Proceedings of the 2023 Design of Medical Devices Conference
DMD2023
April 17-19, 2023, Minneapolis, MN, USA

DMD2023-7977

ON THE DESIGN OF A NOVEL PHONOENTEROGRAM SENSING DEVICE USING AI ASSISTED COMPUTER-AIDED AUSCULTATION

Shivam Damani
Department of Medicine, Mayo Clinic
Rochester, MN

Devanshi N. Damani
Department of Cardiovascular Medicine
Rochester, MN

Renisha Redij
Division of Gastroenterology and Hepatology, Department of Medicine, Mayo Clinic
Rochester, MN

Arshia K. Sethi
Division of Gastroenterology and Hepatology, Department of Medicine, Mayo Clinic
Rochester, MN

Pratyusha Muddaloor
Division of Gastroenterology and Hepatology, Department of Medicine, Mayo Clinic
Rochester, MN

Anoushka Kapoor
Division of Nursing, Mayo Clinic
Rochester, MN

Anjali Rajagopal
Department of Medicine, Mayo Clinic
Rochester, MN

Keerthy Gopalakrishnan
Department of Medicine, Mayo Clinic
Rochester, MN

Xiao Jing Wang
Division of Gastroenterology and Hepatology, Department of Medicine, Mayo Clinic
Rochester, MN

Victor G. Chedid
Division of Gastroenterology and Hepatology, Department of Medicine, Mayo Clinic
Rochester, MN

Alexander J. Ryu
Department of Medicine, Mayo Clinic
Rochester, MN

Christopher A. Aakre
Department of Medicine, Mayo Clinic
Rochester, MN

Shivaram P. Arunachalam
Department of Medicine, Mayo Clinic
Rochester, MN

ABSTRACT

Bowel sounds have been previously used to study intestinal motility and overall digestive health in various clinical settings. However, the blurred definition of bowel sounds and their subtypes, limited resources for interpretation, poor sensitivity, and low positive predictive value led to their restricted utility. Recent advances in artificial intelligence and machine learning have steered interest in developing unique tools using the phonoenterogram to analyze diverse bowel sounds. In our study, bowel sounds were recorded from eight healthy volunteers using the Eko Duo stethoscope. A novel deep-learning algorithm was designed to classify the recordings into baseline or prominent bowel sounds. A total of 11,210 data points (5,605 balanced sounds) were used to train and test the model to yield an accuracy of 0.895, a precision of 0.890, and a recall of 0.854 reflecting successful segregation of these sounds into respective groups. More extensive studies enrolling healthy and diseased subjects with a device specifically tailored to record bowel sounds are needed to generalize these results and determine their application in the patient population.

Keywords: Phonoenterogram (PEG), computer-aided auscultation (CAA), deep learning, bowel sounds

1. INTRODUCTION

Bowel Sounds are auscultatory findings appreciated during an abdominal exam. Several studies have revealed altered bowel sounds and their diagnostic potential in structural and functional gastrointestinal diseases.

Irritable bowel syndrome (IBS) and functional dyspepsia are the most common functional gastrointestinal disorders (FGIDs),. They are diagnoses of exclusion and require several invasive and non-invasive investigations like endoscopy, colonoscopy, abdominal imaging, and biochemical tests. The lack of a definitive diagnosis despite several investigations leads to patient dissatisfaction and mental strain [1]. Thus, there is an unmet clinical need for a novel cost-effective, non-invasive test to aid in their diagnoses. Phonoenterography is the process of recording and analyzing bowel sounds which can potentially be used to diagnose and monitor gastrointestinal pathologies [2]. Direct auscultatory interpretation of bowel sounds during a physical exam and manual analysis of phonoenterogram (PEG) is challenging owing to background disturbances in the environment, limited auditory spectrum, and discriminatory capacity of the human ear making it difficult to interpret subtle changes in bowel sounds which may reflect disorders [3,4]. Leveraging computer-aided auscultation techniques with artificial intelligence and machine learning can help overcome these challenges and possibly enhance the current diagnostic modalities for gastrointestinal diseases. However, it is tedious to annotate bowel sounds in phonoenterograms manually; hence, new methodologies are needed for efficient and accurate automated identification and labeling of bowel sounds.

Phonoenterography appears to be a promising modality for the non-invasive diagnosis and monitoring of disorders of the gastrointestinal tract in adults and children alike. However, to date there are no existing devices for high fidelity recording of bowel sounds to enable AI assisted computer aided auscultation to impact clinical practice. To enable the design of novel PEG sensing device, good understanding of the nature of bowel sounds to precisely identify and discriminate normal bowel sounds from the baseline bowel sounds and noise present during recordings. The purpose of this work was to develop a deep-learning model to classify baseline and prominent bowel sounds that can assist with the design and development of a novel PEG sensing device to enhance GI digital practice.

3. MATERIALS AND METHODS

2.1 Data collection

The Eko DUO stethoscope was used to record phonoenterograms (PEGs) from 8 healthy adult volunteers (5 female and 3 male) at the left upper quadrant (LUQ) and the right lower quadrant (RLQ) to match the regions of the pyloric sphincter and ileocecal junction (as shown in figure 1). A Transpore tape was used to secure the microphone of the stethoscope and helped apply adequate tension to minimize motion artifacts during respiration. The Eko DUO stethoscope was set to obtain readings with the microphone spectrum ranging from 250-5000 Hz in a quiet environment. Two types of PEGs were collected (a) recordings with respect to meals: bowel sounds were recorded after an overnight fast every 30 minutes from -1 hour to +4 hour of meal consumption; (b) 24-hour recording: bowel sounds were recorded every hour for a day to understand physiological changes with sleep, meals, activity, and defecation. A total of 242 minutes of phonoenterographic recordings were collected and analyzed in this study.

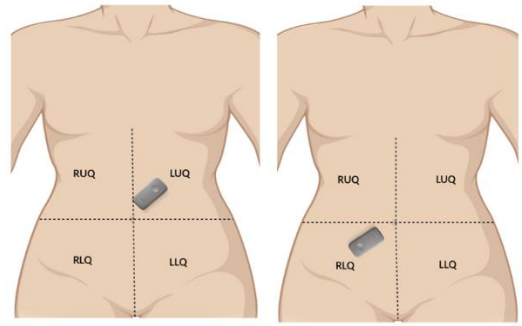

FIGURE 1: Figure showing the microphone placement of the Eko DUO stethoscope in the LUQ and RLQ to obtain PEG recordings [5].

2.2 Labeling and conventions

Bowel sounds were annotated using the Label Studio software after a 16x amplification by a physician as the only observer. The recordings were grouped into (a) Inaudible/ obscure/ baseline bowel sounds: Bowel sounds that are not heard by an unaided ear or a stethoscope via bell or the diaphragm but are appreciated as low amplitude sound on amplification to 16x and (b) Audible/prominent/distinct bowel sounds: Bowel sounds that can be heard by an unaided ear or by a stethoscope without the need for amplification. Two prominent sounds were considered discrete if they are separated by obscure/baseline sounds. The observer's confidence in accurately detecting bowel sounds from background noise was set to >85%.

2.3 Data Pre-Processing

5,605 prominent bowel sounds were annotated and exported from the label studio software. Equally matched baseline bowel sounds were used. Audio data typically has complex features, so extracting useful features to represent this audio is necessary for the model to learn. The Mel-spectrogram is one of the efficient methods for audio processing. The Mel spectrum contains a short-time Fourier transform (STFT) for each frame of the energy/amplitude spectrum, from the linear frequency scale to the logarithmic Mel-scale, and then goes through the filter bank to get the eigenvector, these eigenvalues can be roughly expressed as the distribution of signal energy on the Mel-scale frequency. In our study, we used the python package librosa to process audio data.

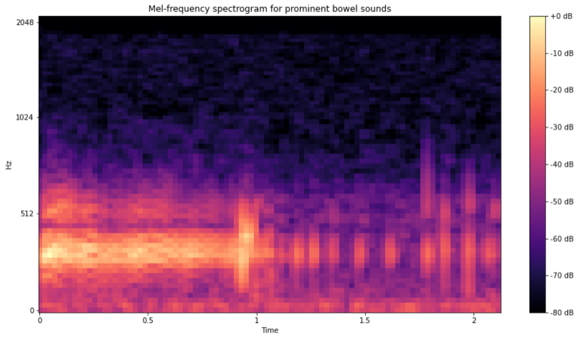

FIGURE 2. Figure representing the Mel-frequency spectrogram for prominent bowel sounds

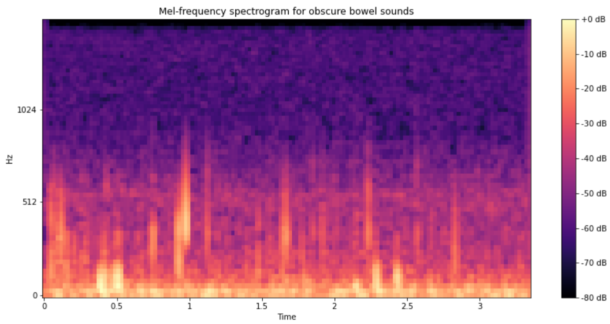

FIGURE 3. Figure representing the Mel-frequency spectrogram of an obscure/baseline bowel sound

Figure 2 and Figure 3 compares the Mel-frequency spectrograms of the baseline versus prominent bowel sounds and as seen in the image, the frequency of the different bowel sounds varies drastically.

2.4 Model development

The dataset was split into 80 % (8,968) data in the train set, 20% (2,242) data in the test set to test the accuracy of the model. Deep learning methods are applied and proven in different cases like image recognition and classification. Our study used Convolutional Neural Networks (CNNs). We used convolutional and pooling layers and performed batch normalization to make the outputs of the convolutional layer stay identically distributed, which can improve the performance of the model. Ultimately, we use fully connected layers as the output layer of the model. The model was trained by an Adam optimizer, whose learning rate, epochs, and batch sizes were hyperparameters that were tuned using bayesian optimization.

4. RESULTS AND DISCUSSION

A schematic setup of the device at the two auscultatory points is depicted in figure 1. The recordings obtained from the left upper quadrant and right lower quadrant were not taken simultaneously but in quick succession. The model performed reasonably well with an accuracy of 0.895, an F1 score of 0.871, a precision of 0.89, and a recall of 0.854 on the test data demonstrating the ability of the deep learning model to classify prominent and obscure baseline bowel sounds. Table 1 represents the confusion matrix of the model.

TABLE I. Confusion matrix

	Positive	Negative
True	1107	901
False	136	188

This study defines and categorizes a phonoenterogram recording into prominent, and baseline/obscure bowel sounds. The above-mentioned abdominal quadrants were selected as they correspond to locations of change in pressure owing to the presence of sphincters or valves. We used computer-aided auscultation techniques to visualize and annotate the PEG recordings obtained from eight healthy volunteers, followed by developing and training a new model to segregate the groups. As seen in the results sections, the model performed reasonably well and was able to correctly identify prominent bowel sounds versus not approximately 90% of the time. A precision of 89% was obtained with well-balanced sensitivity and specificity.

Recent work in bowel sounds reveals a lack of standardization in the definition, identification, data collection, and manual and automated analysis strategies [6,7]. These challenges stem from the inherent nature of bowel sounds such as an irregular pattern of occurrence, and non-uniform lengths and frequencies [6]. Variations also occur with physiological processes like defecation, diet, and activities of daily living making it hard to interpret PEGs. Hence, the first step toward any novel bowel sounds-based diagnostic, prognostic, or monitoring approach relies largely on the accurate detection and classification of bowel sounds [6].

Studies to date have focused primarily on either the identification and classification of bowel sounds into their various subtypes or studying the changes in bowel sounds with diet or liquids [6, 8,9,10]. The inter-bowel sound period was generally eliminated. As a part of the amplification of bowel sounds for accurate annotation of the start and end points of prominent bowel sounds, we noted that low-amplitude bowel sounds existed in the inter-bowel sound period. Significant information may be present in the baseline bowel sounds in addition to the predominantly studied prominent bowel. Hence, in our study, we aimed at the accurate classification of the two regions in each PEG recording. Further studies are required to explore this concept and its application to various pathologies. Although a small sample size, the results from this methodology are encouraging to extend this to a larger and more diverse cohort with the goal of transforming patient care with computer-aided auscultation.

Although endoscopic procedures are currently the gold standard diagnostic modalities for various conditions, they are invasive, expensive, require sedation or anesthesia, and are not useful in the diagnosis of functional disorders Thus, the quest for newer, simpler, cost-effective, and non-invasive methods to diagnose and monitor patients continues. This has led the scientific community to turn back to bowel sounds, this time, with artificial intelligence and machine learning at their disposal [6].

The practice of bowel-sound auscultation decreased with the advent of sophisticated diagnostic techniques that allowed for direct visualization of pathologies [11]. Availability of a use-friendly PEG sensing device will enable AI assisted computer aided auscultation of bowel sounds that can disrupt GI practice with easy prognosis and diagnosis of various bowel diseases. Current work involves the design and development of a wireless PEG sensing system inspired by the results of this study.

5. CONCLUSION

We demonstrated successful recognition of prominent versus baseline bowel sounds with an accuracy of 0.895 with the novel deep learning model. The results motivate the development of a novel wireless PEG sensing device for digital GI practice.

ACKNOWLEDGEMENTS

This work was supported by the Advanced Analytics and Practice Innovation unit for Artificial Intelligence & Informatics research within the Department of Medicine, Mayo Clinic, Rochester, MN, USA.

REFERENCES

[1] P. M. Hellström and P. Benno, “The Rome IV: Irritable bowel syndrome - A functional disorder,” Best Practice & Research. Clinical Gastroenterology, vol. 40–41, p. 101634, Jun. 2019.
[2] W. C. Watson and E. C. Knox, “Phonoenterography: the recording and analysis of bowel sounds.,” Gut, vol. 8, no. 1, pp. 88–94,Feb.1967.
[3] B. L. Craine, M. Silpa, and C. J. O’Toole, “Computerized auscultation applied to irritable bowel syndrome,” Digestive Diseases and Sciences, vol. 44, no. 9, pp. 1887–1892, Sep. 1999.
[4] L. J. Hadjileontiadis, T. P. Kontakos, C. N. Liatsos, C. C. Mavrogiannis, T. A. Rokkas, and S. M. Panas, “Enhancement of the diagnostic character of bowel sounds using higher-order crossings,” Proceedings of the First Joint BMES/EMBS Conference. 1999 IEEE Engineering in Medicine and Biology 21st Annual Conference and the 1999 Annual Fall Meeting of the Biomedical Engineering Society (Cat. No.99CH37015)
[5]Image created with BioRender.com
[6] N. Wang, A. Testa, and B. J. Marshall, “Development of a bowel sound detector adapted to demonstrate the effect of food intake,” BioMedical Engineering OnLine, vol. 21, no. 1, Jan. 2022.
[7] J. K. Nowak, R. Nowak, K. Radzikowski, I. Grulkowski, and J. Walkowiak, “Automated Bowel Sound Analysis: An Overview,” Sensors, vol. 21, no. 16, p. 5294, Aug. 2021.
[8] X. Du, G. Allwood, K. M. Webberley, A. Osseiran, and B. J. Marshall, “Bowel Sounds Identification and Migrating Motor Complex Detection with Low-Cost Piezoelectric Acoustic Sensing Device,” Sensors (Basel, Switzerland), vol. 18, no. 12, Dec.2018.
[9] K. Kölle, M. F. Aftab, L. E. Andersson, A. L. Fougner, and Ø. Stavdahl, “Data driven filtering of bowel sounds using multivariate empirical mode decomposition,” BioMedical Engineering OnLine, vol. 18, no. 1, Mar. 2019.
[10] O. Sakata, K. Matsuda, Y. Suzuki, and T. Satake, “Basic study of occurrence frequency of bowel sounds after food ingestion,” TENCON 2011 - 2011 IEEE Region 10 Conference, Nov.2011
[11] H. Baid, “A critical review of auscultating bowel sounds,” British Journal of Nursing, vol. 18, no. 18, pp. 1125–1129, Oct. 2009.