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Portable EGG recording system based on a digital voice recorder

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Cutaneous electrogastrogram (EGG) recording offers the benefit of non-invasive gastrointestinal diagnosis. With long-term ambulatory recording of signals, researchers and clinicians could have more opportunities to investigate and analyse paroxysmal or acute symptoms. A portable EGG system based on a digital voice recorder (DVR) is designed for long-term recording of cutaneous EGG signals. The system consists of electrodes, an EGG amplifier, a modulator, and a DVR. Online monitoring and off-line acquisition of EGG are handled by software. A special design employing an integrated timer circuit is used to modulate the EGG frequency to meet the input requirements of the DVR. This approach involves low supply voltage and low power consumption. Software demodulation is used to simplify the complexity of the system, and is helpful in reducing the size of the portable device. By using surface-mount devices (SMD) and a low-power design, the system is robust, compact, and suitable for long-term portable recording. As a result, researchers can record an ambulatory EGG signal by means of the proposed circuits in conjunction with an up-to-date voice-recording device.

Keywords: Portable EGG; Amplifier; Frequency modulation; Electrogastrogram

1. Introduction

Cutaneous electrogastrogram (EGG) record non-invasively, via cutaneous electrodes, the electrical activity of the stomach. First discovered by Alrarez in 1921, the non-invasive nature of cutaneous EGG makes it an attractive tool for the diagnosis of gastrointestinal disorders. Gastric myoelectrical activity has two components: electrical control activity (ECA) and electrical response activity (ERA) [1]. Low-amplitude EGG signals (about 50 – 500 μV) [2] are liable to be affected by movements from the heart, chest, diaphragm, abdominal wall, etc [3]. Low-frequency EGG activity is measured on the surface of the upper right abdominal region. Generally, normal EGG signals contain a dominant frequency between two and four cycles per minute (cpm). A tachygastric EGG signal has a dominant frequency of 4 – 9 cpm, and the dominant frequency at 0.5 – 2 cpm is a bradygastric EGG signal [4,5].

Most previous studies have been interested in the difference of the EGG signals between abnormal and healthy patients. However, for paroxysmal or acute gastrointestinal symptoms, it is very difficult to detect these abnormal signals. An ambulatory technique for continuous, long-period recording would encourage the application of EGG in clinical practices [6]. A portable EGG recording system can record abnormal EGG activities during the course of intestinal or stomach disorders; thus providing invaluable data to clinicians for diagnoses. Furthermore, a portable EGG system could offer additional applications for home care and telemedicine by allowing clinical physicians and gastrointestinal experts to diagnose patients over the Internet.

This paper describes the design of a novel, low-cost and portable EGG recording system containing an EGG module, a digital voice recorder (DVR) and acquisition software. A DVR is a portable audio-frequency recorder, commonly used in recording discussions, etc, and costs

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approximately US$100. Its small size, high capacity and long battery life make it suitable as a portable system capable of recording signals for several hours. However, a DVR is designed for audio purposes, and the frequency of the EGG signal is too low to meet the bandwidth requirements of DVR input. Thus, a frequency modulation device is required, which would allow the low-frequency EGG signal to be recorded by a DVR. Therefore, a frequency modulator is incorporated into the portable system, along with the amplifier and filter circuits.

2. System architecture

Figure 1 depicts the proposed portable EGG recording system and identifies the following blocks: electrodes, an amplifier with a modulator, and a DVR. The recording sequence is as follows.

The EGG signal is detected by a pair of Ag/AgCl surface electrodes (Nessler Swaromed, Innsbruk, Austria) to reduce motion interference [7]. The bipolar signal is then amplified and the noise is filtered via an EGG amplifier circuit. After that, an LCM555-based modulator is used to convert the low-frequency EGG signal into the audio range. Since DVRs are designed for long-term voice recording—for example, the Sony DVR (Tokyo, Japan) used in our system can record voice signals for up to 192 hours—a high-capacity DVR can be adapted to meet the requirement of long-term recording. A personal computer (PC) is used for online monitoring as well as for off-line demodulation. Finally, the raw data from the EGG are saved on the hard disk of the PC for further analysis.

Details of the signal conditioning circuit are shown in figure 2. It consists of an Analog Devices OP490 (4-Op IC, Massachusetts, USA) and some passive components. The first stage is a 2-Op Amp instrument amplifier, providing high-input impedance and 10-times gain. The next stage is a second-order Butterworth low-pass filter followed by a simple resistor/capacitor (RC) filter. The bandwidth, 0.016 – 0.55 Hz, is designed to retain the EGG frequency and attenuate other undesired noises such as breathing electromyogram (EMG) or electrocardiogram (EKG), whose amplitudes are much larger than those of the EGG signal [8]. The final stage is a 40-times non-inverting amplifier, which amplifies the EGG signal to a level of 1.5 ± 0.6 V. To avoid noise coupled with high resistance, non-polarized aluminium capacitors are used in the amplifier filters.

Figure 3(a) depicts the modulation circuit. In order to accommodate the input-frequency range for the long-playing mode of most DVRs, the modulation circuit is designed to convert the amplified EGG, in the voltage range of 0.9 – 2.1 V (1.5 ± 0.6 V), to 400 Hz – 3.5 kHz. An LCM555 timer, an integrated circuit (IC) with low power consumption and low voltage operation, implements this function. The timer is operated in pulse-position modulation (PPM) mode [9]. Figure 3(b) illustrates a simplified model of charging and discharging. In this mode, the frequency is determined by the input voltage, V_{in}. In the charge phase, the switch is turned off. Current passes through the r_S, R_2 and R_3 resistors to charge C_2. V_S (2.5 V in this circuit) is supplied by a voltage reference IC, LM385-25, and r_S represents the internal resistance of V_S. The time of the charge phase is:

$$T_1 = (r_S + R_2 + R_3) C_2 \ln \frac{\frac{1}{2} V_{in} - 2.5}{V_{in} - 2.5}. \quad (1)$$

When C_2 is in the discharge phase, the switch is turned on. Current passes through the r_d and R_3 resistors to

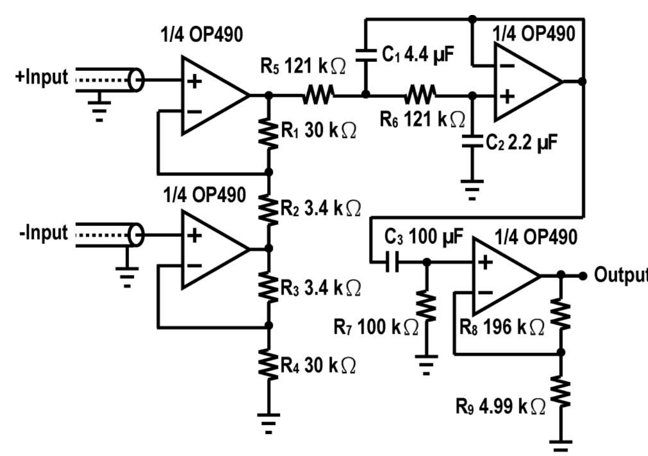

Figure 2. Circuits of the EGG amplifiers and filters.

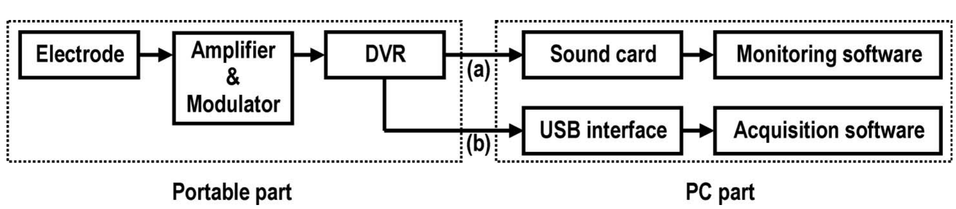

Figure 1. Block diagram of the portable recording system. The portable part consists of an EGG amplifier, a modulator, a DVR and electrodes. (a) For online monitoring, the modulated EGG data are acquired via a computer sound card, demodulated, and immediately displayed as an EGG signal on a monitor. (b) The EGG data could be transferred to a PC through a USB interface for off-line storage.

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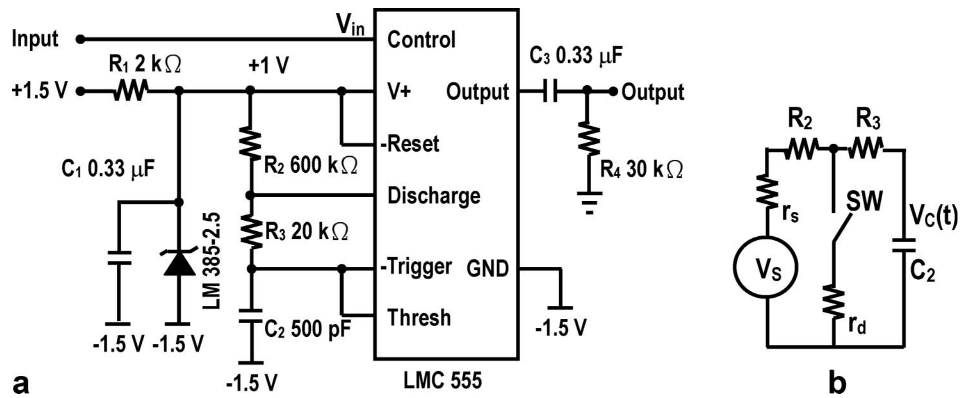

Figure 3. (a) Modulation circuit. This device converts EGG signals to voice frequencies. (b) A model of the charge and discharge of C_2.

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discharge C_2, where r_d represents the internal resistance of the switch. The time of the discharge phase is:

$$T_2 = (r_d + R_3)C_2 \ln 2 \quad (2)$$

The frequency can then be obtained from equations (1) and (2):

$$f = \frac{1}{T_1 + T_2} = 1 \Big/ \left(a + b \ln \frac{\frac{1}{2}V_{in} - 2.5}{V_{in} - 2.5} \right) \quad (3)$$

$$\text{or } V_{in} = 2.5 \times \left(1 - \frac{1}{\frac{2}{e^{\frac{a}{b}}} \times e^{\frac{1}{bf}} - 1} \right) \quad (4)$$

where a and b are constants: $a = T_2 = (r_d + R_3)C_2 \ \ln 2$, $b = (r_S + R_2 + R_3)C_2$. Equation (4) is the transfer function of demodulation. However, because r_S and r_d are unknown, parameters a and b can be determined by a statistical regression.

EGG online monitoring and off-line data acquisition programs have been developed with National Instruments (NI) LabVIEW 7.1 (Texas, USA). The modulated EGG data are acquired via a computer sound card during recording. In this program, CD quality at 44.1 kHz was set as the sound-card sampling frequency. Since the EGG is a low frequency signal, the system demodulates the EGG recording of the sound card input to 10 Hz, which is an adequate sampling frequency [10]. After removing DC bias, a Hamming window and zero padding are applied. A total of 4410 voice samples were expanded to 8192 samples. This process is required for demodulation speed and better frequency resolution [11]. After applying the dominant frequency to the voltage-transfer function, each demodulated EGG sample can be displayed on the monitor. The online monitoring program can ensure that the system has been set up correctly on the patient.

The off-line acquisition program is applied to convert the '.wav' file that has been saved via a USB interface. This approach will speed up the conversion time since transferring the signals via the sound card would take the same length of time as recording. After applying this frequency-to-voltage transfer procedure, the reconstructed EGG signals are stored on the hard disk as numerical-text symbols, which can be read and analysed directly by a spreadsheet program, such as Microsoft Excel.

3. Practical application of the system

As shown in figure 4, the portable EGG module is implemented on a printed circuit board. The cutaneous EGG signal is picked up from two electrodes placed on the upper abdomen with a reference electrode on the right abdomen. The actual arrangement is shown in figure 5. A shielded cable is used to transmit the EGG signal and prevent the electromagnetic interferences. The overall gain of the amplifiers and filters is 394 with a pass-band of 0.016 – 0.55 Hz. The power consumption of the amplifier and modulator is 493.5 μW (164.5 μA). The input/output relationship of the modulator is shown in figure 6. As determined by a statistical regression, parameters a and b of equation (4) are 0.0000380 and 0.00133, respectively. The obtained transfer function is:

$$V_{in} = 2.5 \times \left(1 - \frac{1}{1.94 \times e^{\frac{1}{0.00133 f}} - 1} \right) \quad (5)$$

when the input frequency is in the range 489 Hz (2.20V) to 3177 kHz (0.8 V), which is within the recording bandwidth of the Sony DVR (27 Hz – 3.48 kHz).

Figure 7(A) shows a comparison between an EGG signal recorded with this system and the same signal recorded with a commercial 16-bit analogue/digital card (NI PCC MIO-16E4). From a correlation coefficient analysis ($r = 0.999$), there is no significant difference between the systems. Figure 7(B) shows a tachygastria example ($r = 0.9997$). Figure 8 shows the result of a 3-hour

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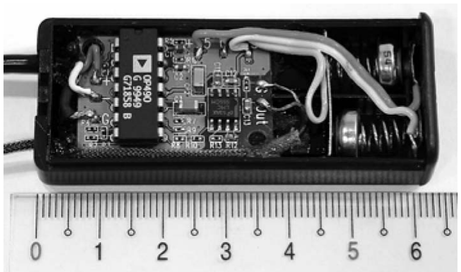

Figure 4. EGG module of the portable part. Dimensions are 63 mm × 20 mm × 15 mm.

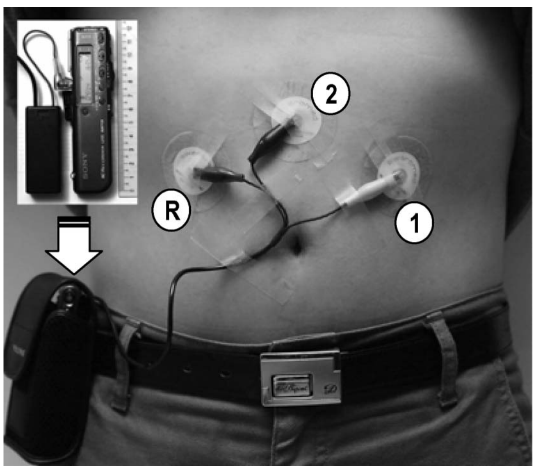

Figure 5. Placement of the electrodes. (1) is the positive electrode, (2) is the negative electrode and (R) is reference. They were fixed after skin abrasion with an alcohol prep-pad. Their impedances are around 10 kΩ.

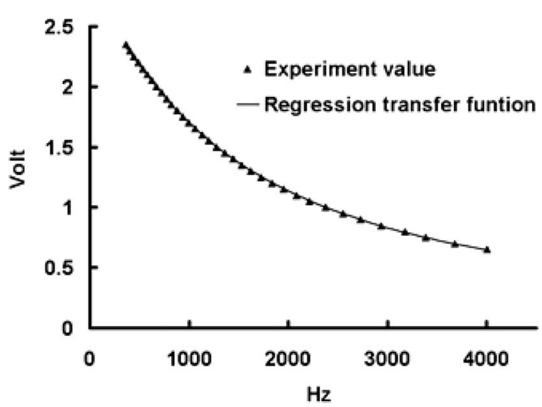

Figure 6. Voltage-to-frequency relationship of the modulation circuit. The solid triangles show the experimental data and the solid line is their regression curve. We use equation (5) as the demodulation function to reconstruct the EGG signal.

ambulatory recording. Based on visual inspection [5], 75% of the data are readable and 60.7% are within normal EGG frequencies.

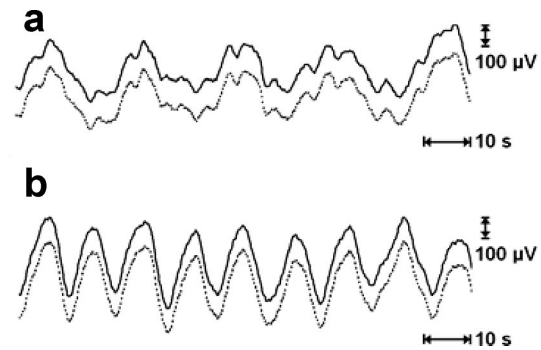

Figure 7. Comparison between our system and a commercial 16-bit A/D card. Figure (a) shows 100 s of normal EGG rhythm data. The solid line is the demodulated result, and the dashed line shows the recording from the A/D card. No significant difference between them can be found. Figure (b) is another example of a tachygastria EGG.

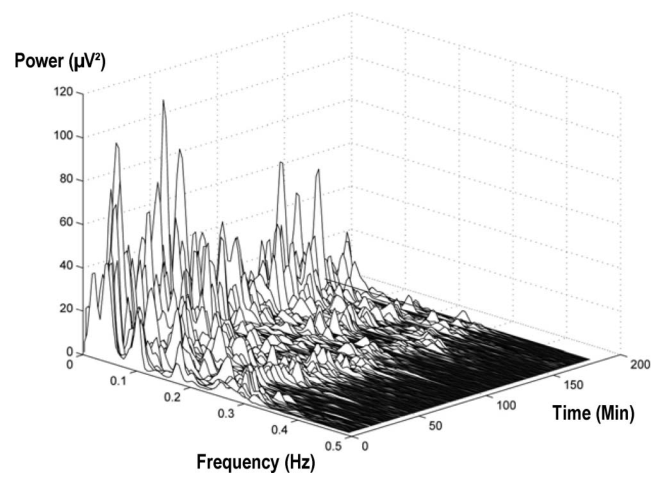

Figure 8. The running spectrum of a 3-hour postprandial recording. The human subject was asked to keep in light motion. Based on a visual inspection, about 75% is readable, with 60.7% of normal EGG frequency within the readable EGG signals.

4. Discussion and conclusion

A low-cost, compact, and updatable EGG recorder is proposed for portable or ambulatory long-term EGG measurements. It can record the EGG signal correctly, and is relatively inexpensive when compared with a commercial EGG recording system. For example, a bedside EGG recording system, Medical Measurement Systems UPS-2020 (Enschede, Netherlands), costs about US$23 000. Although commercial systems are more complete in terms of software functions, researchers may have special requirements for functions that the instrument vendors cannot offer. As the graphical programming tool (NI's LabVIEW) was used to develop the acquisition and analysis programs, the simplicity and flexibility of programming could help researchers in expanding their own toolboxes for specific requirements. This EGG module can work for 118 hours with two silver-oxide button-cells. Hence, the duration of recording is limited only by the memory capacity and battery-life of the DVR. This system uses a DVR with a capacity of 192 hours for voice recording and its battery life is longer than 25 hours. The system can be easily upgraded with a more advanced voice-recording device commonly available for commercial applications, as long as the recording frequency range is within 400 Hz – 3.5 kHz, which is a typical specification for most DVRs.

In order to design a circuit for a portable device, the supply voltage and power consumption should be low. Therefore, a timer IC was used in the modulation circuit instead of the frequency modulation (FM) chip that is usually seen in conventional designs. The current in a special-purpose FM modulator IC is in the order of 10 mA and requires a supply voltage of ± 9 V or more. A low power FM IC, for example the AD654, typically has a current and supply voltage of 2 mA and 5 V, respectively. However, the proposed modulation circuit has a power consumption of 369 μW (123 μA) while supplied by a 3V battery. It is a relatively low power design, which is adequate for a portable device.

The importance of a portable EGG recorder is to capture paroxysmal or acute gastrointestinal symptoms. We have successfully developed such a system, based on a commercial DVR, with which it is possible to record over long periods. If a longer duration of recording is required, the system can easily be upgraded with a higher-capacity voice-recording device.

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