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A wireless bioimpedance device for abdominal fatness monitoring

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Abstract

A wireless bioelectrical impedance (bioimpedance) device for assessing abdominal fatness is presented. The proposed device is based on a bioimpedance measurement circuit designed in 0.35-μm CMOS technology and a commercially available ZigBee device, which provides reliable wireless communication. The traditional techniques for measuring bioimpedance signals are either time-consuming or associated with high cost, high power consumption, and large board space and, hence, are not suited to design an unobtrusive monitoring device. A magnitude-ratio method able to evaluate visceral fat accumulation with low influence of subcutaneous fat volume while providing a cost-effective solution is proposed. The presented device achieves less than 1% relative error over the 100-Ω range with a current of 10 μA at 50 kHz.

Keywords: Bioelectrical impedance analysis; visceral fat; CMOS analog integrated circuits; ZigBee-based wireless applications

1. Introduction

Obesity is one of the most serious public health problems in Europe because it significantly increases the risk of many chronic diseases such as diabetes or cardiovascular disease. Now it is well known that the complications commonly observed in obese subjects are more closely related to the locations of fat depots rather than to the amount of excess fat per se. In particular, the fat stored in the abdominal cavity, i.e., the visceral fat, is metabolically more active than the subcutaneous fat in gluteal and femoral regions. Moreover, cardiovascular diseases associated with obesity are caused in part by toxic substances released by visceral fat[1]. Therefore, an accurate measurement of abdominal fat mass is a key point to study this obesity epidemic, its causes and consequences.

The body-mass index (BMI) has been widely used as an indicator of the extent of obesity in patients. However, the BMI does not always accurately reflect the volume of visceral fat, because the distribution of fat tissue differs greatly between individuals. Recently, several techniques have been developed to assess visceral fat accumulation. In terms of reproducibility and accuracy, X-ray computed tomography (CT) at the umbilical level is considered to be the optimal technique, while waist circumference (Wc) is a simple anthropometric screening tool. However, Wc is an index which includes the contribution due to subcutaneous fat volume (SFV), whereas imaging methods like CT

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are extremely costly and require radiation exposure, which is problematic and unsuited to self-monitoring in a private setting. Hence, there is a need for a reliable and non-invasive method able to assess visceral fat accumulation with low SFV influence and suitable for screening large groups of individuals.

This work discusses a wireless device which allows remote monitoring of visceral fat accumulation by directly applying bioelectrical impedance (bioimpedance) analysis to the abdominal area. The proposed device is based on a bioimpedance measurement circuit designed in 0.35-μm CMOS technology, which acts as an analog front-end, and a low-cost commercially available ZigBee device, which provides reliable wireless communication. In order to provide a compact and cost-effective design, the proposed analog front-end relies on the magnitude-ratio detection (MRD) method[2]. The rest of the paper is organized as follows. Section II gives a brief overview of the human body composition, its analysis based on bioimpedance, and the proposed measurement system architecture. The principle of the impedance measurement technique, the most significant analog circuit blocks of the front-end, and some results achieved with the designed prototype are introduced in Section III. Finally, conclusions are drawn in Section IV.

2. Body Composition and Bioimpedance Analysis

Body composition analysis is the clinical assessment of tissue and fluid compartments in the human body. The most widely used model for body composition assessment is the two-component model, which partitions the total body mass into its lean and fat components[3]. The lean component is referred to as the lean body mass (LBM) and the other portion as the fat mass (FM). Strictly speaking, there is a fat-free mass (FFM) that encompasses the sum of total body water, minerals (namely, bone minerals and soft-tissue minerals), proteins, and glycogen. However, the LBM consists of the FFM plus essential lipid substances present in the spinal cord, in the brain and in certain organs. Nonessential lipids are synonymous with fat as they consist almost entirely of triglycerides. The stored fat mass has hence become virtually synonymous with FM, which can be divided into visceral and subcutaneous fat.

Bioelectrical impedance analysis (BIA) is a practical and non-invasive method to asses human body composition, which is based on detecting the impedance of FFM when a low-amplitude alternating electric current is applied to the body from wrist to ankle. Tissues that contain a lot of water and electrolytes, such as blood or muscles, are highly conductive whereas fat, bones, and air-filled spaces are highly resistive. A current applied to the human body will flow preferentially through the extracellular fluid, the blood, and conductive tissues that comprise the majority of the LBM. Even though the human body conductivity is not constant, a number of researchers have demonstrated that single-frequency BIA (SF-BIA) is a useful, safe, and simple non-invasive technique for assessing body composition[4]. Since conventional whole-body SF-BIA measures the impedance from hands to feet, FM estimates the total fat content but not the local fat distribution. In particular, evaluating the visceral fat is difficult because it encompasses only about 5%-10% of the impedance between arms and legs. Recently, the local measurement of the abdominal bioimpedance has been proven to provide better information about the intra-abdominal fat compartments by focusing the electrical current to the regions of interest[5].

For the measurement of visceral fat area (VFA) with low influence of SFV, a measurement of the Wc and a measurement of the two abdominal impedances, i.e., the total abdominal impedance and the subcutaneous fat impedance, is required[6]. In order to reduce system complexity as well as the number of wired connections associated because of the need of several measurements, a wireless sensor network (WSN) under the ZigBee communication standard is proposed in the present work. The overall system architecture is illustrated in Fig. 1a. Wireless bioimpedance sensor nodes are deployed on surroundings of the waist at the navel level as shown in Fig. 1b. These nodes carry out measurements and transfer the impedance records to the WSN coordinator, which is wirelessly connected to the patient's end device (a personal data assistant, PDA), where data are processed and, consequently, visceral fat is evaluated. The collected records are available to be transferred to a healthcare centre where specialized staff will examine the received data.

The core of the proposed wireless bioimpedance node is the CC2430 System-on-Chip from TI/Chipcon. The CC2430 is optimized for long-term battery operation and includes the CC2420 transceiver and an efficient 8051-based microcontroller, which implements the whole digital processing stage. All the necessary functionalities are

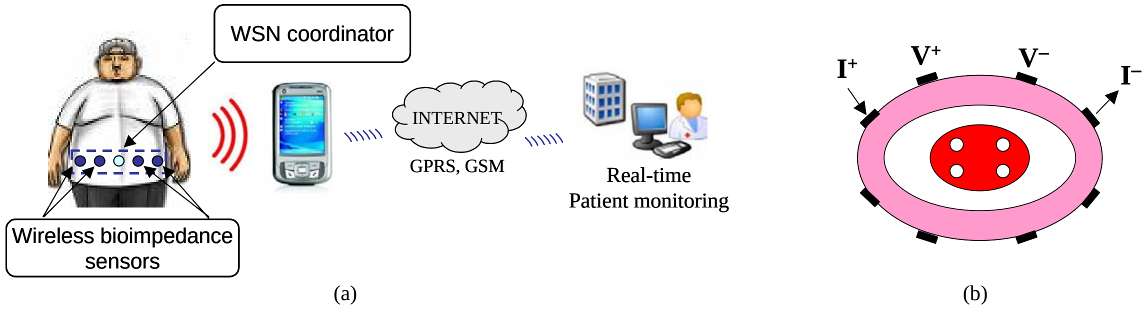


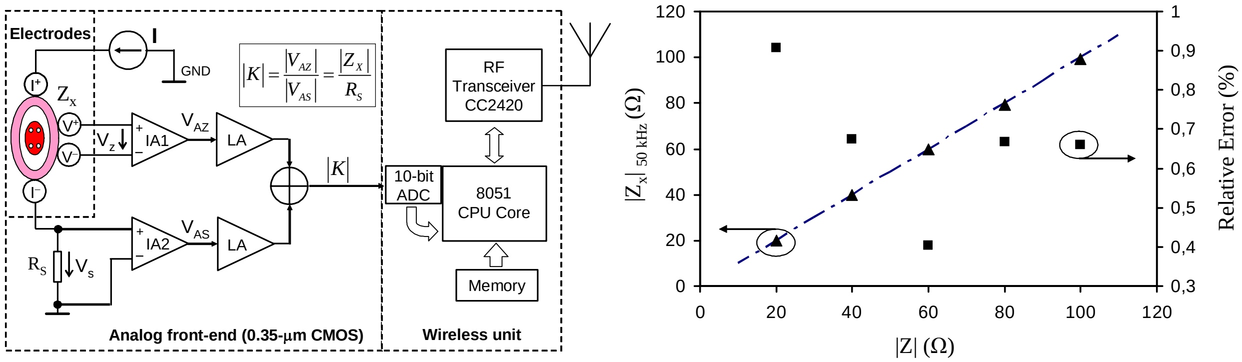
Fig. 1. (a) Proposed overall system architecture. (b) Tetra-polar sensor arrangement used in the abdominal bioimpedance analysis method. The electrodes were symmetrically centered around the body axis. Visceral fat area: red; subcutaneous fat area: pink.

performed in the CC2430 and, hence, no additional circuits such as communication bus between chips are needed. Including a CPU core running at 32 MHz, the microcontroller consumes 7 mA in active mode, while in sleep mode it only consumes 0.9 μA. During receive and transmit modes, the current consumption of the CC2430 is as low as 27 mA. Since the current consumption behaviour of the CC2430 does not look like a flat current curve as a function of time, $Li/SOCl_2$ batteries, which have the highest energy density among all lithium battery types, are used in the proposed bioimpedance node. Their extremely long service life and low self-discharge rate make these batteries ideal for our application, which requires small average currents with some peaks around 10-20 mA. As the CC2430 operates from power supplies ranging from 2.0 V to 3.6 V, it can be directly driven by a single $Li/SOCl_2$ cell. The solution presented in this work uses a Tadiran TLH-5935 battery, which provides a capacity of 1500 mA·h, a pulsed current up to 50 mA, and an open-circuit voltage of 3.6 V.

3. Analog Front-End Design and Results

In order to evaluate visceral fat accumulation, the proposed analog front-end relies on the MRD method which is illustrated in Fig. 2a[2]. It basically consists in measuring the amplitude of a signal by using a gain detector. Current I flows through two electrodes (I^+, I^-) to stimulate the tissue having unknown impedance Z_x. Current I flows through a reference resistor R_s connected in series with Z_x. Two electrodes (V^+, V^-) sense the voltage drop V_z across Z_x, which is amplified by an instrumentation amplifier, IA_1. The voltage signal V_s across R_s is amplified by another instrumentation amplifier, IA_2. These voltage signals are processed by two matched logarithmic amplifiers (LAs) so as to obtain a dc voltage proportional to their magnitude ratio $|K|$. If amplifiers IA_1 and IA_2 are identical and have infinite input impedance, it is straightforward to obtain that the unknown impedance magnitude $|Z_x|$ can be expressed as $|Z_x| = |K|\cdot R_s$. For the target application, the expected range of magnitudes to be measured goes from 10 Ω to 100 Ω. The excitation current magnitude is chosen to be small enough so as not to be perceived by the patient, but large enough to produce voltage signals that are above interfering noise, which might arise from bioelectrical sources such as muscle tissues. We set the excitation current at 10 μA and, therefore, the amplitude of the voltage signals to be measured is approximately in the range from 0.1 mV to 1 mV.

The prototype front-end was designed using AMS 0.35-μm CMOS technology. Specifications for the IA are especially severe due to the input voltage levels provided by the electrodes. Moreover, in order to minimize the effect of the electrode-skin impedance, the IA needs to have a high common-mode rejection-ratio. The designed IA consists of an input transconductance stage and an output transimpedance stage. The IA was designed to operate with 3 V of supply voltage and a total drain current of 140 μA. It has a bandpass-type transfer function in order to filter out low frequency noise and electrode voltage drifts. It must be mentioned that the phase shift due to the amplifier should be taken into account for applications which involve calculating impedances at different frequencies. In addition, each LA is made up of the cascade of eight gain stages, which are basically NMOS differential pairs, with nine associated detectors to provide the logarithmic version of its input signal. The number of gain stages, associated with the achieved values of voltage gain, bandwidth, and power consumption, and the precision of the logarithmic output value determine optimal bioimpedance system performance. The LA output accuracy is ± 0.7 dB with an input signal varying from–65 to 6 dBm, and its input referred noise is 0.2 μV_{rms}. The dc voltage $|K|$ provides an accurate measurement of the magnitude ratio scaled to 19.8 mV/dB, which is satisfactory in



(a) (b)

Fig. 2. (a) Bioimpedance measurement technique based on the MRD method. (b) Simulated magnitude response $|Z_x|$ at 50 kHz without calibration of the designed front-end for visceral fat impedance range. (–·– ideal, ▲ simulated, ■ Error).

our application. The proposed bioimpedance monitoring system has been optimised and characterized by using equivalent circuits that model the effect of electrodes as well as the resistive and capacitive human body electrical impedance components. Simulated results obtained for a 50 kHz sinusoidal excitation signal are provided in Fig. 2b, which illustrates the impedance magnitude provided by the analog-front-end without any calibration algorithm for impedance magnitude values ranging from 20 Ω to 100 Ω. The magnitude error is less than 1% over the whole range of interest.

4. Conclusions and Future Work

The ZigBee-based bioimpedance device presented in this paper allows reliable, low-power, and real-time monitoring of abdominal fatness. The device is based on a low-power ZigBee device and an analog interface circuit designed in 0.35-µm CMOS technology. The feasibility of the presented analog front-end has been validated through simulations using equivalent circuits as the patient under test. Abdominal impedance parameters of the individual under monitoring are measured, based on the magnitude-ratio detection method, are then amplified by a dedicated analog front-end, are subsequently converted into the digital domain, and are finally wirelessly transmitted. The overall wireless sensor network briefly described above is currently being developed for supporting visceral fat measurements in adults across a range of body mass index.

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