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# Design of wearable and wireless electrical impedance tomography system

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ABSTRACT

Electrical impedance tomography (EIT) is a non-invasive approach to reconstruct the cross-section impedance image of the body. Many EIT systems and impedance image reconstruction algorithms have been proposed in previous studies. However, most of these EIT systems are bulky to cause the limitation of applications. In this study, a wearable and wireless EIT system is proposed to reconstruct impedance images non-invasively and wirelessly. By microminiaturizing the conventional EIT system, the proposed system can provide the advantages of small volume and wireless transmission to reduce the application limitation of conventional EIT systems. Finally, the phantom experiment is tested to validate the performance of the proposed EIT system. The experimental results show the average BR value of the reconstructed image obtained by the proposed system being $1.3 \pm 0.2$ and the averaged location error ratio being about $6.27 \pm 3.14\%$. Therefore, the proposed wearable and wireless EIT system can be viewed as a good system prototype and may be applied to more clinical applications in the future.



## 1. Introduction

Electrical impedance tomography (EIT), first proposed by Barber et al. in 1986 [1–3], is a noninvasive technique used to reconstruct the cross-section impedance image of the body [4,5] and has been widely applied to various applications, such as quality control and fault detection [6], and geological exploration [7]. Recently, EIT has also been applied to the research on bio-image reconstruction [8] and shows the capability of disease monitoring clinically [9], such as monitoring pulmonary diseases from EIT two-dimensional reconstructed images [10].

Compared with other non-invasive bio-image reconstruction techniques, such as X-ray, computed tomography (CT) and positron emission tomography (PET), the EIT technique can effectively avoid the accumulation of radiation dose in vivo. Even though MRI is safer than CT and PET and can provide higher spatial resolution, it requires a more expensive procedure. Although the spatial resolution of the reconstructed image by EIT is lower than it by other non-invasive bio-image reconstruction techniques, EIT can provide the advantages of low cost, free radiation, and fast image reconstruction [11]. EIT technique is sensitive to the changes of pulmonary gas and body fluid. Therefore, EIT has the functional imaging capability which other structural imaging techniques (e.g. CT and MRI) cannot achieve. EIT is also more suitable for repeated and simple bio-image reconstruction in clinical applications.

The development of EIT technique is mainly based on two measuring ways to obtain the unknown impedance

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distribution. One way is to apply a steady voltage across the object and then estimate the impedance distribution from the current passing through the object [12]. Another way is to inject a steady current into the object and then estimate the impedance distribution from the measured boundary voltage [3]. However, the mathematical problem of deducing the internal impedance distribution for EIT is an ill-posed inverse problem [13]. In order to calculate the exact solutions of nonlinear partial differential equations, the numerical analysis method is usually required; and, it also requires a large amount of computational complexity. The most frequently used image reconstruction algorithms for EIT contain the approach of finite elements method (FEM) combining with back-projection algorithm, Newton–Raphson algorithm, etc. [14]. In 1986, Barber et al. first developed the back-projection algorithm for EIT [2]. 1993, Hua et al. investigated the electric field distributions by FEM and proposed three different types of FEM models [15]. Santosa et al. proposed the Barber-Brown algorithm with the interpolation of boundary data and low-pass filter image [16]. Rao et al. proposed the modified Newton–Raphson algorithm to ensure the convergence of the continuous mapping of solution space [17]. However, most of above mentioned methods required a bulky machine to provide a steady current source and receive boundary voltages. This also caused the inconvenience in use and increased the application limitation.

In this study, a novel wearable and wireless electrical impedance tomography system is proposed to reconstruct impedance images non-invasively and wirelessly. A wireless electrical impedance tomography module is designed to provide a steady current source and receive and demodulate the boundary voltage wirelessly. The back-projection algorithm, which requires low computational complexity to reconstruct the impedance image, is also used in this study. The advantages of small volume and wireless transmission of the proposed wireless EIT module allow it being embedded into the clothes as a wearable EIT device to reconstruct the impedance image under motion.

## 2. Methods and materials

### 2.1. System design and implementation

The basic scheme and photograph of the proposed wearable and wireless electrical impedance tomography system are shown in Fig. 1a and b respectively. In this study, the proposed system injects a steady current into the body and acquires the boundary voltages to reconstruct the cross-section impedance image of the body. The proposed system mainly contains surface electrodes, a wireless EIT module, and a host system. Surface electrodes are used to attach to the body for injecting the steady current source of the wireless EIT module into the body and receive the boundary voltage. The wireless EIT module is designed to provide and switch a steady current source, and receive, amplify, and demodulate the boundary voltage. Next, these demodulated boundary voltages are transmitted to the host system wirelessly via Bluetooth. The image reconstruction program built in the host system will receive the information of the demodulated boundary voltages and then reconstruct the cross-section impedance image of the body by the back-projection algorithm.

#### 2.1.1. Wireless electrical impedance tomography module

The block diagram and photograph of the wireless EIT module are shown in Fig. 2a and b respectively. It mainly consists of a steady current source circuit, a front-end amplifier circuit, a demodulation circuit, an analog multiplexer circuit, a microprocessor, and a wireless communication circuit. The steady current source circuit is adopted to provide a steady current, and the frequency of the steady current can be set from 10 kHz to 200 kHz by the microprocessor. The contact impedance of the electrodes also affects the accuracy of the system. Therefore, the measuring method of four-electrode configuration is used to reduce the influence of adding the contact impedance of the electrodes on the tissue impedance for the two-electrode system [18].

The basic schematic design of the steady current circuit is shown in Fig. 2c. A square wave source with the specific frequency is generated by the microprocessor and is filtered by a RLC filter to convert the square wave source to a sinusoidal wave source. Next, the sinusoidal wave source is used as the input of the voltage-to-current converter (VCC). In the voltage-to-current converter, most current will pass through the bias path $R_L$ due to the ultra-high input impedance of the operational amplifier. The steady current $I_{out}$ passing through the bias path can be given by $I_{out} \approx \frac{V_{in}}{R_1}$, where $V_{in}$ is the steady voltage source and $R_1$ is the resistor used to adjust the magnitude of the current.

After injecting the steady current, the boundary voltage is then obtained by the surface electrodes and amplified and filtered by the front-end amplifier circuit. The gain of the front-end amplifier is adjustable. Next, the amplified boundary voltage is demodulated by the demodulation circuit. A demodulator (AD630, Analog Devices, U.S.) is used in the demodulation circuit, and the frequency band of the demodulated boundary voltage is from 10 kHz to 200 kHz. In general, the internal tissues of the body contain the real part and imaginary part of the electrical impedance. Therefore, the proposed EIT system has to realize the complex impedance measurement. In the demodulation circuit, a square wave with a specific frequency, that is generated from the microprocessor and is the same as the frequency of the steady current source, is used as the reference signal of the demodulation circuit. After the demodulation, a full-wave rectification waveform generated from the output of the demodulator passes through a low-pass filter to obtain the DC level of the demodulation signal, which is proportional to the signal amplitude and phase difference between the input and reference signals of the demodulator. The microprocessor (MSP430, Texas Instruments, U.S.) is designed to control the analog multiplexer circuit to switch these surface electrode to connect to the steady current source circuit to inject the steady current into the body, or to connect to the front-end amplifier circuit and the demodulation circuit to obtain and demodulate the boundary voltage. Next, the information of the demodulated boundary voltage is digitized by a 12-bit