Final Report

Project Code: RSA6080053

Project Title: Design of A Wide-Dynamic-Range Ultra-Low-Power ECG Signal-Conditioning Integrated Circuit (IC) for Next-Generation Wearable ECG Acquisition Systems

Investigator: Assistant Professor Dr. Woradorn Wattanapanitch, Department of Electrical Engineering, Faculty of Engineering, Kasetsart University

E-mail Address: fengwdw@ku.ac.th

Project Period: From 30 May 2017 to 29 May 2020

Abstract

In recent years, cardiovascular diseases have become, by far, the leading cause of death among the Thai population. Despite the enormous national budget spent on the diagnoses and treatments of cardiovascular diseases in hospital settings, many fellow Thai citizens still succumb to the diseases daily. The death rate due to heart diseases may be reduced if the majority of the Thai population has easy access to state-of-the-art wearable cardiac monitoring systems. To be useful in clinical applications and be widely adopted by the general public, such wearable cardiac monitoring system must be able to provide high-quality recorded electrocardiograms (ECG) for diagnostic and treatment purposes, be low-power, small in size, and be very convenient to use. These aspects put stringent requirements on the design of the ECG signal-conditioning circuits. In this research, we have designed, built, and tested a low-power wide-dynamic-range ECG signal-conditioning integrated circuit (IC), suitable for use in the next-generation cardiac monitoring systems. The IC, fabricated in a standard 0.18-μm CMOS technology, consumes a total current of less than 10 μA from a 1.2-V supply voltage, making it one of the lowest-power ECG readout IC in the literature. Due to its high input impedance, the IC is suitable for recording from dry electrodes, thus paving the way for the development of battery-powered wireless active-electrode ECG readout systems that are comfortable to wear on the body. As part of this research, we have also developed novel architectures for some of the IC's building blocks, which result in high-impact journal publications. We believe that the results from this study are useful not only in ECG recording applications, but also in implantable biomedical devices, other wearable electronics for health monitoring, and low-power sensor nodes in wireless sensor networks.

Keywords: bioelectronics, cardiac monitoring system, mixed-signal integrated circuit design, motion artifact, low-power, instrumentation amplifier, signal-folding amplifier,

Research area/ sub area of this project: Electrical Engineering, Analog/Mixed-Signal Integrated Circuit, Biomedical Circuits and Systems

ชื่อโครงการ: การออกแบบวงจรรวมสำหรับปรับสัญญาณคลื่นไฟฟ้าหัวใจแบบพลังงานต่ำที่มีช่วงพลวัตรของสัญญาณขาเข้าที่กว้างสำหรับเครื่องวัดคลื่นไฟฟ้าหัวใจแบบสวมใส่

บทคัดย่อ

ในไม่กี่ปีที่ผ่านมา โรคหัวใจและหลอดเลือดนับเป็นสาเหตุการตายอันดับหนึ่งของประชากรไทย ถึงแม้ว่ารัฐบาลจะได้ทุ่มเทงบประมาณในการตรวจวินิจฉัยและการรักษาโรคหัวใจและหลอดเลือดในโรงพยาบาล ก็ยังมีประชากรไทยจำนวนหลายคนที่ต้องเสียชีวิตจากโรคหัวใจและหลอดเลือดในแต่ละวัน อย่างไรก็ตาม เราสามารถลดอัตราการเสียชีวิตจากโรคหัวใจได้ถ้าประชากรส่วนใหญ่สามารถเข้าถึงระบบตรวจวัดคลื่นไฟฟ้าหัวใจแบบสวมใส่ที่ทันสมัย ในการจะเข้าถึงและได้รับการยอมรับโดยประชากรส่วนใหญ่ได้ เครื่องตรวจวัดคลื่นไฟฟ้าหัวใจแบบสวมใส่นี้ต้องสามารถตรวจวัดคลื่นไฟฟ้าหัวใจได้อย่างแม่นยำ อีกทั้งต้องมีขนาดเล็ก มีอัตราการกินพลังงานที่ต่ำ และต้องมีการใช้งานที่ง่ายอีกด้วย ข้อกำหนดเหล่านี้ทำให้การออกแบบวงจรสำหรับวัดและปรับสัญญาณคลื่นไฟฟ้าหัวใจมีความท้าทายอย่างยิ่ง ดังนั้นในงานวิจัยนี้ ผู้วิจัยจึงได้ทำการออกแบบ ผลิต และทำการทดสอบวงจรรวมสำหรับปรับสัญญาณคลื่นไฟฟ้าหัวใจแบบพลังงานต่ำที่มีช่วงพลวัตรของสัญญาณขาเข้าที่กว้าง สำหรับการใช้ในเครื่องตรวจวัดคลื่นไฟฟ้าหัวใจแบบสวมใส่แห่งอนาคต วงจรรวมนี้ได้ถูกผลิตในเทคโนโลยีซีมอสแบบมาตรฐานขนาด 0.18 ไมโครเมตร โดยมีอัตราการกินกระแสน้อยกว่า 10 ไมโครแอมป์จากไฟเลี้ยงขนาด 1.2 โวลต์ นอกจากนี้วงจรยังมีความต้านทานขาเข้าที่สูง ซึ่งเหมาะสมสำหรับการใช้วัดคลื่นไฟฟ้าหัวใจจากอิเล็กโทรดแบบแห้ง อันจะส่งผลให้การสวมใส่เครื่องดังกล่าวมีความสะดวกสบายกว่าการใช้อิเล็กโทรดแบบเปียกเป็นอย่างมาก และในงานวิจัยนี้ ผู้วิจัยยังได้พัฒนาสถาปัตยกรรมวงจรรูปแบบใหม่สำหรับวงจรส่วนประกอบต่างๆ ซึ่งได้ถูกรายงานในวารสารทางวิชาการระดับนานาชาติชั้นนำในสาขาวิชานี้ด้วย ผู้วิจัยจึงหวังเป็นอย่างยิ่งว่าความรู้ที่ได้จากงานวิจัยนี้จะเป็นประโยชน์ไม่ใช้เฉพาะในการออกแบบวงจรสำหรับการวัดคลื่นไฟฟ้าหัวใจเพียงอย่างเดียว แต่ยังมีประโยชน์สำหรับการใช้งานแบบอื่นๆ เช่น การออกแบบอุปกรณ์ชีวการแพทย์แบบฝังในร่างกาย และอุปกรณ์วัดสัญญาณชีพแบบสวมใส่อื่นๆ

Introduction to the research problem and its significance

Cardiovascular diseases and heart failure have become the leading causes of death throughout the world in the last few decades. Recently, due to lifestyle changes such as consuming diets high in saturated fat, exercising less, and smoking and drinking heavily, the Thai population is acquiring cardiovascular diseases at an alarming rate. Besides, Thailand is becoming an aging society, with a growing number of older people that outpaces the national birthrate. These aging people possess higher risks of acquiring cardiovascular diseases and heart failure. Such non-communicable diseases have become an epidemic in modern Thai society and have claimed the lives of a large number of our fellow citizens yearly. From the WHO's 2014 statistics, cardiovascular diseases account for 29 percent of all deaths in the Thai population — by far the leading cause of death in our country. There is no better cure for cardiovascular diseases other than changing to healthier lifestyles. Nevertheless, for a country with a large population already suffering from cardiovascular diseases, focusing on the diagnoses and treatments of the diseases should also be an immediate national agenda. Even though Thailand is spending a large amount of money dealing with such diagnoses and treatments, many people still lost their lives to cardiovascular diseases, especially those without easy means to access state-of-the-art medical facilities.

In a fully-equipped health center, medical personnel may observe a patient's electrocardiogram (ECG), the heart's electrical patterns projected onto the patient's body, to determine abnormalities of the heart — abnormalities in the ECG waveforms are usually called arrhythmias. This diagnosis is generally performed at a bulky ECG station at which the patient must lie still to minimize interferences induced by the patient's motions and muscle activities. Long wires are then connected between the ECG acquisition machine and the electrodes attached to various points on the patient's body to acquire the ECG. This cumbersomeness may have shunned even well-to-do patients from having frequent ECG diagnoses. Such frequent diagnoses may help prevent many severe symptoms from going unnoticed, thus helping reduce the number of deaths from cardiovascular diseases and heart failure. For abnormalities that are hard to identify in a limited time at a medical facility, doctors may prescribe the use of a Holter monitoring system, an ambulatory ECG recording device that can continuously record ECG for 24-48 hours. However, most Holter monitors in the market today offer only primitive functionalities while consuming too much power for long-term chronic use; they only store data in the devices' memories to be downloaded and analyzed later by the physicians. With their current power consumption level, most Holter monitors require at least two AAA batteries for 24-48 hours of operation, thus making them relatively large and increasing component and packaging cost. The cost of a commercially-available mid-range Holter monitor in the market today is approximately 2,000-3,000 US dollars, still too expensive for the Thai general public. As a result, most Holter monitors today are only for diagnostic purposes, in which hospitals lease them to patients with some fees.

Now imagine if we have an ambulatory ECG acquisition system that is an order of magnitude smaller than current Holter monitors, and requires only button batteries to operate for months of operation. Also, imagine that such device can wirelessly transmit the recorded data in real-time to a remote computer on the physician's desk and can issue warnings when cardiac arrhythmias occur while being robust, low-cost, and comfortable to wear on the body. These devices may change the face of the Thai healthcare system regarding the diagnoses and treatments of cardiovascular diseases; with such devices, advanced cardiac monitoring can be accessible by patients with limited means. The full adoption of such technology may help in the early diagnoses and warnings of heart problems, which can save many lives that might otherwise be lost to cardiovascular diseases. The technology can also help reduce the overall healthcare cost since early diagnoses can prevent symptoms from getting worse, thus obviating expensive medical procedures needed for treating severe patients.

The small form factor and low power consumption of the devices require that such ECG acquisition systems be as integrated as possible. Figure 1 shows a high-level view of a low-power small-form ECG acquisition system mentioned above. The system consists of three main parts, which can be implemented as low-power integrated circuits (ICs): i) an ECG signal-conditioning IC ii) a wireless transceiver IC and iii) a power management IC. The ECG signal-conditioning IC interfaces directly with electrodes and performs simple signal-conditioning tasks on the input signal. The wireless transceiver IC transmits the conditioned signal to a nearby computing platform, such as a smartphone, for further processing and also receives commands to configure the system. The power management IC supervises all the power-related tasks of the system. While all the ICs are indispensable for the complete functionality of the system, the ECG signal-conditioning IC is the bottleneck for the performance of the overall acquisition system as it determines the quality of the acquired signal. Whether the acquisition system can be used in clinical applications depends mainly on the ECG signal-conditioning IC. There are many technical challenges regarding the signal conditioning that need to be addressed before such ambulatory ECG acquisition systems come into widespread use. These challenges can be categorized as follow:

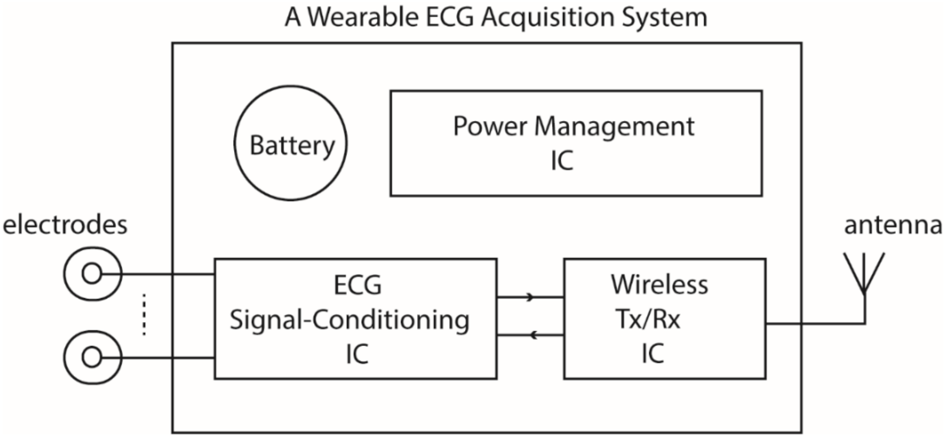

Figure 1: A low-power small-form ECG acquisition system.

Comfortability: Current Holter monitors use low-impedance wet Ag-AgCl electrodes to record ECG from the body's surface. This kind of electrode gives the highest signal quality due to its secure contact with the body through the adhesive gel. Though suitable for the diagnoses at an ECG station in a hospital setting, the gel electrode is not very suitable for the chronic monitoring application. After the electrodes are used for a long time, their adhesive gel becomes dry, causing discomfort to the user and significantly degrading the signal's quality. Thus, the majority of users may not be willing to use the device unless necessary, such as when prescribed by a physician. For less degree of discomfort, the device can use non-contact electrodes [1]. These electrodes are like clothes, which can be made as parts of the user's clothing, thus causing much less discomfort to the skin.

Quality of the Input Signal: Non-contact electrodes have a much higher impedance ($G\Omega$ range) compared to that of the Ag-AgCl electrode (tens of $k\Omega$s range). Due to their high impedances and less secure attachment to the body, non-contact electrodes yield inferior signal qualities compared to those obtained from the Ag-AgCl electrode. If the input impedance of the front-end amplifier is not high enough, the input signal will be attenuated due to the high electrode impedance. Also, non-contact electrodes are very susceptible to motion artifacts, the baseline variations in the recorded signals induced by the movements of electrodes relative to the skin. Motion artifact is a primary concern for most wearable devices intended for use in daily activities, in which the users are not restrained to a sedentary position. Apart from the motion artifact, non-contact electrodes are also susceptible to powerline interference (50/60 Hz interference from the mains). Even with differential recording and infinite common-mode rejection, the ECG recording system may have impedance mismatches in their electrodes, thus converting the common-mode powerline interference on the body into a differential-mode signal. As a result, the output of the front-end amplifier may contain powerline interference that is much larger than the desired ECG waveform; the large interference significantly increases the dynamic range of the input signal, which complicates the design of the signal-conditioning IC.

Power Consumption: Due to its susceptibility to powerline interference and motion artifact, the ECG acquisition system employing non-contact electrodes must accommodate a large input dynamic range, which can be several times of the desired signal's amplitude. The combined powerline interferences and motion artifact can have amplitudes on the order of tens of millivolts. In contrast, the ECG typically has an amplitude of 1 mV_{pp} or less. The large overall input requires that the front-end amplifier of the ECG acquisition system have low gain. As a result, the analog-to-digital converter (ADC) that follows must have a high resolution to resolve the tiny ECG's features buried in the input signal—using a high-resolution ADC in the ECG acquisition system results in high overall power consumption. As a result, the acquisition system may need a larger battery, thus increasing the size and cost of the system; a large device is also less comfortable to wear on the body. As a first step to minimize the overall power consumption and, in turn, the size of the overall system, we need to minimize the required resolution of the ADC.

Output Signal Quality To record ECG waveform with diagnostic level quality, the ECG acquisition system must preserve the fidelity of the output signal even though the ADC's resolution is lowered to reduce the overall power consumption. Since reducing the ADC's resolution requires the front-end amplifier to have a high gain such that the ADC's quantization noise becomes negligible, the acquisition system must reject interferences and motion artifact within the front-end amplifier itself to prevent signal saturation at its output. Due to the limited power and area, we can only incorporate simple interference rejection algorithms on-chip; these algorithms can help reject some degrees of interferences but may distort the desired features of the ECG. Employing high-performance digital algorithms such as the Principle Component Analysis (PCA) or the wavelet transform to reject interferences may help lessen the distortion, but they are power-hungry, and their realization occupies a large chip area, thus are not suitable for low-power on-chip implementation. Our main question is how to use only these simple algorithms to reject interferences while preserving all the important features of the ECG signal.

In this research, we have designed, built, and tested a low-power ECG signal-conditioning IC suitable for acquiring ECG signals from high-impedance (dry/non-contact) electrodes. Circuit techniques and architectures are developed to preserve the important features of the ECG waveform, even when recording amidst large powerline interferences and motion artifacts. Based on the proposed IC, we have also built a prototype of a wireless ECG readout system that can continuously record ECG from patients and send the recorded data wirelessly to a remote computer. We hope that the knowledge gained from this research will be instrumental in the design of miniaturized, low-cost wireless ECG recording systems, which, one day, can help save thousands of lives that might have been lost from cardiovascular diseases and heart failure.