Changes in bowel sounds of inpatients undergo general anesthesia

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Abstract

Background: General anesthesia can affect intestinal function, but there is no objective and effective indicator to evaluate the inhibition and recovery of intestinal function. The main objective of this study is to assess whether bowel sounds (BSs) change before and after general anesthesia, then it can be explained that the BS can be an effective indicator of intestinal function.

Methods: We randomly selected 26 inpatients and collected three sets of 5-minute continuous BSs before operation (Pre-op), after operation (Pro-op) and three hours after operation(3h-Pro-op) separately for each patient. The data were de-noised with adaptive filtering and wavelet threshold denoising, and processed with fractal dimension to identify the effective bowel sounds (EBSs). Then the linear and nonlinear characteristic values (CVs) of each EBS were extracted and paired t -test and rank-sum test were used to evaluate the changes of the BSs after general anesthesia.

Results: For the difference between Pre-op and Pro-op, as well as between Pro-op and 3h-Pro-op, there are statistical differences ($p<0.05$). Specifically, the linear CVs that can reflect the occurrence frequency, overall energy and overall duration of EBSs and the nonlinear CVs that can reflect the dispersion degree of stability and complexity of EBSs were statistically significant. However, there is no statistical difference in the CVs reflecting the energy and duration, as well as the stability and complexity of locally EBSs ($p>0.05$). Also, there is no statistically significant difference between all the characteristic values between Pre-op and 3h-Pro-op ($p>0.05$).

Conclusion: The BSs change after general anesthesia. Furthermore, the BSs are weakened after general anesthesia and recovered to the state before general anesthesia three hours later. Therefore, the BS can be an indicator of intestinal function under general anesthesia, so as to provide guidance for postoperative feeding , which is of great clinical significance.

Background

General anesthesia can inhibit gastrointestinal function, so postoperative feeding needs to wait for the gradual recovery of gastrointestinal function to give appropriately and timely. At present, there is no clear objective evaluation method for postoperative recovery of gastrointestinal function, so the time of resuming oral input is arbitrary. However, for patients undergoing general anesthesia, it is important to be able to take in nutrition relatively early for postoperative recovery. The evaluation of gastrointestinal function after general anesthesia has important clinical significance.

Studies on noninvasive methods judge the recovery of gastrointestinal function after general anesthesia are mainly the methods of the anal exhaust [1], electrogastrogram [2], bowel sounds (BSs) auscultation and dynamic magnetic resonance imaging [3].

Anal exhaust mainly depends on the patients' chief complaint, which cannot objectively and timely reflect the recovery of gastrointestinal function. Electrogastrogram is more objective and real than anal exhaust, but it is easily influenced by other bioelectric signals, and the current analysis of electrogastrogram data is not particularly mature and widely accepted. Dynamic magnetic resonance imaging (DMR) relies on large imaging equipment, so it is difficult to monitor patients in a long time during the perioperative period.

Auscultation of BSs is an important noninvasive way to judge gastrointestinal function. BSs are produced with the moving of substances in the intestine, so the sounds can objectively reflect the situation of intestinal peristalsis in real-time. Researches on BSs use the characteristics of BSs to observe gastrointestinal state and diagnose gastrointestinal diseases. In clinical practice, the observation of gastrointestinal peristalsis is used to monitor feeding events, thus providing a reference for the monitoring of blood glucose in the artificial pancreas system [4]; BS can also be used as one of the indicative parameters of gastrointestinal diseases [5]. Gastrointestinal tract development if lesions occur, such as gastroduodenal disease, intestinal disease, and large bowel disease, the corresponding intensity or number of BSs may also be abnormal. In addition, BS can indicate other diseases. Recent studies have found that BSs can not only indicate gastrointestinal state, but also have clinical significance for sepsis [6], Parkinson's disease [7] and other diseases. The above studies show that BSs can reflect gastrointestinal functions, so we can consider the application of changes in BSs to the evaluation of gastrointestinal function recovery in patients after general anesthesia.

However, using a handheld stethoscope for short-time auscultation is still the main way to obtain intestinal sounds in clinic. As for the strong randomness of gut sound, the result is questioned through a short time of subjective judgment [8–10]. In the study of BSs, the sounds are mainly acquired by means of the assembly of mature pickup parts and storage parts. There is no special bowel sound equipment in the clinical environment to collect bowel sound data.

In this paper, considering the requirements of the perioperative medical environment and the patient's poor cooperation before and after the operation, we used the self-developed wearable bowel device. The device can be easily attached to the patient's abdomen, and the sound data can be collected and stored with no pressure. If the results of BSs analysis indicate that the occurrence of changes of BSs in patients undergoing general anesthesia, it provides theoretical support for the use of bowel sounds as a reference index for anesthesia recovery evaluation.

Results

The research has been approved by the Medical Ethics Committee of Chinese PLA General Hospital for clinical research (No. 2018-176-01). We randomly selected 26 inpatients from the Second Department of Otolaryngology, Head and Neck Surgery, Chinese PLA General Hospital. Each subject signed the informed consent. We recorded clinical factors that might influence bowel sounds, including age, gender, BMI, anesthetic type, and exclusion of patients with gastrointestinal dysfunction. Three sets of 5-minute continuous BSs were collected for each patient. The first set of data was collected before operation (Pre-op) which defined as the time that fast for 24 hours and before entering the operating room. The second set was collected after entering the recovery room and completing tracheal extubation (Pro-op). The last set was collected at 3 hours after extubation (3 h-Pro-op) in the ward if conditions permit. The acquisition location of bowel sounds was determined as the right lower abdominal region [11]. Considering the influence of different devices and different operators on the accuracy of the test, one person used the same device to test the subjects' BSs during the experiment.

Table 1
Patient data

Age(yr)	**39(9–77)***
Sex(M/F)	15/11
BMI	24.88(4.56) **
Operation time(min)	123.65(67.06) **
Anesthesia type	General anesthesia

Notes. BMI, Body Mass Index. * Values are presented as mean(range). ** Values are presented as mean (standard deviation).

We obtained 70 sets of 5-minute BSs from 26 patients as shown in Table 1. The patients were asked to confirm the absence of intestinal disease. The 70 sets consist of 26 sets of preoperative, 26 sets of postoperative and 18 sets of three hours after surgery.

Table 2
Statistical analysis results between Pre-op and Pro-op

CVs	Pre-op (n = 26)	Pro-op (n = 26)	*p*-values
Num_bs	23.23(13.61)	10.34(10.86)	0.000*
Sum_bs	5,768,536.19(4,326,873.91)	2,121,638.23(1,928,966.98)	0.001*
Sum_Duration_bs	98,292.19(52350.29)	45,808.92(41512.55)	0.000*
Mean_Duration	0.500(0.287)	0.515(0.433)	0.790**
Std_Duration	0.660(0.580)	0.411(0.372)	0.065*
Mean_Mag_bs	58.177(38.967)	47.921(38.363)	0.362*
Std_Mag_bs	39.340(32.061)	10.124(35.826)	0.096**
RR-Mean	0.108(0.050)	0.082(0.028)	0.046**
RR-std	0.066(0.064)	0.019(0.034)	0.003**
Lmean-Mean	29.789(6.750)	27.352(12.817)	0.422*
Lmean-std	12.089(13.025)	6.564(6.134)	0.008**
ENTR-Mean	4.030(0.205)	3.947(0.322)	0.469**
ENTR-std	0.380(0.105)	0.234(0.167)	0.000*
TT-Mean	32.858(8.974)	30.141(16.471)	0.483*
TT-std	17.147(18.951)	8.405(9.488)	0.004**

Notes. * Values of this line are presented as mean (standard deviation), the statistical method is paired *t*-test. ** Values of this line are presented as median (quartile range), the statistical method is *rank-sum* test. CVs, characteristic values. Pre-op, before operation. Pro-op, after operation.

Characteristic values (CVs) were calculated for each effective bowel sounds (EBS), including 7 linear parameters and 8 nonlinear parameters. After statistical analysis, *p*-value less than 0.05 was considered statistically significant; otherwise, no statistical difference was considered.

Table 2 shows the statistical analysis results of the CVs of BSs between Pre-op and after Pro-op. The results show that in the linear time-domain parameter analysis of BSs, the frequency of EBSs, namely Num_bs, the number of BSs within 5 minutes, is statistically significant. The parameters that can represent the intestinal sound energy include Mean_Mag_bs, Std_Mag_bs, and Sum_bs. Among these three parameters, Mean_Mag_bs and Std_Mag_bs have no statistical significance, but there is a statistical difference in Sum_bs. The duration parameters of intestinal sounds included Mean_Duration, Std_Duration, and Sum_Duration, in which the difference between the two parameters of Mean_Duration and Std_Duration was not statistically significant, while the Sum_Duration difference was statistically significant. This indicated that the energy and duration of locally EBSs were not affected by general anesthesia, but the difference in the sum of energy and duration of bowel sounds was statistically significant. Therefore, The frequency of bowel sounds, the energy of BSs and the duration of BSs were affected by the operation general anesthesia and were weakened as a whole, but the energy and duration of locally EBSs were not affected, indicating that general anesthesia affected the overall intestinal peristalsis intensity and did not inhibit the local intestinal peristalsis state. In the nonlinear recursive parameter analysis, the mean values of RR, Lmean, ENTR and TT were not statistically different. However, the standard deviation of RR, Lmean, ENTR and TT showed statistical differences. RR, Lmean and TT all reflect the stability of the signal, while ENTR reflects the complexity. There was no statistical difference in the mean of the recursive parameters of BSs, but there was a statistical difference in the standard deviation of these recursive parameters, indicating that the dispersion degree of stability and complexity of the system became smaller.

Table 3
Statistical analysis results of CVs between Pro-op and 3 h-Pro-op.

CVs	**Pro-op (n = 18)**	**3 h-Pro-op (n = 18)**	***p*-values**
Num_bs	7.0(11.5)	20(24)	0.002**
Sum_bs	1,417,106.815(2,695,398.732)	4,164,854.843(7,324,520.576)	0.011**
Sum_Duration_bs	39,630.167(38007.662753)	83,282.222(53,044.882)	0.003*
Mean_Duration	0.530(0.300)	0.440(0.236)	0.199**
Std_Duration	0.328(0.342)	0.480(0.366)	0.170*
Mean_Mag_bs	51.892(41.220)	58.564(33.982)	0.577*
Std_Mag_bs	10.417(43.974)	35.874(62.101)	0.157**
RR-Mean	0.078(0.027)	0.103(0.044)	0.102**
RR-std	0.029(0.044)	0.069(0.037)	0.017*
Lmean-Mean	28.048(15.141)	30.685(8.675)	0.541*
Lmean-std	5.322(8.423)	12.214(9.214)	0.016**
ENTR-Mean	4.001(0.523)	3.972(0.264)	0.777**
ENTR-std	0.191(0.154)	0.393(0.100)	0.001*
TT-Mean	30.794(19.410)	33.285(12.157)	0.646*
TT-std	6.223(9.759)	16.801(12.988)	0.016**

Notes. * Values of this line are presented as mean (standard deviation), the statistical method is paired *t*-test. ** Values of this line are presented as median (quartile range), the statistical method is *rank-sum* test. CVs, characteristic values. Pro-op, after operation. 3 h-Pro-op, three hours after operation.

Table 4
Statistical analysis results of characteristic values between Pro-op and 3 h-Pro-op.

CVs	**Pre-op (n = 18)**	**3 h-Pro-op (n = 18)**	***p*-values**
Num_bs	23.5(18.25)	20(24)	0.845**
Sum_bs	6,150,012.901(4,826,065.496)	5,483,036.313(5,221,266.508)	0.613*
Sum_Duration_bs	100,070.611(43,353.005)	83,282.222(53,044.882)	0.209*
Mean_Duration	0.565(0.492)	0.440(0.236)	0.043**
Std_Duration	0.754(0.669)	0.480(0.366)	0.164*
Mean_Mag_bs	57.345(42.065)	58.564(33.982)	0.914*
Std_Mag_bs	34.746(20.342)	42.825(31.226)	0.346*
RR-Mean	0.114(0.049)	0.120(0.054)	0.645*
RR-std	0.050(0.057)	0.068(0.032)	0.248**
Lmean-Mean	29.129(7.657)	30.685(8.675)	0.573*
Lmean-std	12.679(9.011)	13.601(7.473)	0.752*
ENTR-Mean	4.023(0.199)	4.022(0.237)	0.988*
ENTR-std	0.352(0.107)	0.393(0.100)	0.307*
TT-Mean	32.337(10.111)	33.285(12.157)	0.802*
TT-std	17.746(11.587)	18.331(9.279)	0.878*

Notes. * Values of this line are presented as mean (standard deviation), the statistical method is paired *t*-test. ** Values of this line are presented as median (quartile range), the statistical method is *rank-sum* test. CVs, characteristic values. Pro-op, after operation. 3 h-Pro-op, three hours after operation.

Table 3 shows the statistical analysis of BSs between Pro-op and 3 h-Pro-op. The frequency of EBSs increased with statistical significance three hours later. Compared with the Pre-op and Pro-op comparisons, the Mean_Mag_bs, Std_Mag_bs, Mean_Duration, and Std_Duration, which represent the mean and standard deviation of single EBS energy and duration, have no statistical difference. However, there was a statistical difference between Sum_bs representing total energy and Sum_Duration representing total duration, both of which were larger, indicating that the overall energy and duration of BSs had recovered to a certain extent after three hours.

Table 4 shows the results of the statistical analysis of CVs of Pre-op and 3 h-Pro-op. The results showed that there was no statistical difference among all the parameters, indicating that there was no statistical difference in the intestinal peristalsis of 3 h-Pro-op comparing with Pre-op.

Discussion

General anesthesia can inhibit the gastrointestinal function of patients which include delay gastric emptying, small bowel transit and colonic transit [12, 13]. For this reason, Patients undergoing general anesthesia cannot take food immediately after surgery. A good clinical indication of the return of coordinated bowel motility after surgery can not only guide postoperative timely feeding, but also evaluate the recovery of anesthesia. In this paper, the data of 5-minute BSs of Pre-op, Pro-op, and 3 h-Pro-op which can reflect the bowel function at the time point were tested respectively. After processing and analyzing the BSs data, the CVs were extracted and statistically analyzed to evaluate the changes of the BSs after general anesthesia. The data of Pre-op and Pro-op were compared to see whether the intestinal function was weakened to illustrate the inhibitory effect of general anesthesia on intestinal function. The data of Pro-op and 3 h-Pro-op were compared to observe whether the intestinal function was stronger to indicate the recovery status three hours after general anesthesia. We also compared 3 h-Pro-op and Pre-op data to see if bowel function returned to the state before the general anesthesia.

The statistical results of the CVs are shown that 1) The difference of BSs between Pre-op and Pro-op was statistically significant. 2) The difference of BSs between Pro-op and 3 h-Pro-op was statistically significant. 3) There was no significant difference between Pre-op and 3 h-Pro-op. Specifically, the effect of general anesthesia on bowel function is holistic. In the statistical analysis between Pre-op and Pro-op, as well as between Pro-op and 3 h-Pro-op, there was no statistical difference in characteristic values of local BSs in the liner time-domain, but the differences in the overall occurrence frequency, total energy, and duration of intestinal sounds were statistically significant. And there was a weak trend after surgery compared with that before surgery, and there was a strong trend of recovery after 3 hours compared with that after surgery. Among the nonlinear dynamic parameters, there was no statistical difference in the mean value of the parameters that could express the complexity and stability of the local BSs, but the difference in the standard deviation of the nonlinear parameters was statistically significant, indicating that the complexity and stability dispersion degree of the BSs changed after the general anesthesia. The degree of dispersion was smaller after the operation, and recovered within three hours. The statistical analysis of Pre-op and 3 h-Pro-op showed that there was no statistical difference in either local characteristic parameters or overall characteristic parameters, whether it was linear time-domain parameters or nonlinear dynamic parameters, indicating that intestinal function had returned to the preoperative state to a certain extent after three hours of surgery.

In this paper, 5 minutes BSs of Pre-op, Pro-op and 3 h-Pro-op were collected to represent the status of the three periods, which has certain limitations. Under ideal conditions, the BSs should be measured continuously from the preoperative to postoperative, but the current surgical environment and perioperative nursing procedures do not allow the full-time measurement. However, the 5-minute BSs can effectively reflect the intestinal function to a certain extent [14, 15], so the research based on the 5-minute BSs is effective.

Another limitation is that many experience thresholds are used in the analysis, especially in the recognition of EBSs. Will the subjectivity of this experience value affect the judgment result of general anesthesia on the change of bowel sounds? The answer is no. In this paper, the same recognition threshold and method are used to analyze and identify the intestinal sound data of the tested patients of Pre-op, Pro-op and 3 h-Pro-op, respectively, in order to judge the changing trend of these three time points, so it is not affected. Furthermore, in the current study of BSs, there is no recognized gold standard for the recognition accuracy of EBSs, and there is no marked database to verify the accuracy. Most of the reference standards in the current study are based on the subjective judgment of clinicians, but the accuracy of such subjective judgment is also questioned [8].

Conclusion

In conclusion, after general anesthesia, the BSs change. The BSs were weakened after surgery, and three hours later, the BSs returned to the preoperative state. Therefore, the BS can be used as an indicator of intestinal function changes under general anesthesia, so as to provide guidance for postoperative feeding, which is of great clinical significance.

Methods

Data collection

Patients' BSs were collected using a self-developed wearable bowel sound device [16]. The device uses Knowles' SiSonic MEMS microphone, which has an ultra wide band (UWB) flat frequency response (± 2dB, 10 ~ 10000 Hz) and a tightly matched sensitivity of ± 3dB. Since the frequency of BSs is mainly distributed in 100–1000 Hz [17], this microphone is practical for the pick-up of BSs. The collection and storage of BSs and environmental noises are realized by the wearable BSs device which has carried out performance tests to ensure the reliability of data [18]. The sample rate of BSs was 8 kHz.

Signal processing

In the process of BSs acquisition, environmental noise is easy to be introduced, which directly affects the quality of the BS signal. Therefore, it is necessary to remove environmental noise to better analyze and identify the BSs. We use the noise acquisition channel of the recorder to collect the environmental noise, and the adaptive noise cancellation is used to remove the noise. Specifically, the least mean square (LMS) [19] algorithm is adopted, the order of the filter is determined to be 32, and the step size factor is set as 0.000001 to achieve a good adaptive cancellation.

Adaptive filtering can eliminate the environmental noise, but the high-frequency noise in the signal still affects the identification and analysis of effective bowel sounds (EBSs). As an effective and practical method, wavelet denoising has achieved good results in signal and image denoising, and has been widely used in engineering applications. Donoh [20, 21] proposed a wavelet threshold denoising method. The wavelet coefficient of signal contains important information after wavelet transform with *Mallat* algorithm. The wavelet coefficient of the noise is less than the wavelet coefficient of the signal. By selecting a suitable threshold, the wavelet coefficients greater than the threshold are considered to be generated by signals and should be retained, while those less than the threshold are considered to be generated by noise and set to zero to achieve the purpose of denoising. In the process of wavelet decomposition, the wavelet basis, the number of decomposition layers and the threshold should be determined. For the selection of wavelet basis, we chose *sym8* wavelet basis which is from the two common wavelet bases of *db* wavelet system and *sym* wavelet system. For determining the number of decomposition layers, too large or too small will both affect the final de-noising effect. In this paper, the number of decomposition layers is determined to be 5 after comparing the denoising effects of different decomposition layers. For the determination of threshold value, *Birge-Massart* [22] algorithm is used to obtain the threshold value of each layer of one-dimensional wavelet transform, and soft threshold function is used for denoising.

After the adaptive filtering and wavelet denoising, the waveform (Fig. 1) can be used to identify EBSs. The fractal dimension (FD) can quantitatively describe the complexity of the signal. The FD of EBSs is different from that of background sounds [23]. To calculate the FD of time series, we can either reconstruct the phase space first and then calculate the correlation dimension of time series [24–26] or directly calculate the FD in the time domain. The time series in this paper is the audio signal with a high sampling rate and large data volume, so the FD is calculated directly in the time domain. The Katz method [23, 27, 28] used in FD calculation which can effectively judge the randomness of waveform. When calculating the FD of the BS signal, we employed a sliding window to realize the short-time processing of audio signals. The length of the sliding window is set to *int* (0.006**fs*), where *int* indicates the integer part of the argument, and *fs* is the sampling frequency of the BS signal. The constant 0.006 is empirically set and justified by the efficient performance of the algorithm [23]. The FD of the data in the sliding window is calculated respectively. In order to ensure that the length of the data before and after calculating the FD is equal, the first and the last FD are used to make up the data at both ends. After the FD sequence calculated, the peak value is extracted to ensure the effective recognition of the BSs. The peak extraction method adopts FD-peak peeling algorithm (FD-PPA) [29].

FD-PPA makes the EBSs more obvious in the waveform, but the endpoint detection is needed to extract the EBSs. The purpose of voice endpoint detection (VAD) technology is to identify the starting point and ending point of speech accurately from a segment of the signal containing speech and distinguish speech and non-speech signals. It is an important aspect of speech processing technology. As for the BS signal, we identify the EBSs which satisfying certain conditions, while the others are considered as non-bowel sound signals. In this paper, the time series after FD-PPA are used as the input sequence to judge the starting and ending points of EBSs. The threshold for entering the BS segment, the length threshold of identified noise, and the maximum allowed mute length in the BS segment are set. Based on the above three thresholds, the endpoint of EBSs is determined. As a rule of thumb, the first is the threshold for entering BS segments which is set to 1.01. When the input value is greater than 1.01, it is considered to be the starting point of EBSs. The second parameter is the minimum duration threshold of the EBS signal, and the BS segment less than this threshold is considered as noise. And this threshold is set to 50 milliseconds [30]. The maximum mute length allowed in the BS segment is the third threshold which is set to 250 ms. If the mute length in the BS segment is less than this value, the BS is considered unfinished, otherwise, the BS segment is considered finished.

After the VAD, there are also many kinds of vocal signals mixed in, such as heart sounds, breath sounds and background noises similar to BSs. Limited to the problem of environmental noise collection and filter residue, we set three thresholds to remove three kinds of residual noise based on experience. Specifically, the envelope of each EBS is obtained by complex analytic wavelet transform [31]. Then, we exclude the sound segment whose envelope maximum value is less than 50, which means that a sound segment with a too small amplitude is considered as noise. In the measured data, the confounding of heart sounds is obvious. We extracted the envelope of sound segment and calculated the peak number. And based on the experience in judging heart sounds we rule out the sound segment whose peak value is less than 3. We also found that for BS segments with a very small signal-to-noise ratio, there was residual noise and it was identified as a gut sound, which also needed to be removed. As for this speech segment with residual noise, we filter out the envelope peak number which is more than 3 in the length of 1000 sampling points based on experience.

Table 5
The linear CVs of EBSs

Linear CVs	**Calculation methods**	**Physiological significance**
Num_bs	The number of identified effective bowel sounds during the measurement	Frequency of bowel sounds in the five minutes
Sum_bs	The sum of the absolute values of the identified effective bowel sounds	Reflecting the total energy of the bowel sounds
Sum_Duration_bs	The sum of the duration of the identified effective bowel sounds	Reflecting the total duration of bowel sounds
Mean_Duration	The mean of the duration of effective bowel sounds	Mean duration of effective bowel sounds
Std_Duration	The standard deviation of the duration of effective bowel sounds	Standard deviation of duration of effective bowel sounds
Mean_Mean_bs	The mean of the mean absolute value of effective bowel sounds	The average energy of effective bowel sounds
Std_Mean_bs	The standard deviation of the mean absolute value of effective bowel sounds	The standard deviation of the energy of the effective bowel sound

Notes. CVs, characteristic values. EBSs, effective bowel sounds.

Chatactersitic values extraction

The characteristic values (CVs) can quantitatively reflect the characteristics of BSs, so we extracted linear and nonlinear CVs for quantitative evaluation and statistical analysis. The linear CVs are mainly time-domain parameters, as shown in Table 5.

Physiological signals have been shown to be chaotic [32]. As the basic physiological signal, gut sound also has nonlinear dynamic characteristics. Therefore, nonlinear CVs are calculated in this paper. Recurrence quantification analysis (RQA) [33] can measure the complexity of a short and non-stationary characteristic signal with noise [34]. It has been broadly applied in the analysis of physiological data [35–37]. In this paper, phase space reconstruction is carried out for each EBS signal. Based on the recursive graph, recursive quantitative analysis is carried out and quantitative parameters are extracted [38], as shown in Table 6. There are multiple EBSs in each period, so in order to realize the subsequent statistical analysis, the mean value(-mean) and standard deviation(-std) of each CV in each period are calculated respectively.

Table 6
The nonlinear CVs of EBSs

Nonlinear CVs	Calculation methods	Physiological significance
RR	The percentage of recurrent points falling within the specified radius	Reflect the similarity of signal fluctuation
Lmean	The mean of the diagonal lengths in recurrence plot	related to the separation velocity of adjacent trajectories
ENTR	The Shannon information entropy of all diagonal line lengths	A measure of signal complexity
TT	the average length of vertical line structures	Degree of system stability
Notes. CVs, characteristic values. EBSs, effective bowel sounds.		

Fig. 2 shows an overview of BSs data acquisition, processing, and analysis, and ‖f(t)‖ is calculated as Eq. (1).

$$\|f(t)\| = \sqrt{\int_{-\infty}^{\infty} |f(t)|^2 dt} \tag{1}$$

Statistical ananlysis

We attempted to reveal the difference of BSs among Pre-op, Pro-op and 3 h-Pro-op. The CVs can quantitatively represent the signals, so we conducted statistical analysis on the CVs of the three periods in 26 patients, and then determined whether there were statistical differences. Statistical differences between Pre-op and Pro-op were first verified, and then the statistical differences between Pro-op and 3 h-

Pro-op were verified. The CVs for statistical analysis include linear CVs and the mean and standard deviation of nonlinear CVs.

Statistical analyses were performed using IBM SPSS Statistics 25. For data satisfying normal distribution, the statistical method of paired *t*-test was used. Otherwise, the *rank-sum* test was used. A value of $p < 0.05$ was considered to indicate statistical significance.

Abbreviations

BSs: Bowel Sounds; Pre-op: Before Operation; Pro-op: After Operation; 3h-Pro-op: Three Hours After Operation; EBSs: Effective Bowel Sounds; CVs: Characteristic Values; DMR: Dynamic Magnetic Resonance; LMS: Least Mean Square. FD: Fractal Dimension; VAD: Voice Endpoint Detection; RQA: Recurrence Quantification Analysis.

Declarations

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Authors' contributions

GW, MW, and WW mainly designed the experiment, analyzed the data, achieved the result and writing the manuscript. HL analyzed the data and writing the manuscript. SZ and LL helped to acquire data.

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Availability of data and materials

The datasets generated during and/or analyzed during the current study are available from the corresponding author at reasonable request.

Ethics approval and consent to participate

The research has been approved by the Medical Ethics Committee of Chinese PLA General Hospital for clinical research (No. 2018-176-01). Each subject signed the informed consent.

Consent for publication

When bowel sounds were obtained from patients, prior approval was obtained for future use of these records.

Competing interests

The authors declare that they have no competing interests.

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Figures

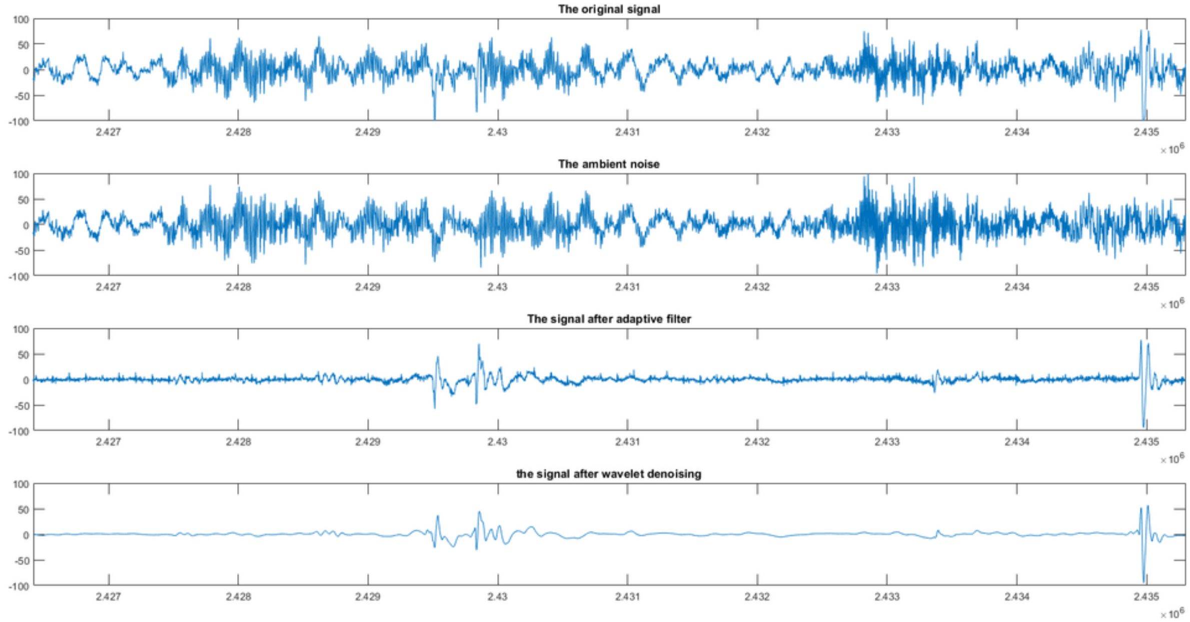

Figure 1

The bowel sounds signal after adaptive filtering and wavelet denoising.

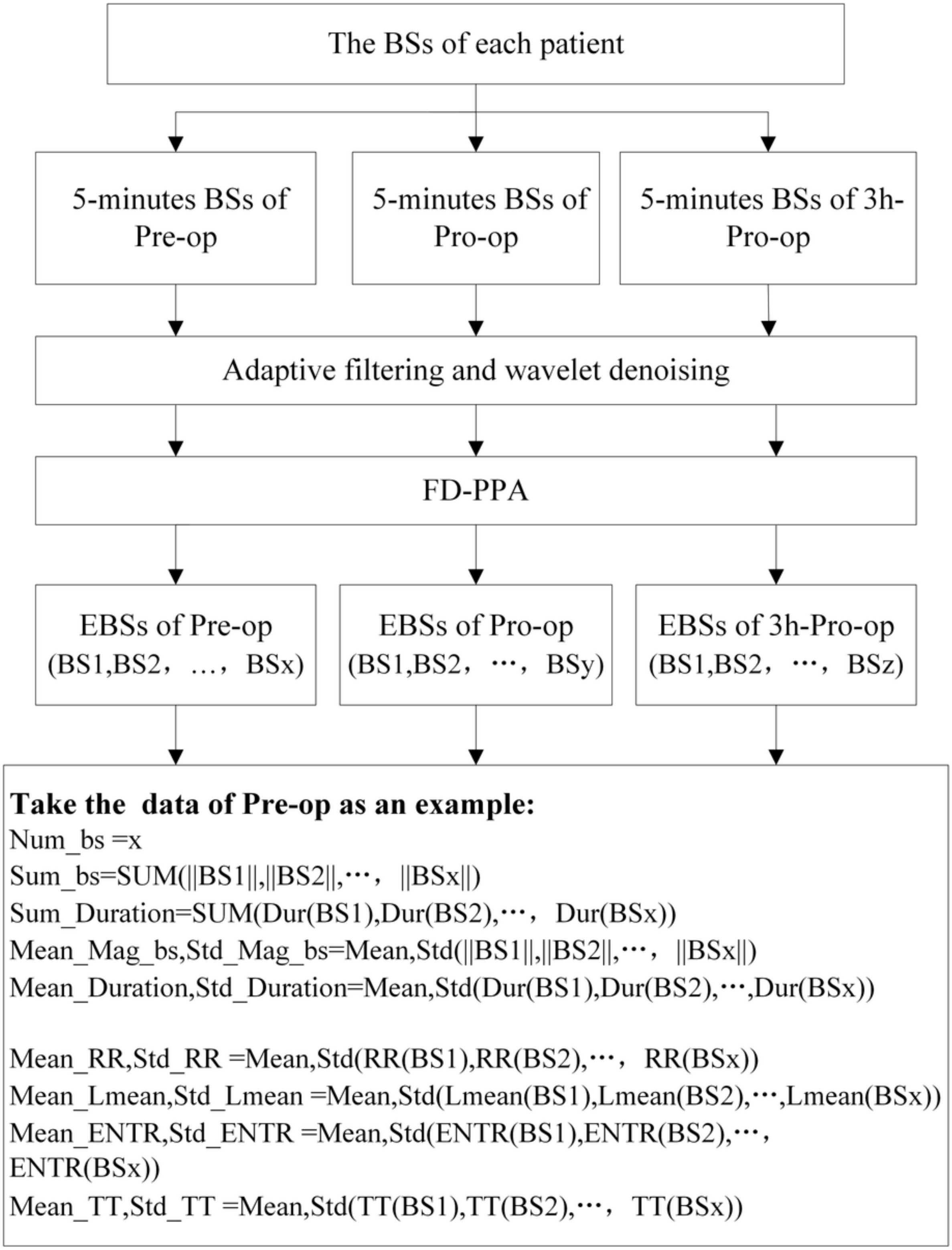

Figure 2

Overview of BSs data acquisition, processing, and analysis. BS is short for the bowel sound. Pre-op is short for before operation. Pro-op is short for after operation. 3h-Pro-op is short for three hours after operation. FD-PPA is short for FD-peak peeling algorithm. EBS is short for the effective bowel sound.