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Swallowing Pressure and Pressure Profiles in Young Healthy Adults

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Objectives/Hypothesis: To measure the swallowing pressure (SP) of normal subjects using a 2.64-mm-diameter high-resolution manometry (HRM) catheter with 36 circumferential sensors.

Study Design: Repeated measures with subjects serving as controls.

Methods: Thirty healthy subjects swallowed water at different temperatures and volumes to examine the maximum SP at the velopharynx, meso-hypopharynx, upper esophageal sphincter (UES), and cervical esophagus, and the duration of lowered pressure at the UES.

Results: The maximum SP at any location was unaffected by the volume of water, whereas the maximum SP at the UES and cervical esophagus was affected by the temperature. The duration of lowered SP at the UES was significantly prolonged with 10 versus 2 mL of cold water. The pressure curve in males had two peaks (at the velopharynx and UES), whereas that of females had a single peak at the UES.

Conclusions: Our data obtained with 2.64-mm HRM demonstrated that as the bolus volume is increased, the duration of lowered SP at the UES is prolonged. The higher maximum SP at the velopharynx in males versus females suggests that there may be a gender difference in pressure at the velopharynx that has not been described previously. This implies that it is necessary to take gender differences into consideration when evaluating the etiology of swallowing dysfunction by examining the SP and SP curve. Moreover, the thinner catheter is less invasive and may contribute to obtaining more physiological measurements.

Key Words: Swallowing pressure, bolus volume, high-resolution manometry, swallowing physiology, upper esophageal sphincter.

Level of Evidence: 4

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INTRODUCTION

The effect of bolus volume on swallowing pressure (SP) is key to our understanding of normal and dysfunctional swallowing physiology. Many studies of pharyngeal pressure during swallowing have been conducted using catheters with a few pressure sensors and have contributed to our understanding of pressure-modulated bolus movement.[1–8] These studies were performed using catheters with a few unidirectional sensors. As the pharynx is a relatively long, asymmetrical, moving structure, classical manometry with a few unidirectional sensors requires multiple swallows to evaluate the SP and cannot provide adequate spatial resolution or accommodate variation in the asymmetry or length of the pharynx.[9–11]

To overcome these drawbacks, high-resolution manometry (HRM), which is capable of monitoring pressure from the pharynx to the stomach and plotting the pressure topography, is an improvement in esophageal and pharyngeal manometry.[9–12] HRM with a 4.0-mm-diameter catheter uses 36 circumferential sensors to measure pressure events. The presence of a large number of sensors and their circumferential nature allow for accurate pressure measurements in the asymmetrical pharynx.[9–11] A previous study using HRM provided a more comprehensive picture of how bolus volume affects swallowing physiology.[12] Recently, HRM with a 2.64-mm-diameter catheter was developed for pressure monitoring mainly in esophageal lesions. Effective clinical application of this new instrument requires establishing normal and abnormal values across physiological and experimental conditions. Therefore, this study was performed to measure the SP of normal subjects using a 2.64-mm-diameter HRM catheter with 36 circumferential sensors and established normal standard physiological data including the bolus pressure profiles, gender differences, and bolus temperature for swallowing from the level of the velopharynx to the cervical esophagus in healthy adults using this HRM.

MATERIALS AND METHODS

Subjects

Fifteen male and 15 female subjects (average age, 25.3 ± 3.6 years) participated in this study with the approval of the institutional review board of Kumamoto University. None of

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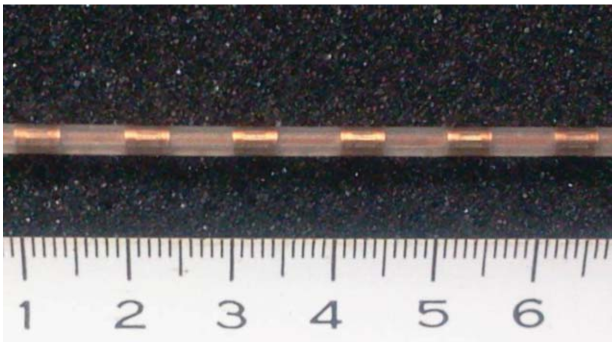

Fig. 1. The catheter had an outer diameter of 2.64 mm and 36 circumferential sensors spaced 1 cm apart. Each sensor spanned 0.7 mm and received input from 12 circumferential sectors.

the subjects had a history of dysphagia, gastrointestinal disease, upper gastrointestinal tract surgery, or other significant medical conditions.

Equipment

A solid-state, high-resolution manometer was used for all data collection. The catheter had an outer diameter of 2.64 mm and 36 circumferential sensors spaced 1 cm apart. Each sensor spanned 0.7 mm and received input from 12 circumferential sectors. The sampling rate was 20 msec for the time and 50 Hz for the frequency, respectively, and the pressure range was between −20 mm Hg and 600 mm Hg (ManoScan 360; Given/Sierra Scientific Instruments, Mountain View, CA) (Fig. 1). These inputs were averaged, and the mean pressure was recorded as the pressure detected by the individual sensors. The manometric data were analyzed using ManoView analysis software (Given/Sierra Scientific Instruments). The results are shown as the pressure topography and pressure waveform (Fig. 2).

Measuring the Swallowing Pressure

First, 4% lidocaine hydrochloride was applied to the nasal passage with a cotton swab, and the subjects gargled with a solution of 4% lidocaine (2 mL) for 5 seconds. The catheter was lubricated with 2% lidocaine jelly to ease its passage through the nasal cavity. The catheter was inserted 40 cm from the nostrils into the cervical esophagus and was taped at the nasal ala. Then, we waited 5 minutes for the subjects to acclimate to the presence of the catheter. Saliva, hot water (35°C), and cold water (0°C) were swallowed, with the subjects in a sitting position with a neutral head position, in the order of saliva, hot water (2, 5, and 10 mL), and cold water (2, 5, and 10 mL). Swallowing was repeated three times at 30-second intervals. We also asked the subjects to say "papapa" before the swallowing pressure measurements, to determine the boundary between the velopharynx and meso-hypopharynx.

Data Analysis

Zones of the pharynx for measuring swallowing presure were defined following the previously described method.[9,13] The resting upper esophageal sphincter (UES) pressure (Fig. 3A) and the length of the part in the cervical esophagus showing the resting UES pressure were examined. Maximum values of the swallowing pressure were measured at the velopharynx (Fig. 3B), meso-hypopharynx (Fig. 3C), UES (Fig. 3D), and cervical esophagus (Fig. 3E), which was defined as the portion down to 5 cm below the lower end of the UES. The distances from the nasal nostril to these points were also measured. The duration of lowered SP at the UES was defined as the time lapse between the two pressure peaks for bolus passage (Fig. 3F).

The SP curve was obtained by plotting the maximum SP at each point at distances of 8 to 25 cm from the nostril (Fig. 4).

Statistical Analysis

One-way analysis of variance was performed to examine how bolus volume, sex, and the distance from the nasal nostril affected pharyngeal pressure. The unpaired Student t test was used to determine if the maximum SP at any portion differed between males and females. The one-sample t test was performed to compare our data with published data. In all analyses, $P < .05$ was taken to indicate statistical significance.

RESULTS

Resting Pressure and Length of the UES

The mean resting pressure and length of the UES are shown in Table I. There were no significant differences in either parameter by gender.

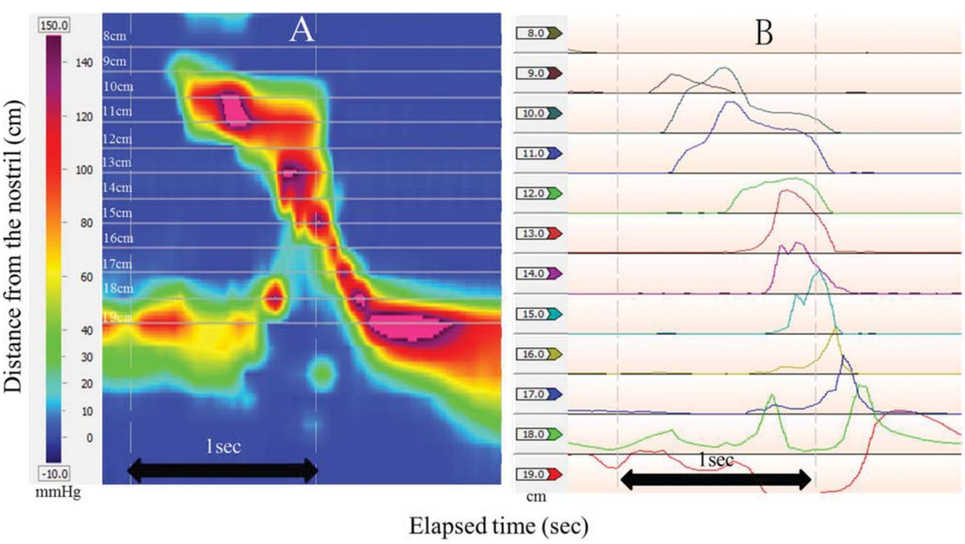

Fig. 2. (A) Pressure topography with time on the x-axis (double-headed arrow indicates 1 second), and distance from the nostril on the y-axis. Each pressure was assigned a color. (B) Pressure waveform with time on the x-axis (double-headed arrow indicates 1 second), and pressure on the y-axis.

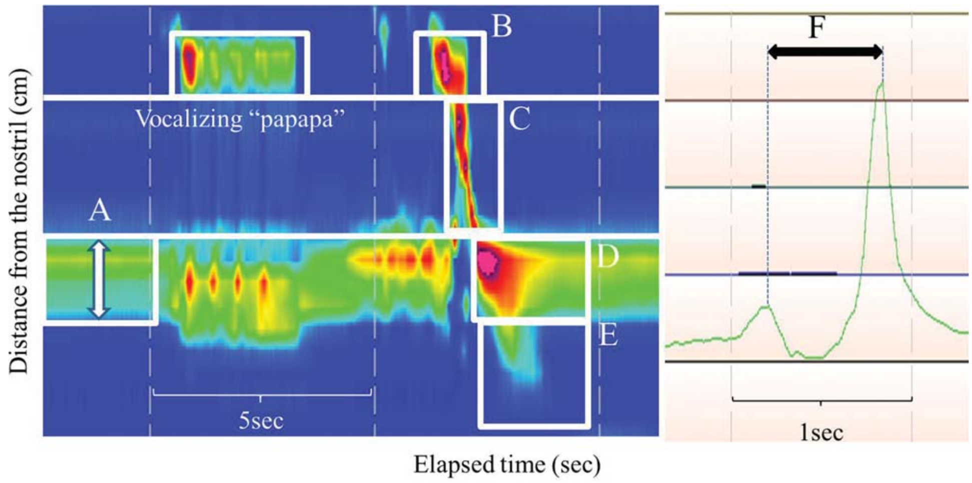

Fig. 3. The resting upper esophageal sphincter (UES) pressure (A) and the length of the section in the cervical esophagus showing the resting UES pressure were examined. The maximum swallowing pressure (SP) was measured at the velopharynx (B), meso-hypopharynx (C), UES (D), and cervical esophagus (E), which was defined as the portion extending to 5 cm below the lower end of the UES. The distances from the nostril to these points were also measured. The duration of the lowered SP at the UES (F) was measured and defined as the time lapse between bolus passage between the maximum pressure in the UES before and after swallowing. The spatiotemporal plots for the UES when vocalizing "papapa" and when swallowing are shown.

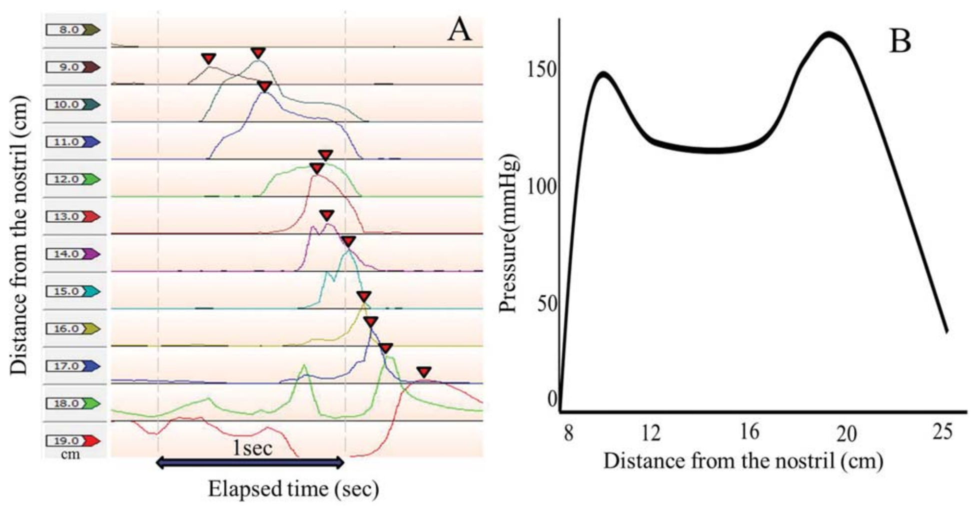

Fig. 4. The swallowing pressure curve (B) was obtained by plotting the maximum swallowing pressure at each point, 8 to 25 cm from the nostril (A).

Maximum Swallowing Pressure

Table II shows the mean maximum SP in all subjects by gender at the velopharynx, meso-hypopharynx, UES, and cervical esophagus when swallowing saliva and hot and cold water. Neither the volume nor the temperature of the water significantly affected the maximum SP at the velopharynx and meso-hypopharynx, whereas the maximum SP was significantly greater with 5 and 10 mL of cold versus hot water at the UES (5 mL, $P = .0218$; 10 mL, $P = .0704$) and cervical esophagus(5 mL, $P = .0009$; 10 mL, $P < .0001$). The maximum SP at the velopharynx of the male subjects was significantly higher than that of the females when swallowing saliva ($P = .0029$), 2 and 5 mL of hot water (2 mL, $P = .0148$; 5 mL, $P = .0352$; 10 mL, $P = .1175$), and 5 and 10 mL of cold water(5 mL, $P = .0329$; 10 mL, $P = .0259$) (Table II).

TABLE I.
Mean Value and Length of Resting Upper Esophageal Sphincter Pressure.

	Pressure, mm Hg	Length, cm
All subjects, n = 30	44 ± 13	3.4 ± 0.5
Sex		
Male, n = 15	47 ± 16	3.5 ± 0.5
Female, n = 15	42 ± 9	3.2 ± 0.5

Duration of Lowered Swallowing Pressure at the UES

Table III shows the mean duration of the lowered SP at the UES when swallowing saliva and hot and cold

TABLE II.
Mean Value of the Maximum Swallowing Pressure at the Velopharynx, Meso-hypopharynx, UES, and Cervical Esophagus When Swallowing Saliva and Hot and Cold Water.

Region	Subjects	Saliva	2 mL Hot Water	5 mL Hot Water	10 mL Hot Water	2 mL Cold Water	5 mL Cold Water	10 mL Cold Water
Velopharynx, mm Hg	All subjects	134 ± 32	135 ± 41	139 ± 44	146 ± 41	130 ± 44	136 ± 46	139 ± 45
	Male	151 ± 25*	154 ± 40†	156 ± 47‡	158 ± 45	146 ± 50	153 ± 51§	157 ± 50‖
	Female	117 ± 31*	117 ± 35†	122 ± 35‡	134 ± 34	114 ± 31	118 ± 33§	121 ± 29‖
Meso-hypopharynx, mm Hg	All subjects	166 ± 31	157 ± 26	159 ± 29	156 ± 28	157 ± 36	156 ± 37	158 ± 41
	Male	151 ± 19¶	150 ± 22	159 ± 31	154 ± 27	163 ± 40	159 ± 40	163 ± 44
	Female	182 ± 33¶	165 ± 28	160 ± 28	157 ± 29	150 ± 30	153 ± 34	153 ± 37
UES, mm Hg	All subjects	166 ± 41	174 ± 41	177 ± 41#	184 ± 45	171 ± 46	187 ± 47#	194 ± 39
	Male	155 ± 35	175 ± 46	173 ± 44	184 ± 47	168 ± 52	182 ± 49	192 ± 43
	Female	178 ± 43	173 ± 34	180 ± 38	185 ± 43	175 ± 39	193 ± 44	196 ± 35
Cervical esophagus, mm Hg	All subjects	78 ± 37	69 ± 30	62 ± 27**	62 ± 27††	71 ± 29	71 ± 28**	81 ± 31††
	Male	76 ± 35	70 ± 32	67 ± 29	65 ± 28	67 ± 26	71 ± 32	78 ± 35
	Female	81 ± 37	67 ± 27	57 ± 22	58 ± 25	76 ± 30	70 ± 24	84 ± 25

*Comparison $P < .01$, unpaired t test.
†Comparison $P < .05$, unpaired t test.
‡Comparison $P < .05$, unpaired t test.
§Comparison $P < .05$, unpaired t test.
‖Comparison $P < .05$, unpaired t test.
¶Comparison $P < .01$, unpaired t test.
#Comparison $P < .05$, paired t test.
**Comparison $P < .01$, paired t test.
††Comparison $P < .01$, paired t test.
UES = upper esophageal sphincter.

water. The duration of lowered SP at the UES was significantly longer with both 5 and 10 mL of hot and cold water than with saliva (hot water: 5 mL, $P = .0119$; 10 mL, $P = .0005$; cold water: 5 mL, $P = .0017$; 10 mL, $P < .0001$). The duration of lowered SP at the UES was prolonged significantly with 10 versus 2 mL of cold water ($P = .0135$). There were no gender differences in the duration of lowered SP at the UES.

HRM With a 2.64-mm-Diameter Catheter Versus Classical Manometry With a Few Sensors

The SPs at the velopharynx, mesopharynx, and hypopharynx, and the UES were significantly ($P < .01$) greater than those determined using classical manometry (Table IV).[14,15]

Comparison of HRM With a 4.0-mm-Diameter Catheter

The pressure and width of the UES at rest were significantly lower and narrower ($P < .01$) and the maximum SP at the UES was significantly lower ($P < .05$) in the present study with 2.64-mm HRM compared to data obtained using the HRM with a 4.0-mm-diameter catheter (Table V).[9,10,12] The duration of lowered SP at the UES[12] was relatively the same except for saliva ($P < .01$) (Table VI).

Swallowing Pressure Curve

The pressure curves when swallowing saliva and cold water by gender are shown in Figure 5. The pressure curves for the male subjects had two peaks (at the

TABLE III.
Mean Value of the Duration of the Lowered Swallowing Pressure at the Upper Esophageal Sphincter When Swallowing Saliva and Hot and Cold Water.

Subjects	Saliva	2 mL Hot Water	5mL Hot water	10 mL Hot Water	Saliva	2 mL Cold Water	5 mL Cold Water	10 mL Cold Water
All subjects	0.86 ± 0.12 s*†	0.94 ± 0.15 s	0.99 ± 0.15 s*¶	1.02 ± 0.16 s†	0.86 ± 0.12 s‡§	0.93 ± 0.12 s‖	1.02 ± 0.16 s‡¶	1.07 ± 0.20 s§‖
Male	0.87 ± 0.12 s	0.97 ± 0.12 s	1.03 ± 0.13 s	1.06 ± 0.12 s	0.87 ± 0.12 s	0.97 ± 0.11 s	1.06 ± 0.13 s	1.10 ± 0.17 s
Female	0.85 ± 0.11 s	0.90 ± 0.16 s	0.94 ± 0.16 s	0.99 ± 0.18 s	0.85 ± 0.11 s	0.90 ± 0.13 s	0.97 ± 0.17 s	1.04 ± 0.21 s

*Comparison $P = .0119$.
†Comparison $P = .0005$.
‡Comparison $P = .0017$.
§Comparison $P < .0001$.
‖Comparison $P = .0135$.
¶Comparison $P = .0389$, one way analysis of variance, Scheffe, paired t test.

TABLE IV.
Comparison With Classical Manometry.

Study	No. of Sensors	Receiving Unit	Velopharynx, mm Hg	Meso-hypopharynx, mm Hg	UES, mm Hg	Resting Pressure, mm Hg
Mori[14]	2	Unidirectional	94†	89§	60¶	5–40
Ohmae[15]	4	Unidirectional	103*	107‡	104‖	31**
Our study	36	Circumferential	136*†	156‡§	187‖¶	44**

*Comparison $P < .01$, one-sample t test.
†Comparison $P < .01$, one-sample t test.
‡Comparison $P < .01$, one-sample t test.
§Comparison $P < .01$, one-sample t test.
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¶Comparison $P < .01$, one-sample t test.
**Comparison $P < .01$, one-sample t test.
UES = upper esophageal sphincter.

TABLE V.
Comparison of High-Resolution Manometry With a 4.0-mm-Diameter Catheter (Swallowing Pressure and Resting UES).

Study	Sex	Outer diameter, mm	Velopharynx, mm Hg	Meso-hypopharynx, mm Hg	UES, mm Hg	Resting Pressure, mm Hg	Length, cm
Takasaki [9]	Male	4	163 ± 95	183 ± 84*	236 ± 79†	70 ± 30‡	4.0 ± 0.7§
Our study		2.64	153 ± 51	159 ± 40*	182 ± 49†	47 ± 16‡	3.5 ± 0.5§
Takasaki [9]	Female	4	125 ± 43	167 ± 65	244 ± 87‖	62 ± 27¶	3.6 ± 0.6#
Our study		2.64	118 ± 33	153 ± 34	193 ± 44‖	42 ± 9¶	3.2 ± 0.5#
McCulloch[10]	All subjects	4	169 ± 50††	306 ± 163§§	239 ± 78¶¶		
Hoffman [12]		4	154 ± 42**	315 ± 170‡‡	327 ± 127‖‖		
Our study		2.64	136 ± 46**††	156 ± 37‡‡§§	187 ± 47‖‖¶¶	44 ± 13	3.4 ± 0.5

*Comparison $P < .01$, one-sample t test.
†Comparison $P < .05$, one-sample t test.
‡Comparison $P < .01$, one-sample t test.
§Comparison $P < .01$, one-sample t test.
‖Comparison $P < .05$, one-sample t test.
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††Comparison $P < .01$, one-sample t test.
‡‡Comparison $P < .01$, one-sample t test.
§§Comparison $P < .01$, one-sample t test.
‖‖Comparison P $< .01$, one-sample t test.
¶¶Comparison $P < .01$, one-sample t test.
UES = upper esophageal sphincter.

velopharynx and UES), whereas the pressure curves for the female subjects had a single peak at the UES.

DISCUSSION

Duration of Lowered Swallowing Pressure at the Upper Esophageal Sphincter and Maximum Swallowing Pressure

The duration of lowered SP at the UES was significantly prolonged with hot and cold water versus saliva. Moreover, it was significantly prolonged with 10 versus 2 mL of cold water, suggesting that as the bolus volume is increased, the duration of lowered SP at the UES is prolonged. This phenomenon was described in a previous study conducted with 4.0-mm-diameter HRM.[12] The longer opening of the UES accommodates a larger bolus, as reported in previous videofluoroscopic-manometric studies[16,17] and confirmed in our data. As described by McCulloch et al. and Hoffman et al.,[10,12] an increased number of sensors used with HRM (up to 36) provides

TABLE VI.
Comparison of High-Resolution Manometry With a 4.0-mm-Diameter Catheter (Duration of Lowest Swallowing Pressure at the Upper Esophageal Sphincter).

Study	Outer Diameter, mm	Saliva	5 mL Cold Water	10 mL Cold Water
Hoffman[12]	4	0.92 ± 0.17 s*	0.98 ± 0.16 s	1.11 ± 0.15 s
Our study	2.64	0.86 ± 0.12 s*	1.02 ± 0.16 s	1.07 ± 0.20 s

*Comparison $P < .01$, one-sample t test.

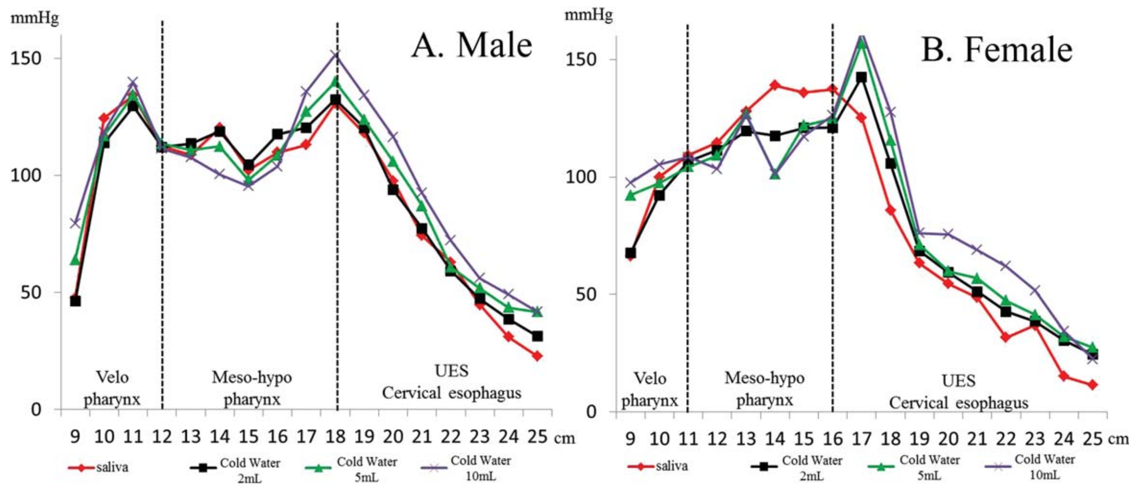

Fig. 5. The swallowing pressure curves when swallowing saliva and hot and cold water (2, 5, and 10 mL) for male subjects (A) and females subjects (B). The pressure curve for males had two peaks (at the velopharynx and upper esophageal sphincter [UES]), whereas the pressure curve for females had a single peak at the UES (B).

more comprehensive assessment of both the timing and pressure events, eliminating potential "blind spots" that may occur if using a manometric catheter with a few sensors[9–11] requiring multiple swallows to evaluate the SP. Our study demonstrated that the SP at the UES and cervical esophagus with 5 mL cold water were both significantly higher than those with 5 mL hot water. This suggested that the temperature of water enhances not only the induction of the swallowing reflux but also the SP at the UES and cervical esophagus.

The SP curve is a useful tool for evaluating swallowing dysfunction.[3,17]A previous study indicated that the SP curve of healthy subjects has three peaks: at the velopharynx, hypopharynx, and cervical esophagus (Fig. 6).[3,18] In comparison, our curve differed from the reported SP curve. Male subjects had two peaks (at the velopharynx and UES), whereas female subjects had a single peak at the UES. The higher maximum SP at the velopharynx in males versus females suggests that there may be a gender difference in pressure at the velopharynx that has not been described previously.

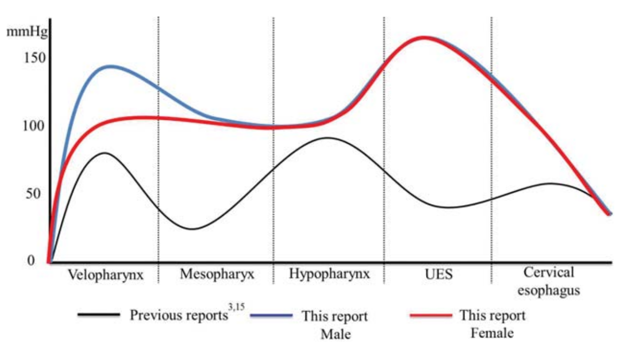

Fig. 6. The pressure curve obtained in our study was compared with curves from previous studies. We found that the pressure curve for males had two peaks (at the velopharynx and upper esophageal sphincter [UES]), whereas the pressure curve for females had a single peak at the UES.

A previous study demonstrated that the amount of the postnasal drip for females tends to be larger than that for males, calculated by a nasometer, which suggests that the velopharyngeal pressure for males may be higher than that for females (unpublished data). Although there was no significant difference, Takasaki et al. demonstrated that the average of the SP at the velopharynx for males (163 mm Hg, $n = 19$) is higher than for females (125 mm Hg, $n = 14$). These perspectives support our data. Moreover, our study demonstrated that the maximum SP at the meso-hypopharynx during saliva swallowing is different by gender. As shown in Table VII, the length of the pharynx for males is significantly longer than that for females. This also might be one of the causes for the difference of SP at both the velopharynx and meso-hypopharynx between males and females.

These imply that it is necessary to take gender differences into consideration when evaluating the etiology of swallowing dysfunction by examining SP and the SP curve.

HRM With a 2.64-mm-Diameter Catheter Versus Classical Manometry With a Few Sensors

We compared the present data with data obtained with classical manometry with a few sensors and with

TABLE VII.
Distance From the Nostril to Each Rostrad Point.

Sex	Velopharynx, cm	Meso-hypopharynx, cm	UES, cm	Cervical Esophagus, cm
Male	8.4 ± 0.6	11.9 ± 0.6*	$17.9 \pm 1.2^{\dagger}$	$21.2 \pm 1.0^{\ddagger}$
Female	8.0 ± 0.6	10.6 ± 0.8*	$16.1 \pm 0.7^{\dagger}$	$18.8 \pm 0.9^{\ddagger}$

*Comparison $P < .01$, unpaired *t* test.
†Comparison $P < .01$, unpaired *t* test.
‡Comparison $P < .01$, unpaired *t* test.
UES = upper esophageal sphincter.

HRM with a 4.0-mm-diameter as described below. Although we adopted the suitable statistical analysis—one-sample t test—we need to emphasize that this is not a direct comparison between different manometry techniques, therefore the comparison in recorded pressures is speculative.

The difference between HRM with a 2.64-mm-diameter catheter versus classical manometry with a few sensor may have been due to the different number of pressure sensors used. Classical manometry with a few unidirectional sensors requires multiple swallows to evaluate the SP and cannot provide adequate spatial resolution or accommodate variation in asymmetry or the length of the pharynx.[9–11] Conversely, HRM with a large number of circumferential pressure sensors allows accurate pressure measurements in the asymmetric pharynx.[9–11] The pressure at the UES was significantly higher in the present study compared to the values obtained with classical manometry, because the circumferential nature of the sensors allows detection of stronger pressure at the cricoid cartilage due to mechanical contact with the catheters. Moreover, using a single pressure sensor at the UES to measure the UES opening is limited by UES and catheter movements that occur with swallowing.[10,12]

Comparison of HRM With a 4.0-mm-Diameter Catheter

Comparison of HRM with a 4.0-mm-diameter catheter demonstrated that the SP tends to increase with the diameter of the catheter, as reported previously.[19] Our data obtained with 2.64-mm HRM differed partially from values obtained with 4.0-mm HRM[9,10,12] and classical manometry.[14,15] This is why we need to establish normal standards for physiological swallowing data for healthy adults using this instrument. As the variation in our data tended to be smaller than for the previous data, a thinner catheter may be less invasive, which may contribute to obtaining more physiological measurements.

CONCLUSION

We demonstrated that neither the volume nor temperature of water swallowed significantly affected the maximum SP at the velopharynx, mesopharynx, and hypopharynx. The duration of the lowered SP at the UES was significantly prolonged with hot and cold water versus saliva. In addition, it was significantly prolonged with 10 versus 2 mL of cold water. The higher maximum SP at the velopharynx in males versus females suggests that there may be a gender difference in pressure at the velopharynx. The data obtained with 2.64-mm HRM differed partially from values obtained with classical manometry and 4.0-mm HRM. A thinner catheter may be less invasive and may contribute to obtaining more physiological measurements.

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