Paper 092, ENT 202

Stethoscope for Monitoring Neonatal Abdominal Sounds

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Abstract

This research involves the development of a custom electronic stethoscope system for monitoring abdominal, or so-called bowel, sounds in premature infants. Possible causes of bowel dysfunction in premature infants include bowel obstruction, functional or anatomic, which may be reflected as an abnormality or lack of peristalsis. Such dysfunction is problematic to feeding the infant. This peristalsis may be monitored acoustically to determine the health of the patient’s digestive tract. Due to the relative lack of research involving infants in this field, we are performing this research in several phases. Starting with our initial research, our current system utilizes a commercial electronic stethoscope.

The second phase is development of a custom electronic stethoscope system appropriate for a bowel sounds monitoring device, for which our preliminary research is being used in the design. Our custom stethoscope will have unique characteristics. The stethoscope will remain attached to the patient for extended periods and, compared to the patient, must be small in size. Unlike an adult, regions in the neonate abdomen are much smaller and may not be acoustically isolated. Also, unlike a conventional device, the stethoscope must be optimized for listening to sounds common in the abdomen. Results from this new stethoscope are compared with other preliminary results that we have obtained and will be used to further characterize bowel sounds in premature infants.

Introduction

The overall goal of our research is to develop an electronic monitoring device for premature infant gastrointestinal sounds detection and analysis. Such a device will continuously present data in a form meaningful to medical personnel and may help diagnose or prevent life threatening problems such as necrotizing enterocolitis, which is an inflammatory disease of the premature. Additionally, vomiting, gastroesophageal reflux, and pulmonary aspiration of gastric contents may be prevented.

Premature infants receive nutrition much earlier in the development cycle than infants with full-term delivery. Given the situation, the premature digestive system may not be receptive to nutrition, and caretakers must decide whether it is safe to feed the premature infant. Gastrointestinal dysfunction has a number of causes that include immaturity of the digestive tract, birth defects, mild intolerance or allergic reaction to food, enzyme abnormality, electrolyte imbalance, abnormal vascular supply, infection, and systemic illness. Symptomatic of such dysfunction is an abnormality, or lack of peristalsis, which is the pattern of smooth muscle contractions that moves materials through digestion.

Peristalsis may be monitored acoustically to determine the health of the patient's digestive tract. It is currently common practice for nurses to use traditional stethoscopes to periodically listen for and analyze bowel sounds. We assert that gastrointestinal sounds, or so-called bowel sounds, are to be considered among other vital signs. Unfortunately, the ability to identify the aural cues in bowel sounds is a learned skill that takes time to develop. Also, given the sometimes transient nature, some bowel sounds may not be heard. In addition, the interpretation of bowel sounds is currently entirely subjective and based on training and experience. Further, the human ear is limited in its sensitivity and specificity in detecting bowel sounds. Based on these reasons, clinical acumen is limited, and such findings may or may not be correct.

The goal of this specific project is to develop a specialty stethoscope designed for recording the bowel sounds of premature infants. Due to the relative lack of research in this field, we are performing this research in several phases. Our initial research utilizes an FDA approved commercial electronic stethoscope and is part of a clinical study at the Connecticut Children's Medical Center [1]. Based on this research, we are developing a new prototype stethoscope system. Results from this new stethoscope will be compared with other preliminary results that we have obtained and will be used to further characterize bowel sounds in premature infants.

Related Research

Relevant references include Tomomasa, et al. [2], who recorded and analyzed bowel sounds of infants with pyloric stenosis, before and after applying a corrective pyloromyotomy. According to Wikipedia [3], infantile hypertrophic pyloric stenosis is a condition whereby an obstruction in the lower stomach causes severe vomiting in the first few months of life. Few cases are mild enough to be treated medically. The definitive treatment is with a surgical pyloromyotomy, known as Ramstedt's procedure, which involves dividing the muscle that narrows the pylorus. Occasionally, the procedure must be repeated to provide an adequate opening.

To record bowel sounds, the study used methods previously reported by Tomomasa et al. [4], [5] whereby a handmade device using a condenser microphone was attached with electrocardiograph adhesive tape to the abdomen. Signals were amplified and recorded with an audio cassette deck over periods 60 minutes long when fasted. The analog recordings were later sampled and analyzed using a personal computer. Following an 80 Hz high-pass filter to suppress cardiovascular sounds present in the 20 to 50 Hz range, sampling was performed at 1,000 Hz. Three-minute bins were used to calculate the sound index (SI) as the sum of absolute signal amplitudes expressed as volts per minute.

The results show that bowel sounds increased after pyloromyotomy, correlating with gastric emptying, except for the first 24 hours when gastric emptying reached the plateau level. They cite Benson et al. [6] who demonstrated by manometry that small intestinal motility was abnormal after major abdominal surgery. Bowel sounds were also monitored by stethoscope and were found to be absent from subjects for more than 20 hours. Approximately 60 hours were required for bowel sounds to return in 50 percent of the subjects. To summarize, bowel sounds are a good indicator of the return of gastric emptying, as well as bowel motility after pyloromyotomy and can be useful in deciding when to resume feeding post-operatively in each patient.

With respect to the interests of this paper, Dimoulas et al. [7] provide a useful survey of additional relevant research. They cite the pioneering work of Cannon [8] and others. Issues in recording bowel sounds involving noise, dynamic range, and pickup are outlined. Cardiac and respiratory acoustic interference has been reported where the heartbeat sounds have a very weak nature and are observed mostly in the cases of infants. Patterns of bowel sounds are defined and classified. Data was sampled at a rate of 8 kHz and was found to be entirely adequate. A 16-bit quantization was selected to provide adequate dynamic range.

Initial Research

Figure 1 shows the stethoscope configuration used in our initial research, which is based on a commercially available electronic stethoscope [9] and acquisition module [10] that connects to a laptop computer (not shown) for data collection. The black box contains a custom amplifier used to better condition the stethoscope signal to the acquisition module. Like conventional devices, this stethoscope includes earpieces that are placed in the listener’s ear canal, ear tubes that are solid material fitted to the ear pieces, tubing, as well as a chest piece, or stethoscope head, that is placed against the region of interest. Reference to the head as a pickup is suggestive of electro-mechanics, like that in an electronic stethoscope.

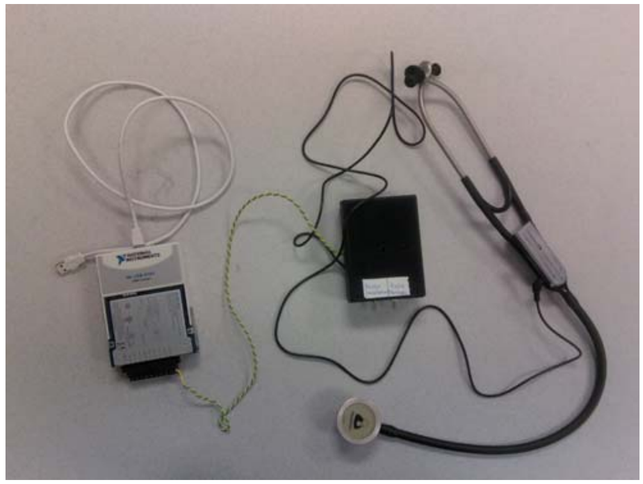

Figure 1: Initial Research Configuration with Commercial Devices

The initial research configuration is approved by our Institutional Review Board (IRB), which allows us to actually use the device in the Neonatal Intensive Care Unit (NICU). The IRB analysis was eased greatly since the Thinklabs stethoscope is an FDA approved device. Bowel sounds were recorded in a number of situations, such as before and after feeding. Figure 2 shows bowel sounds from a normal premature infant, less than two months in chronological age, recorded before feeding. To an untrained ear, such a recording sounds like popping at first. While limited and not satisfying our design goal, this configuration has helped us to understand the nature of infant bowel sounds.

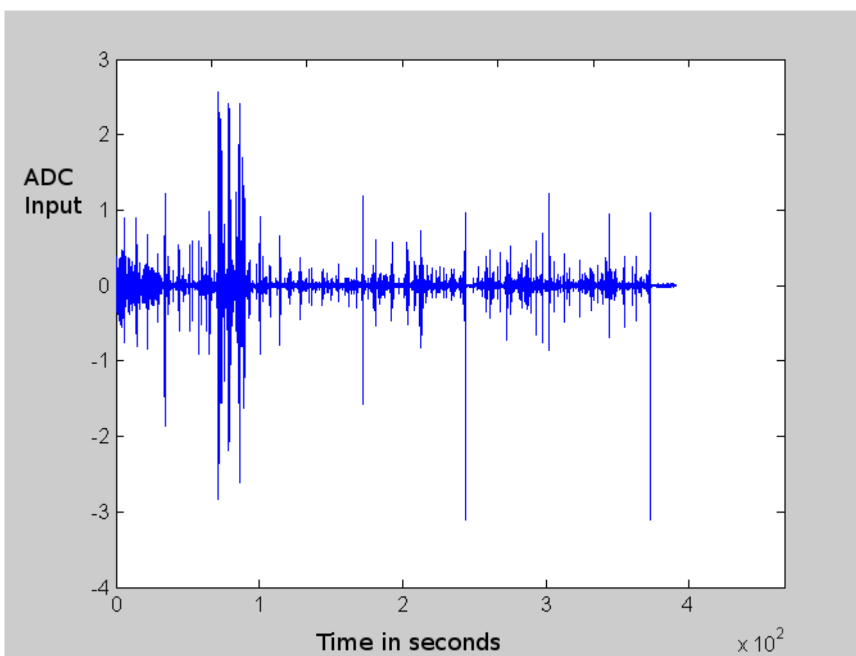

Figure 2: Normal Premature Infant Bowel Sounds before Feeding

ISBN 978-1-60643-379-9

To understand how this configuration is limited for our use, consider that the stethoscope head is somewhat large and heavy. A feature to extend battery life limits use of the stethoscope to approximately two-minute intervals. Such a stethoscope is for general use and, for our specific application, may introduce selective distortion. The stethoscope must be carefully held against a patient, which introduces undesirable acoustic artifacts.

Our initial research is being used to design a custom stethoscope system, specifically for such a bowel sound monitor. The stethoscope has unique characteristics. Eventually, such a stethoscope will remain attached to the patient for extended periods and, compared to the patient, will be small in size. Unlike an adult, regions in the infant abdomen may not be acoustically isolated. Also, unlike a conventional device, the stethoscope must be optimized for listening to sounds common in the abdomen. Following our IRB approval, results from this new stethoscope will be compared with other results that we have obtained and will be used to further characterize bowel sounds in premature infants.

Prototype Stethoscope Concept

Figure 3 summarizes our prototype stethoscope system. The stethoscope head, or pickup, to the left is constructed with a contact mechanism that is in physical contact with the patient, as well as a transducer, which converts the resultant mechanical signal to an electrical signal. The acquisition card contains amplifiers, anti-aliasing filters, and an analog to digital converter (ADC) used to sample and digitize the transducer signal. An off-the-shelf development board [12] contains a field programmable gate array (FPGA) used to implement the processor system. We are first using a laptop computer for data collection, but a compact flash device will allow for long-term stand-alone data collection capability.

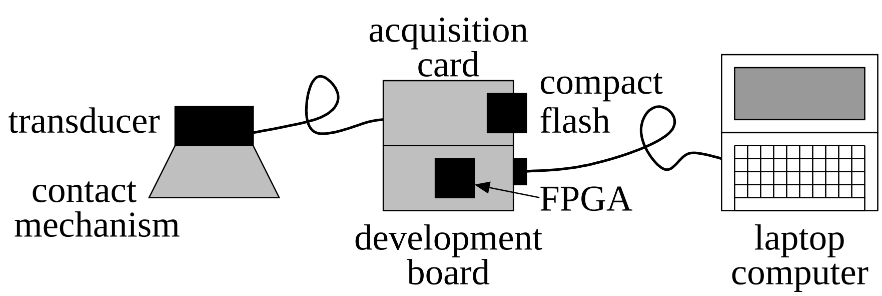

Figure 3: Prototype Stethoscope System

The acquisition card is a custom design made with discrete components. Such use of an FPGA to construct the embedded microprocessor system is appealing because, in prototyping, we benefit in having the utmost in flexibility. Significant changes can be quickly made to the corresponding embedded processor system without incurring any tooling charges. Future research may also involve the use of wireless technology.

The pickup is the most critical component in the design. To be acceptable for use with premature infants, the device must be small but still have a reasonably large contact area, have very little nominal contact pressure, little weight, and maximum sensitivity to the desired signal. To date, our research has produced the two prototype pickup devices in

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Figure 4. The devices have similar construction to those described previously, having a contact mechanism and a transducer. The device to the left is a small tube container with an electret microphone and is sealed with thin plastic sheet material. To the right is a conventional stethoscope head that has been bored-out and contains an electret microphone. While the tube contact area is slightly smaller, our first impression of the measurements is that it compares more favorably to the bored-out stethoscope head.

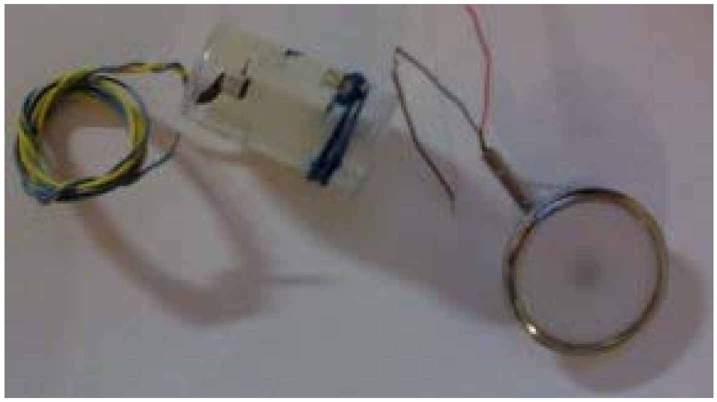

Figure 4: Experimental Pickups

Several other devices were also briefly tried. Piezoelectric elements were more sensitive to the mechanical aspect of being mounted rather than to the desired signal. Dynamic speakers were not very sensitive. The commercial contact devices considered applied too much contact pressure. To allow for long-term patient contact, yet prevent injury to infant skin, an acceptable device may incorporate a specialty adhesive, similar to that currently used for ECG leads and thermal reflective patches. Klear-Trace© brand electrodes [11] are such examples. Future work will refine the contact mechanism and will consider such a specialty adhesive.

Acquisition Card and System Board

Figure 5 shows the prototype stethoscope system with the tube type pickup attached using test leads. The acquisition card is in the upper right, with a Compact Flash (CF) card to the far right. The lower card is an off-the-shelf development board [12] used to implement the digital aspects of the design. This prototype stethoscope currently does not actually have a headphone connector for direct listening because we presently rely on an attached personal computer to examine the incoming signals. Providing such a headphone connector makes the stethoscope more usable as a standalone system.

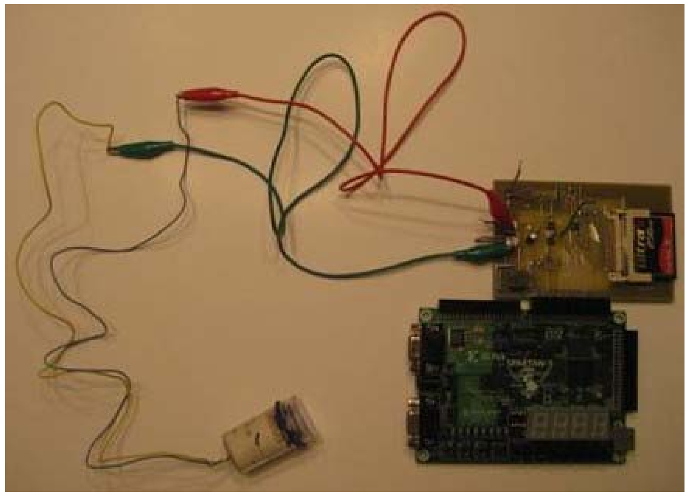

Figure 5: Prototype System with the Tube Pickup

The availability of low-cost, high density field programmable gate arrays (FPGAs) provides new opportunities for the development of small embedded processor systems. Figure 6 outlines how the prototype stethoscope contains such a system. A processor is needed to provide all the required behavior, which includes managing a data acquisition system, communicating with other devices, and performing data logging. Also, having the stethoscope implemented as an embedded microprocessor system will enable us to consider advanced algorithms such as those used to mitigate or remove interfering noise.

Much of the system is in the FPGA, which is an array of configurable logic blocks along with a configurable interconnecting resource that is called the FPGA fabric. Such FPGA-based systems are most appropriate in low volume applications that call for the utmost flexibility. Given the modest performance requirements and that development of the stethoscope is only one step in our research, the initial research use of FPGA technology is particularly appealing.

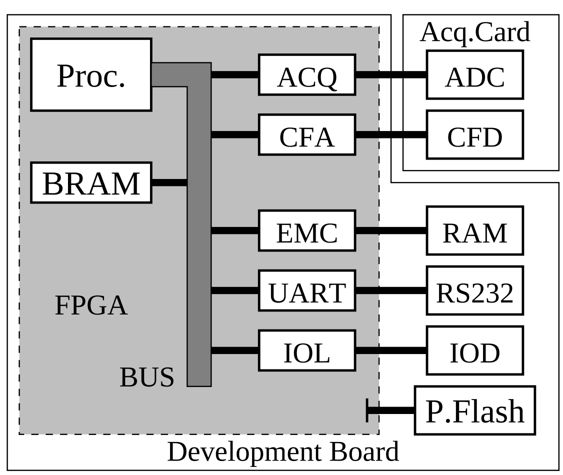

Figure 6: Stethoscope Embedded Processor System

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With modest performance requirements, we chose to use a fairly generic 32-bit RISC type softcore microprocessor [13], which means that rather than being an embedded core, the processor (Proc.) is implemented in the fabric along with the rest of the system. Code written with a hardware description language, such as VHDL, is used to produce an image file or bit file, stored in the platform flash (P.Flash), which configures all aspects of the FPGA, including the on-chip block RAM (BRAM) memory. Note that the image file here is not executable but rather can be thought of as being the system itself. Once the FPGA is configured, the system executes machine code just like any processor. As such, the software is written in C using conventional software development tools.

The acquisition card (Acq.Card) contains acquisition components (ADC), which are controlled by the acquisition logic (ACQ). Likewise, a compact flash device (CFD) is controlled by compact flash adapter logic (CFA). On the development board, the external memory controller (EMC) provides access to 1 Mbyte of RAM. A UART provides RS232 communications. Input-output logic (IOL) connects input-output devices (IOD), such as switches, push-buttons, and LEDs and the seven segment display.

For sampling, we selected the AD7685 which provides 16-bit samples at rates as high as 250 kHz. Sample rates are presently limited by the data rate of the associated communications. To further address the issue of large dynamic range inherent with bowel sounds as described by Dimoulas et al. [7], we include digitally controlled potentiometers to maximize the dynamic range of the sampler. Input configurations are provided for differential, as well as single ended, signal sources.

Given that the required IRB analysis of the prototype system is not completed, we are not yet able to use the system to actually record premature infant bowel sounds. Unlike our Thinklabs stethoscope-based system, the prototype system is not FDA approved and requires a more rigorous study. To prepare for examining the prototype system, we first considered heartbeat sounds. Figure 7 is a sample published recording of an adult heartbeat sound [11] sampled at 44.1 kHz that was dynamically enhanced.

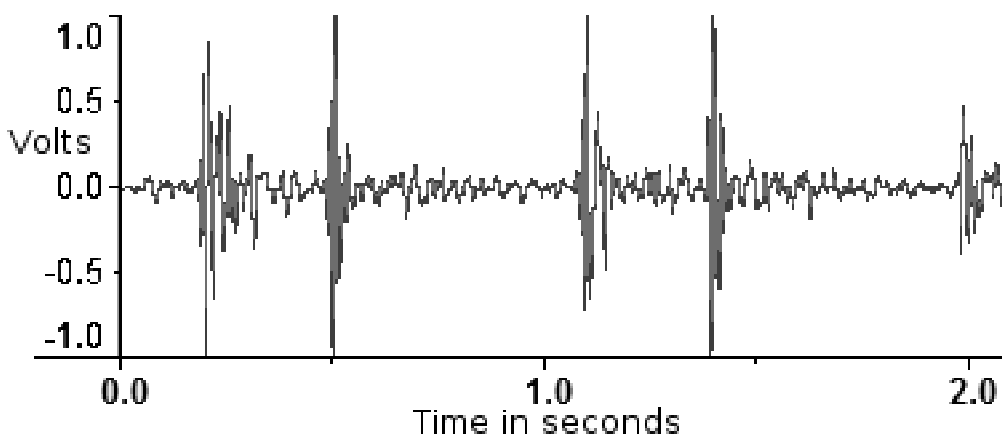

Figure 7: Adult Heartbeat Sound

Figure 8 and Figure 9 are among the first results we produced with the prototype stethoscope system. As a first test, we recorded Andrew Maloney's heartbeat; Maloney is one of our participating graduate students. Figure 8 shows the analog signal of a pair of beats before sampling. Figure 9 presents the corresponding digital output of a single beat plotted by LabVIEW [14]. In this test, the sample rate is 3,000 Hz. Results from the Thinklabs' electronic stethoscope and our prototype compared over an extended period of time appear very similar.

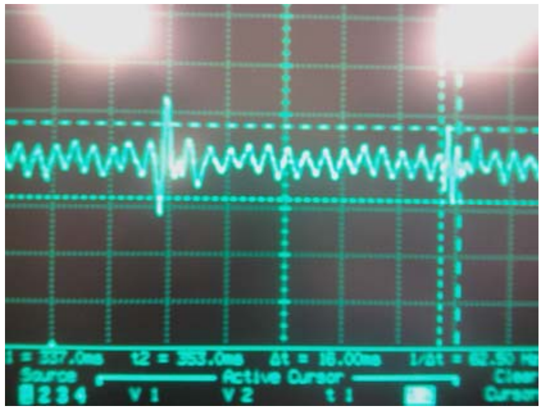

Figure 8: Analog Input to Sampler of Adult Heartbeat

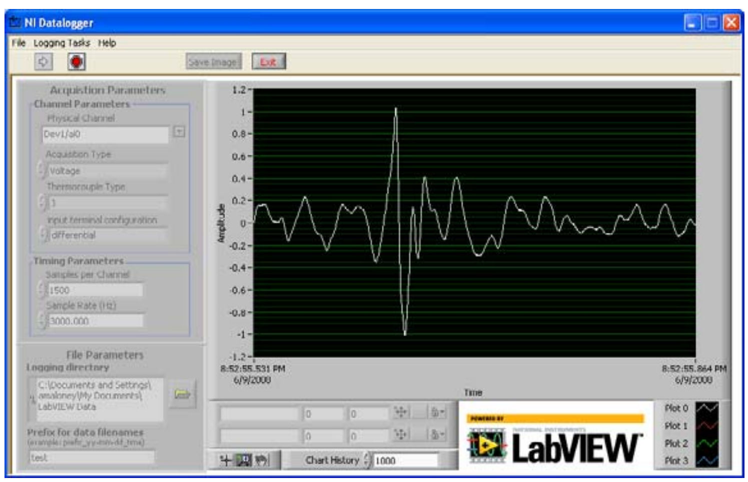

Figure 9: First Digital Results from Prototype of Adult Heartbeat

Figure 10, displayed in MATLAB, shows bowel sounds from our graduate student produced by the prototype stethoscope using the bored-out stethoscope head. In comparing this to Figure 2, taken of a premature infant with the initial research configuration, they share a similar pattern of peaks although they are different. The amplification and anti-alias filtering used to obtain Figure 10 does not eliminate the considerable background noise.

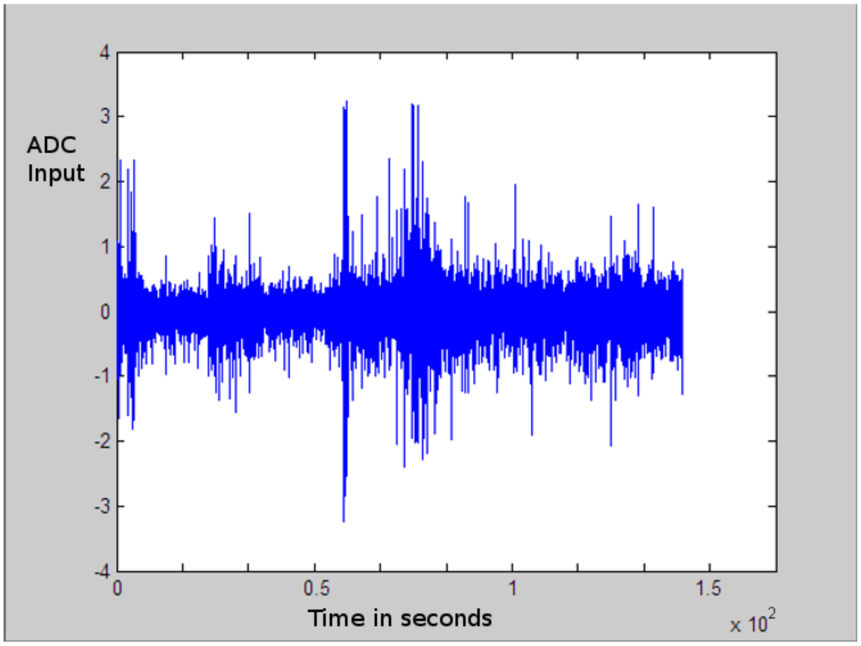

Figure 10: Prototype Recording of Adult Bowel Sounds

Next Research Phases

The first issue, with respect to the prototype stethoscope system, is obtaining approval from our IRB to allow us to use the device in the NICU. We are also planning the next generation prototype stethoscope, on which we will use a next generation stethoscope head. Through interviews with one of our authors, Dr. Eisenfeld, along with attending nurses, students produced a Quality Function Deployment (QFD) report. Such a report is based on a short list of questions first posed to the perceived customers of a proposed product. Results from the list are used to inspire a second list of questions. A summary of the final results serves as useful input to the product design cycle. The most important elements identified were computer control, weight, the ability to capture, filter, and amplify all bowel sounds without signal loss, as well as compatibility with other existing hardware in the NICU.

Summary

In closing, the subject of this paper is the development of a custom electronic stethoscope system for monitoring abdominal or so-called bowel sounds in premature infants. This research is part of a larger project to design a system for monitoring and evaluating bowel sounds. This paper outlines initial research being performed, based on an FDA approved stethoscope. This research has led to the design of a unique prototype stethoscope for use in this regard. We are seeking approval from our IRB to allow us to use the device in the NICU. Listening to adult bowel sounds is a necessary first step in our research toward developing such a monitor system. We are also planning the next generation prototype stethoscope. Work in the larger project will involve practical analysis and classification of such recordings. Situations that involve comparing bowel sounds before and after eating will be considered. This is based on the premise that bowel sounds are notably more pronounced before eating because the muscles of the stomach and intestines are active before digestion.

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Biography

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