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Generation mechanisms of bowel sounds by simultaneous measurements of X-ray fluoroscopy and bowel sounds

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***Abstract*— In clinical practice, bowel sounds are often used to assess bowel motility. However, the diagnosis differs depending on the literature because diagnoses have been based on empirically established criteria. To establish diagnostic criteria, researching the mechanism of bowel-sound occurrence is necessary. In this study, based on simultaneously measured X-ray fluoroscopy and bowel sounds, correlation and Granger causality among bowel movement, luminal content movement, and abdominal sound were estimated. The results supported our hypothesis that the bowel moves luminal contents and luminal contents generate abdominal sounds.**

I. Introduction

The human gastrointestinal tract rhythmically contracts to move luminal contents [1]. If such bowel motility does not work normally, ileus and/or other bowel disorders can develop [2]. Auscultation, one of the most common diagnostic techniques, is often used to assess bowel motility by listening to bowel sounds from the abdomen [1]. The first study of auscultating bowel sounds was in 1905 [3], and the diagnosis has been established for a long time. However, the diagnosis was determined empirically, so there is a lack of supporting evidence [4]. To establish diagnostic criteria, researching the mechanism of bowel-sound occurrence is necessary.

Studies on the mechanism of bowel-sound occurrence are limited. Politzer et al. recorded bowel sounds by passing saline or air through a tube inserted through the mouth into the stomach, jejunum, and cecum [5]. They found a (non-significant) difference in the number of bowel sounds depending on what was poured through the tube and noted that intestinal contents may affect the bowel-sound occurrence [5]. However, the relationships between bowel movement, movement of luminal contents, and bowel sounds is still unknown. In this study, we test a hypothesis that bowel sounds are caused by movement of luminal contents, which is caused by bowel movement (Fig. 1) using simultaneously measured X-ray fluoroscopy and bowel-sound.

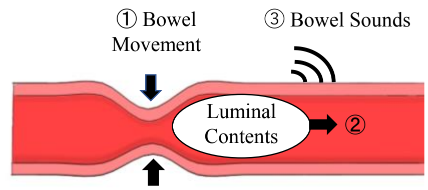

Fig. 1 Our hypothesized mechanism of bowel-sound occurrence.

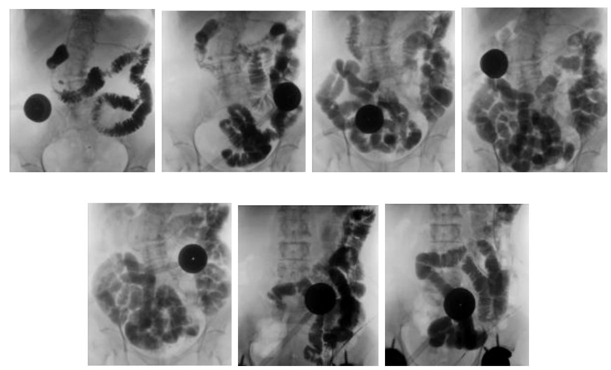

Fig. 2 Initial frames of X-ray fluoroscopy images in each dataset

II. Methods

A. Data acquisition

Bowel sounds and X-ray fluoroscopy images were recorded on the abdomen of 2 male volunteers who underwent subtotal esophagectomy (2 weeks post-surgery). A contrast agent (gastrografin) was flowed from the intestinal fistula tube placed during the operation, and measurements of X-ray fluoroscopy images (60 - 110 sec, 30 fps, 620 × 700 px, 8-bit depth) and bowel sounds (1 min, fs = 48000) on the subjects' abdomen were carried out simultaneously. Each of the subjects' recordings were taken over multiple times, and a total of 7 datasets were obtained (Fig. 2). Bowel sounds were recorded by a condenser microphone (Olympus ME52W) inserted into the tube of a stethoscope (3M Littmann Classic II SE).

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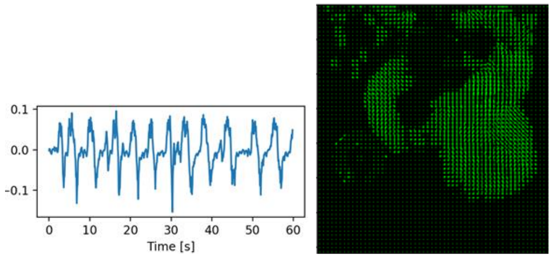

(a) u_1 (b) v_1

Fig. 3. Example of the first principal component of the optical flow.

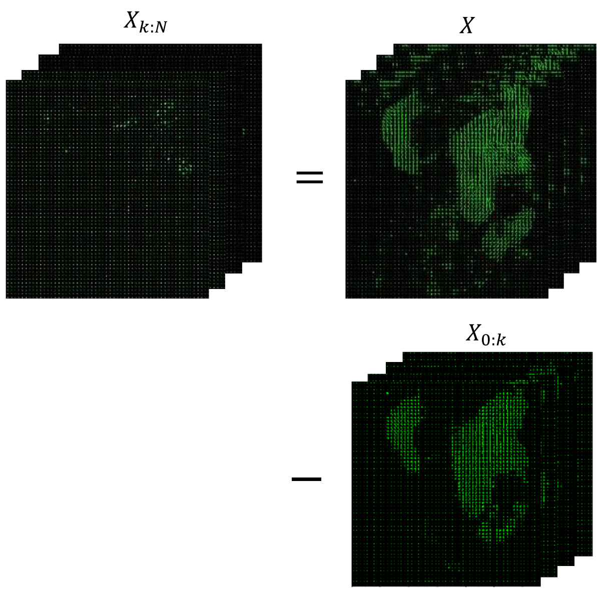

Fig. 4. Scheme of the removal of respiratory movement from the estimated optical flow.

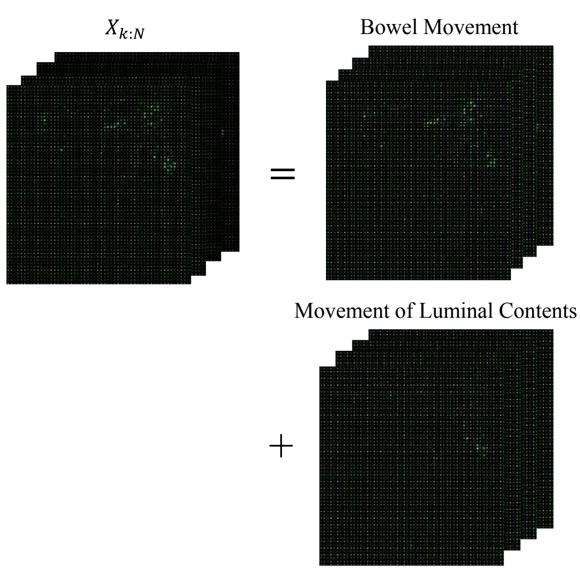

Fig. 5. Scheme of the separation of bowel movement and movement of luminal contents.

B. Estimation of bowel motility

In each dataset, bowel motility was calculated from the recorded images using following steps.

1. Fluoroscopy images were resampled into 10 fps and 310 × 350 px to reduce the computational complexity.
2. Optical flows (OF), the velocities of movement of brightness, between consecutive images were estimated using Farneback's algorithm [6]. The OF, thus, reflect bowel movement.
3. The singular value decomposition of the X, which is the OF sequence vector (three - dimensional), was calculated using Eq. (1)

$$X = \sum_{i=0}^{N} \sigma_i u_i v_i \tag{1}$$

where u_i and v_i denote the orthogonal vectors, σ_i denotes the singular value, and N is the rank of the OF. Fig. 3 shows the example of first principal component of X. Since u_1 fluctuate periodically like respiration and v_1 is pointing roughly downward, the first principal component of X represents respiratory fluctuations.

4. The first k vector, with a contribution rate of 0.2, was used to express the low-rank approximation from Eq. (2)

$$X_{0:k} = \sum_{i=0}^{k} \sigma_i u_i v_i \tag{2}$$

where $X_{0:k}$ is the low-rank approximation of the X. As respiratory movements are periodic, and the same movements appeared repeatedly, they were a major component of the OF. Therefore, $X_{0:k}$ reflects the respiratory movement of the OF, and $X_{k:N}$ reflects the OF that reduced respiratory movement (Fig. 4).

5. The bowel movement was calculated using Eq.(3)

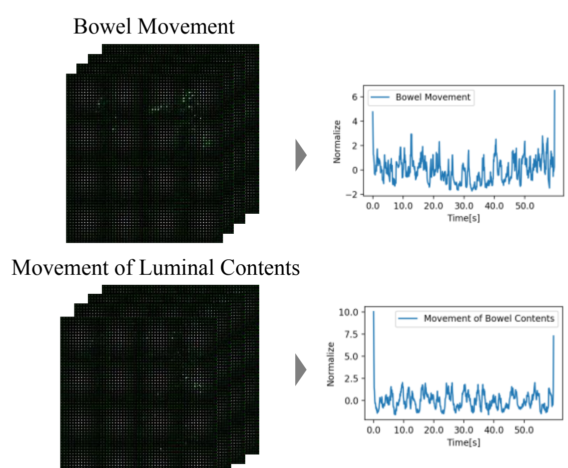

Fig. 6. Scheme of calculating the level of bowel movement and movement of luminal contents in each second

$$X' = \sum_{i \in A}^{N} \sigma_i u_i v_i \quad (3)$$

$$A = \{i \mid k < i \le N, arg\ max(U_i(f)) < 0.4, i \in \mathbb{N}\}$$

where X' is the bowel motility, and A is the set of number of principal component that satisfy the condition, and $U_i(f)$ is the power spectrum of u_i. And the movement of luminal contents was calculated using Eq.(4)

$$X'' = \sum_{i \in B}^{N} \sigma_i u_i v_i \quad (4)$$

$$B = \{i \mid k < i \le N, arg\ max(U_i(f)) \ge 0.4, i \in \mathbb{N}\}$$

where X'' is the movement of luminal contents, and B is the set of number of principal component that satisfy the condition (Fig. 5). The threshold of peak frequency was set at 0.4 Hz, which is sufficient to include the variation of bowel movement (a dozen times per minute [7]).

6. The magnitude of bowel movement and movement of luminal contents were spatially averaged respectively. Both magnitudes are time-series data, and their values were normalized (Fig. 6). They reflected the level of bowel motility and movement of luminal contents, respectively, at each time point.

C. Estimation of RMS sound pressure

The RMS sound pressure in each dataset was calculated from the recorded sounds using the following steps.

1. The recorded sounds were denoised using spectral subtraction [8] and a bandpass filter (Fig. 7b). In spectral subtraction, a 5%-time interval, with a small RMS sound pressure in the recorded sound, was used as the noise. In the bandpass filter, 100-1000 Hz was chosen because the main energy of the bowel sounds is among 100 to 500 Hz, and only approximately 0.5% of the energy is beyond 1000 Hz [9].

2. The RMS sound pressure was calculated every 1/10 s using Eq. (3)

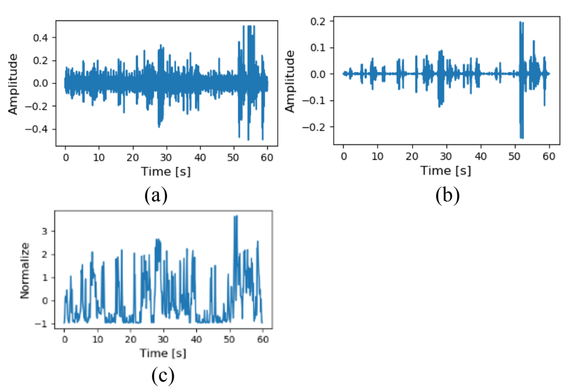

Fig. 7. Estimation of the level of bowel sounds.
(a) Example of recorded sound, (b) The sound reduced noise, (c) RMS sound pressure

$$RMS\ sound\ pressure(t_i) = log_{10}\sqrt{\sum_{t=t_i}^{t_i+\frac{fs}{10}} y(t)^2}\ [dB] \quad (3)$$

where y(t) is the amplitude of the recorded sound in the range $-1 \le y(t) \le 1$, and fs is the sampling frequency. The RMS sound pressure at each time point was normalized to time-series data (Fig. 7c) and reflected the level of bowel sounds at each time.

D. Estimation of correlation and Granger causality

To verify our hypothesis, correlation and Granger causality between bowel movement, movement of luminal contents, and bowel sounds was calculated. Granger causality [10] is used to identify causal relationships between variables from time-series data. In this study, Granger causality was evaluated in the following steps. First, the vector autoregression model (VAR) was fitted to the time-series data of bowel movement, movement of luminal contents, and bowel sounds. The VAR order was selected using the Akaike information criterion (AIC). Second, Granger causality tests were performed to examine the causal relationship between bowel movement, movement of luminal contents, and bowel sounds.

III. Results

Table 1 shows the number of datasets when the 7 datasets were classified by the correlation among ① bowel movement, ② movement of luminal contents, and ③ bowel sounds. There was little correlation ($|r| < 0.2$) among all datasets. Table 2 shows the number of datasets classified by the P-value for the Granger causality test among ① bowel movement, ② movement of luminal contents, and ③ bowel sounds. There is more datasets on causal or causal trends ($p < 0.1$) than on non-causal trends ($0.1 \le p$) when comparing ① and ② as well as

Table 1. Number of datasets classified when the 7 datasets were classified by the correlation

Comparison	$0.2 \le \|r\|$	$\|r\| < 0.2$
①-②	0	7
②-③	0	7
①-③	0	7

r: Correlation Coefficient
① bowel movement, ② movement of luminal contents, ③ bowel sounds

Table 2. Number of datasets when the 7 datasets were classified by the P-value of Granger causality test

Comparison	$p < 0.05$	$0.05 \le p < 0.1$	$0.1 \le p$
① - ②	7	0	0
② - ③	3	1	3
① - ③	0	2	5

p: P-value for Granger Causality Test
① bowel movement, ② movement of luminal contents, ③ bowel sounds

② and ③. On the other hand, there is less datasets on causal or causal trends than on non-causal trends when comparing ① and ③.

IV. Discussion

The results infer that there are Granger causalities between ① and ② and between ② and ③. From these inferences, the results support our hypothesis (Fig. 8). Since there are no correlations between ① and ② or between ② and ③, it can be inferred that there are a delays between them. The delay between ② and ③ may be attributed to the assumption that the stethoscope only picks up sounds in the vicinity. If there is movement of luminal contents at a further distance, then the movement of luminal contents will be transmitted to the bottom of the stethoscope after a delay, and then the sound will be heard.

No Granger causalities between ② and ③ were found in 3 of the 7 datasets. This may be due to the bowel sounds occurring in the bowel where the contrast agent cannot be observed.

In future, a larger number of subjects are required to obtain more reliable results. In addition, both patients had undergone surgical procedures, which may not reflect well on the general population. Further, both male and female volunteers should be tested.

V. Conclusion

Based on simultaneously measured X-ray fluoroscopy and bowel-sound, correlation and Granger causality among the bowel movement, luminal content movement, and abdominal sound were estimated. The results obtained supported our hypothesis that bowel sounds are caused by movement of luminal contents, which is caused by bowel movement.

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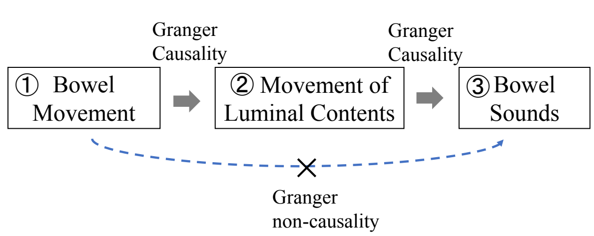

Fig. 8. Scheme of our hypothesis that bowel sounds are caused by movement of luminal contents, which are caused by bowel movement

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