed the effect of the magnitude of suction and suction duration on the amount of aspirated specimens.

A. Experimental Setup

The aspiration was carried out on pig livers by varying the magnitude of suction and the duration of suction. Needle insertion was performed with the 25-gauge needles using the needle insertion system we developed. Additionally, specimen aspiration was performed while conducting the needle motion, which has been confirmed to increase the amount of specimen [9]. The experimental overview is shown in Fig. 1. The suction conditions' parameters are shown in TABLE I.

Experimental procedures

① The mass of the glass slide was measured using an analytical balance (1-17260-01, AS-ONE Corp., Japan).
② A 25-gauge needle (12411600, 90 mm long, Unisis Corp., Japan) was attached to the insertion unit and a tube (X1-FL100(SB), Top Corp., Japan), and the syringe (SS-10ALZ40, Terumo Corp., Japan) was connected to the tube.
③ The needle was inserted into a pig liver to a depth of 20 mm.
④ A linear actuator (L12030P10, IR ROBOT, Korea) was used to pull syringes to each suction magnitude (volume) in TABLE I, and the specimen was collected by aspiration. During the aspiration, the needle was inserted 10 mm deep, rotated 180°, returned 10 mm, and rotated 180° again. Based on our previous research to increase the collection amount [9], this motion was repeated until each suction duration in TABLE I.
⑤ When it reached the suction duration, the negative pressure was released and the needle was removed from the liver.
⑥ The needle was removed from the needle insertion unit.
⑦ The sample was sprayed onto the glass slide using the syringe.
⑧ The mass of the glass slide was measured, and the difference from the previous measurement was regarded as the mass of the specimen aspirated.

Under each condition, as shown in TABLE I, six trials were conducted.

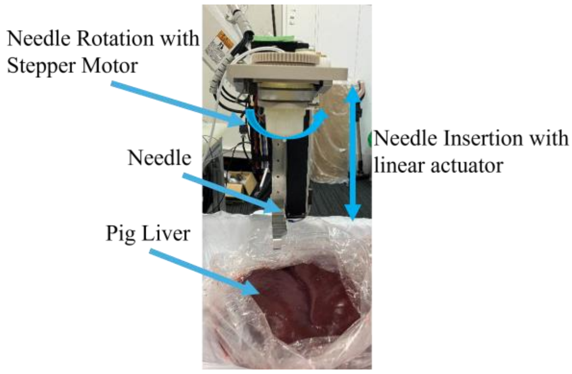

Figure1. Experimental overview

TABLE I. SUCTION MAGNITUDE AND DURATION CONDITIONS

		Suction duration [s]		
		20	30	40
Suction magnitude (by 10 mL syringe volume) [mL]	5	1	4	7
	8	2	5	8
	12	3	6	9

B. Result

Fig. 2 shows the change in the collection amount of specimens with suction of 5 mL when the suction duration was changed (comparison between conditions 1, 4, and 7). When the suction duration was increased from 20 s to 30 s, the collection amount increased significantly. Conversely, when the suction duration was increased from 30 s to 40 s, no significant change in the collection amount was observed.

Fig. 3 shows the change in the collection amount of specimens with suction of 12 mL when the suction duration was changed (comparison between conditions 3, 6, and 9). In this case, no significant change in the collection amount was observed even when the suction duration was changed. Similar results were obtained when the suction magnitude was 8 mL and the suction time was changed.

Fig. 4 shows the change in the collection amount of specimens with the suction duration of 20 s when the suction magnitude was changed (comparison between conditions 1, 2, and 3). In this case, no significant change in the collection amount was observed even when the suction magnitude was changed.

Fig. 5 shows the change in the collection amount of specimens with the suction duration of 40 s when the suction magnitude was changed (comparison between conditions 7, 8, and 9). In this case, no significant change in the collection amount was observed even when the suction magnitude was changed. Similar results were observed when the suction duration was 30 s and the suction magnitude was changed.

C. Discussion

The results showed that when the magnitude of suction was low, increasing the suction duration increased the collection amount until 20 s. When negative pressure was increased, there was no change in the collection amount with the change in suction duration. Therefore, even if the suction duration is increased, the collection amount will reach saturation at a specific point and will no longer increase.

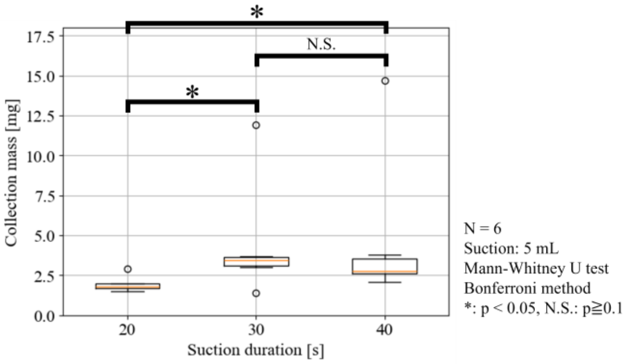

Figure 2. Change in the collection amount when changing the suction duration with a suction of 5 mL

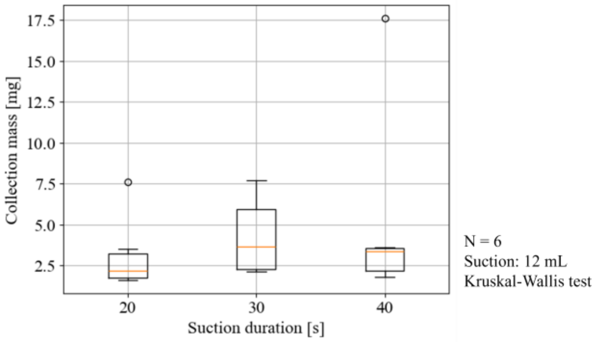

Figure 3. Change in the collection amount when changing the suction duration with a suction of 12 mL

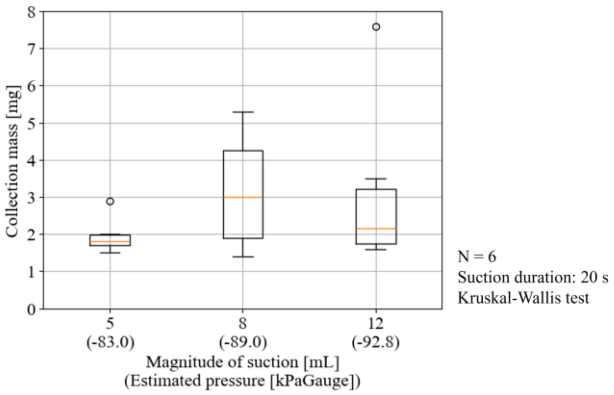

Figure 4. Change in the collection amount when changing the magnitude of suction with a suction duration of 20 s

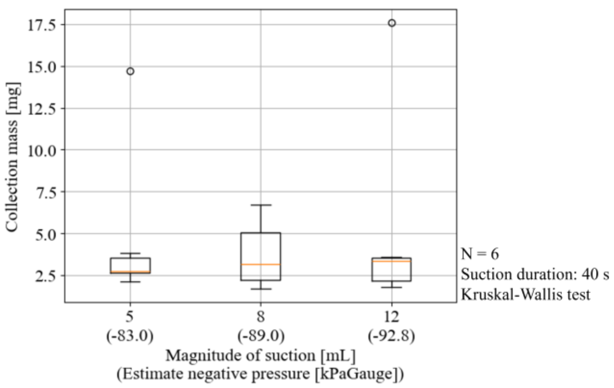

Figure 5. Change in the collection amount when changing the magnitude of suction with a suction duration of 40 s

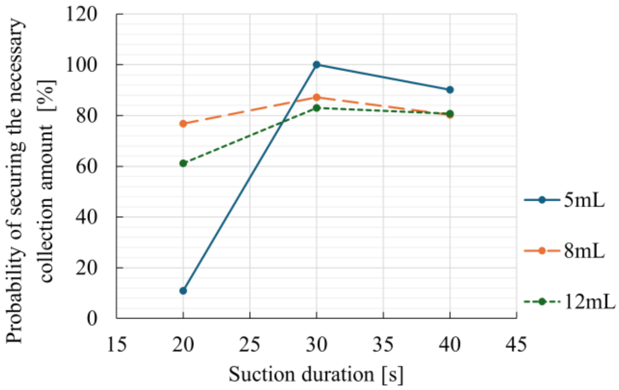

Figure 6. Probability of securing the necessary collection amount

When the magnitude of suction was changed, no significant change was observed in the collection amount at any suction duration.

From the above, it seems that the collection amount with the 25-gauge needle was saturated by applying 5 mL suction for 30 s. Therefore, a high magnitude or duration of suction will have a small effect on the collection amount and may only increase blood contamination.

Additionally, we consider the necessary collection amount. Previous studies have shown that 2.0 mg of specimens or more is necessary to make a diagnosis [13]. We assumed that the collection amount was normally distributed and that the mean and variance of the collection amount in the experiment were consistent with the actual values. Thus, the probability of securing the necessary collection amount was calculated under each condition using the average and variance of the collection amount obtained in the experiment, as shown in Fig. 6. Comparing the probability of securing the necessary amount by suction duration, the probability was low at 20 s; however, there was little change between the probabilities at 30 s and 40 s. Comparing the probability by the magnitude of suction, the probability was low at 5 mL only when the suction duration was 20 s. However, the change in the probability was small between 8 mL and 12 mL, and even when the suction duration was increased, the change was small. Generally, in FNAC, specimens are obtained multiple times. Therefore, regardless of the magnitude of suction, the necessary collection amount can be obtained by suctioning for 30 s or more.

III. Analysis of Blood Contamination

One of the factors that deteriorate the quality of specimens is blood contamination. When blood contaminates the specimen, it becomes difficult to observe the morphology of the cells. In this experiment, we analyzed how the magnitude and duration of suction affected blood contamination. The subject of aspiration was pig kidneys into which ink had been injected to simulate blood. The amount of blood contamination was evaluated using the proportion of liquid in the collected amount.

A. Experimental Setup

The aspiration was carried out on the pig kidneys into which ink had been injected to simulate blood by varying the magnitude and duration of suction. The ink was used to confirm the distribution of the liquid injected into the kidneys. The aspiration was performed on the area of the kidney where the ink was distributed. As presented in II, using 25-gauge needles, the aspiration was carried out by applying the needle movement to increase the collection amount [9]. The suction conditions' parameters are shown in TABLE II.

TABLE II. SUCTION CONDITIONS IN THE EXPERIMENT OF BLOOD CONTAMINATION

Conditions number	Suction magnitude (by 10 mL syringe volume) [mL]	Suction duration time [s]
1	5	20
2	5	30
3	5	40
4	8	20
5	12	20

Experimental procedures

① The renal artery and renal vein of the pig kidney were injected with 10% diluted India ink.

② The mass of the glass slide was measured using an analytical balance (1-17260-01, AS-ONE Corp., Japan).

③ Like experimental procedures from ③ to ⑧ of II, specimens were collected on glass slides under each suction condition from the pig kidney.

④ The glass slides were tilted to collect the liquid components in the specimen, and the liquid was absorbed with filter paper.

⑤ The mass of the slide was measured again, and the difference was regarded as the mass of the liquid component.

B. *Result*

Fig. 7 shows the change in the mass ratio of the liquid components in the collection amount when the magnitude of suction is changed (comparison between conditions 1, 4, and 5). In this case, the ratio of the liquid component significantly increased with the increase in the magnitude of suction.

Fig. 8 shows the change in the mass ratio of the liquid components in the collection amount when the suction duration is changed (comparison between conditions 1, 2, and 3). In this case, no significant difference in the change in the ratio of the liquid components by changing the suction duration was observed.

C. *Discussion*

The results show that the mass ratio of the liquid components in the collection amount increased with the increase in the magnitude of suction. Conversely, the suction duration had little effect on the liquid ratio. Therefore, the effective method for reducing blood contamination is to reduce the magnitude of suction.

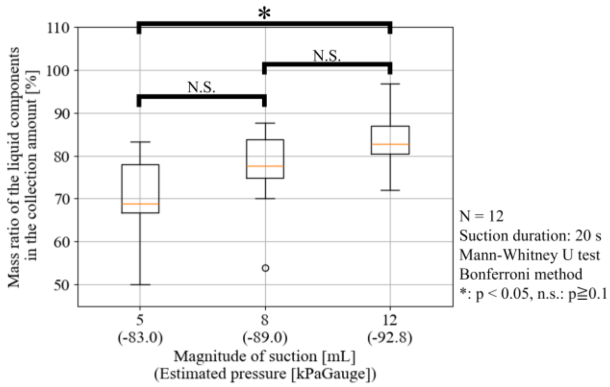

Figure 7. Change in the mass ratio of the liquid components when changing the magnitude of suction with the suction duration of 20 s

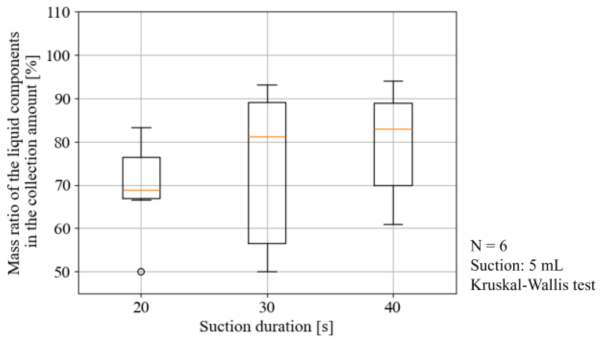

Figure 8. Change in the mass ratio of the liquid components when changing the suction duration with the magnitude of suction of 5 mL

IV. DISCUSSION

The suction pressure generated during collection is assumed to be caused by the isothermal expansion of air in the tube connecting the needle and syringe. When the volume inside the tube is V_0 and the atmospheric pressure is P_0, the total volume inside the syringe and the tube is expanded to V, the internal pressure (P) can be expressed as follows.

$$P = \frac{P_0 V_0}{V} \quad (1)$$

$P_0 = 101.3$ kP, and $V_0 = 1.1$ mL from the catalog value; the suction pressure can be calculated using equation (1). Using these, a pressure of −83.0 kPaG was generated when the magnitude of suction by syringe volume was 5 mL. Further, a pressure of −89.0 kPaG was generated when the magnitude of suction by syringe volume was 8 mL, and a pressure of −92.8 kPaG was generated when the magnitude of suction by syringe volume was 12 mL. The collection amount is determined by the balance between the frictional force acting between the specimen and the inner surface of the needle and the force due to the suction pressure. If the pressure inside the organ is close to the atmospheric pressure, the suction force inside the needle is proportional to the difference between the suction pressure and the atmospheric pressure. Under the conditions in which the experiment was conducted, the change in force due to the suction pressure was small, and therefore, the effect on the collection amount was small. Whereas the blood contamination was observed to change with changes in the magnitude of suction. Therefore, the change in the magnitude of suction significantly impacts blood contamination.

There are two possible hypotheses regarding the mechanism of blood contamination in FNAC. One is that bleeding caused by the needle injury is aspirated. The other is that blood is sucked out from tissues by aspiration. These two mechanisms differ in whether blood is already present at the needle tip or blood is collected by suction. If the former mechanism is dominant, the longer the suction time, the higher the blood contamination because the time of contact between the blood and the needle increases. If the latter mechanism is dominant, the higher the magnitude of suction, the higher the blood contamination because the force trying to suck out the blood increases. However, blood contamination did not change with changes in the suction duration but was affected by changes in the magnitude of suction. Therefore, in 25-gauge FNAC, the dominant mechanism of blood contamination is the latter, i.e., blood is sucked out from tissues by aspiration.

Furthermore, the increase in the collection amount when the suction duration is increased is not only because of the suction duration but also because of the increased number of needle reciprocations in the experiment. In the experiment, the number of needle reciprocations increased with the suction duration. The increase in the number of needle reciprocations has been confirmed to increase the collection amount [9]. It is suggested that the increase in the collection amount was due to the combination of the increase in the suction duration and the number of needle reciprocations.

To conclude, specimens of sufficient quality and quantity can be collected using a small magnitude of suction and a long suction duration. The experimental results showed that the necessary amount can be collected even with a magnitude of suction of 5 mL. Therefore, the magnitude and duration of suction are set to 5 mL and 30 s, respectively, if the collection amount is small. Increasing the suction duration may make it possible to aspirate specimens of sufficient quality and quantity.

V. CONCLUSION

In this study, we investigated the suction conditions to reduce blood contamination and collect the necessary amount of specimens in FNAC using 25-gauge extra - fine needles. It is confirmed that the magnitude of suction affected the collection amount, and the suction duration time affected blood contamination.

This study analyzed the effects of the suction conditions on collection amount and blood contamination but did not derive the optimal suction conditions. As the optimal suction conditions may differ depending on the subjected organs, it is necessary to consider the optimal suction conditions for each organ in future work.

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