DESIGN AND EVALUATION OF ARTIFACT-RESISTANT FINGER-RING PLETHYSMOGRAPHIC SENSORS

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ABSTRACT

A miniaturized, telemetric, photoplethysmograph sensor for long-term, continuous monitoring is presented in this paper. The sensor, called a "ring sensor", is attached to a finger base for monitoring beat-to-beat pulsation, and the data is sent to a host computer via a RF transmitter. An efficient double ring design is developed to lower the influence of external force, acceleration, and ambient light, and to hold the sensor gently and securely on the skin, so that the circulation at the finger may not be obstructed. A prototype ring sensor is designed and built based on the artifact-resistive attachment method. It is verified through experiments that the ring sensor is resistant to interfering forces and acceleration acting on the ring body. Benchmarking tests with FDA-approved photoplethysmograph and EKG reveal that the ring sensor is comparable to those devices in detecting beat-to-beat pulsation despite disturbances.

INTRODUCTION

As the population of aged people increases, vital sign monitoring is increasingly important for securing their independent lives. On-line, continuous monitoring allows us to detect emergencies and abrupt changes in the patient conditions. Especially for cardiac patients, on-line, long-term monitoring plays a pivotal role. It provides critical information for long-term assessment and preventive diagnosis for which long-term trends and signal patterns are of special importance. Such trends and patterns can hardly be identified by traditional examinations. Those cardiac problems that occur frequently during normal daily activities may disappear the moment the patient is hospitalized, causing diagnostic difficulties and consequently possible therapeutic errors. Continuous and ambulatory monitoring systems such as ambulatory ECG are therefore needed to detect the trait.

The ambulatory ECG (Holter) device, one of the most widely accepted ambulatory monitoring systems, was developed and extensively studied by N.J. Holter [1]. Bellet also devised a continuous 2-hour tape recording system using a similar device [2]. When the ambulatory ECG device was first introduced, the device was not immediately widespread due to concerns over lack of documentation of coronary artery disease, reliance upon T-wave changes, and lack of recorder fidelity [3]. After many improvements and validity tests, the ambulatory ECG technology has gained increasing popularity. The ambulatory ECG, however, is not applicable to long-term monitoring for a period of several weeks or months. The machine is bulky, heavy, and uncomfortable to wear due to cumbersome wires and patches. Recently, a variety of vital sign sensors have been developed that are compact and easy to wear. Yamashita, et al. [4] attempted to develop a simple telemetry device for monitoring pulse at a finger. Wristwatch-type pulse oximetry and blood pressure sensors have been developed and commercialized by several companies including Casio (BP-100 and JP200W-1V) and Omron (HEM-608 and HEM-609). These devices, although much easier to wear, have not yet been used clinically. Many technical issues still need to be solved for clinical use. The goal of this paper is to develop technology for reducing motion artifact and obtaining reliable measurements of vital signs for long-term use. A miniaturized photoplethysmograph (PPG) device in a ring configuration will be designed and tested. Its benchmarking tests with FDA approved PPG and EKG will show the validity of the technology.

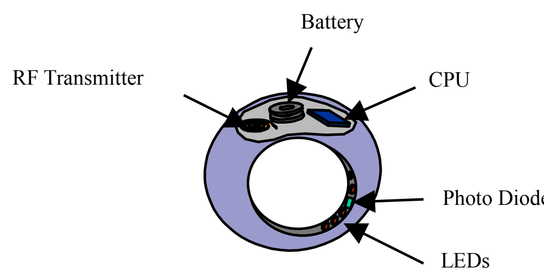


Figure 1 : Conceptual diagram of the ring sensor

BASIC CONSTRUCTION

The ring sensor is a miniaturized, telemetric, monitoring device worn by a patient as a finger ring. The ring encapsulates photoplethysmographic, pulse oximetry combined with wireless communication and miniaturization technologies. This device optically

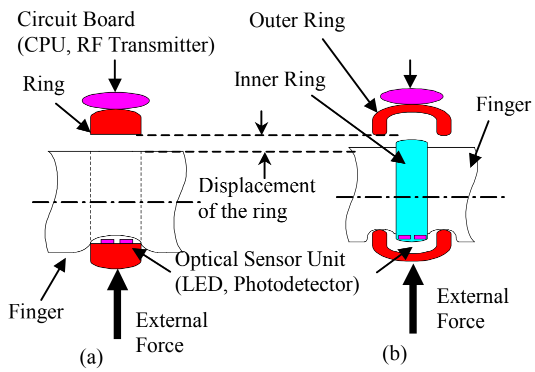


Figure 2 : Dislocation of ring sensors due to external load
(a) Traditional single body design under external force
(b) New isolating ring sensor under external force

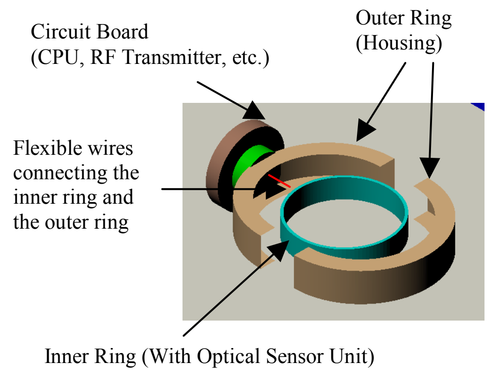


Figure 3 : Construction of isolating ring

captures the pulsation and oxygen saturation of the arterial blood flow, and transmits the signals to a host computer via a RF transmitter. Figure 1 shows a conceptual diagram of the ring sensor [5][6]. The ring sensor consists of optoelectronic components, a CPU, a RF transmitter, a battery, and a ring chassis. The optoelectronic components, i.e. micro photodiodes and LEDs, detect the blood volume waveforms and oxygen saturation level at the patient's digital artery. The CPU controls the LED lighting sequence as well as the data acquisition and transmission process. These signals are locally processed by the on-board CPU and transmitted to a host computer for diagnosis of the patient's cardiovascular conditions. The ring sensor is completely wireless and miniaturized so that the patient can wear the device comfortably twenty-four hours a day.
This miniaturized sensor in a ring configuration is a rational design choice for twenty-four hour continuous monitoring, since a finger ring is probably the only thing that a majority of people will be willing to wear at all times. Other personal ornaments and portable instruments, such as earrings and wristwatches, are not continually worn in daily living. When taking a shower, for example, people remove wristwatches. Bathrooms, however, are one of the most dangerous places in the home. Many thousands of people, mostly hypertensives and the elderly, die in bathrooms every year. Miniature ring sensors provide a promising approach to guarantee the monitoring of a patient at all times. Also, a ring configuration provides the anatomical advantage of having transparent skin and tissue at the finger compared with other parts of the body so that it is feasible to monitor arterial blood volume at the finger base using an optoelectronic sensor. Subsequently, a variety of simple cardiac circulatory disorders may be detected by monitoring arterial blood volume at the finger base.

ARTIFACT-RESISTANT MECHANICAL DESIGN

Isolating Ring Architecture

Figure 2-(a) shows the cross-sectional view of the original ring sensor where the optoelectronic sensor unit, i.e. the LEDs and photodiodes, is attached directly to the body of the ring. (previously developed by the authors [5][6]) The problems with this design are:

- When the ring touches the environment surface, the ring is pushed to one side, creating an air gap between the sensor unit and the skin, or increasing the pressure with which the sensor unit is attached. This incurs significant fluctuation in the sensor reading.
- The body of the ring sensor, including the battery and circuitry, tends to be heavy. A small acceleration of the finger and even the gravity of the ring itself may cause a displacement relative to the skin surface. Securing the ring body requires a large force applied to the finger skin.
- It is difficult to shield the sensor unit from the ambient lighting.

To resolve these problems of the original ring design, a new design is presented in this section. The new design, called a "isolating ring configuration", is illustrated in Figure 3. The main idea of this design is to separate the sensor unit from the rest of the ring body that is much heavier than the optical sensor unit alone. The separation is achieved by having two rings that are mechanically decoupled to each other. The inner ring shown in the figure holds the sensor unit alone, while the outer ring contains the CPU, signal processing unit, battery, and RF transmitter. Only a thin, flexible cable connects the two rings. This decoupled design has the following advantages.

Alleviating the influence of external forces applied to the ring
Forces due to mechanical contacts are born by the outer ring, and are not directly transmitted to the sensor unit on the inner ring. As shown in Figure 2-(b), the load of the external force is bypassed to the finger bone and is supported by the two feet of the bridge-like outer ring. Thereby the force does not directly influence the actual sensor unit attached to the inner ring inside the outer ring.

Alleviating the effect of acceleration on the sensor
The inertia of the sensor unit is very small since it contains only a few LEDs and photodiodes. Due to the small inertia of the inner ring, the inertia force acting on the sensor unit is negligibly small. In consequence, the position of the optical sensor does not change significantly although the finger is accelerated.

Reducing the skin pressure
The outer ring doesn't have to be secured tightly, while the inner ring doesn't need a large pressure to secure the body, since it is light. Therefore, the possibility of necrosis caused by local ischemia and occlusion is lowered. This solves a critical problem for wearable sensors and long-term monitoring systems such as the ring sensor.

Reducing the influence of the ambient lighting
The outer ring shields the sensor unit and thereby reduces optical disturbances from the ambient lighting. The isolating ring structure provides the sensor unit with an optical shield.

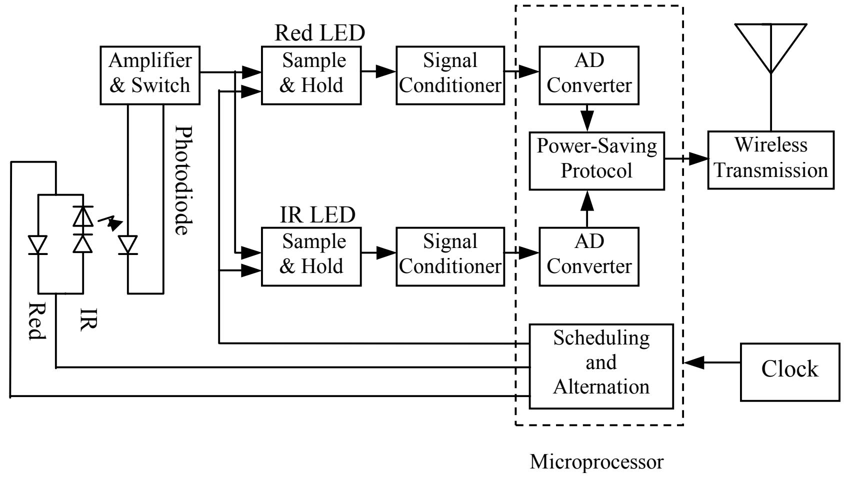


Figure 4 : Block diagram of electronic circuit

Thus the isolation ring structure resolves those critical problems of the original single-body ring sensor.

ELECTRONICS DESIGN

Figure 4 shows a block diagram of the ring sensor circuitry. The basic circuit configuration is a standard photoplethysmographic circuit combined with a wireless transmitter. There are a single photodiode and LEDs of two different wavelengths, red and near infrared, involved in the circuit. The output from the photodiode is amplified and conditioned at the first stage operational amplifier. While the red and infrared LEDs are alternately turned on and off, the signal from the first stage op-amp is sampled by the two sample-and-hold circuits at different timings in order to obtain the reflected light intensity from each LED. Each channel of the signal is conditioned and converted to a digital signal with an AD converter. Using the standard RS-232 protocol, the two channels of digital signals are transmitted via a RF transmitter.

LEDs and Photodiode

One red LED and two infrared LEDs are used as the light sources. The peak wavelength of the red LED is 660 nm, and that of the infrared LEDs is 940 nm. The photodiode has the peak wavelength of 940 nm and the spectral sensitivity ranges from 500 nm to 1000 nm, which meets our needs. The voltage drop across the red LED is 1.6 V and that of the infrared LEDs is 1.2 V, and two infra-red LEDs are connected in serial. These LEDs are in a die form with a size of 0.3mm × 0.3mm.

The First-Stage Amplifier

The slew rate of the first stage amplifier must be high enough to capture the flickering LEDs, while its power consumption must be kept low. We chose OPA336 surface mount style amplifier from Burr-Brown. This amplifier has a slew rate of 0.03 V/μs and current consumption of 20 μA.

Signal Conditioner

The signal conditioning part consists of filters and amplifiers. The signal from the first stage amplifier contains a large portion of DC signal, which is cut off by a high-pass filter. The resultant AC signal is on the order of millivolts, needing amplification on the order of 10^3. We used a die-form operational amplifier, MAX407, from Maxim, which consumes an extremely low current of 1.2 μA per amplifier. Slew rate is not an important factor since the frequency of the signal in this stage is less than 10 Hz. The cut-off frequency of the low-pass filter was set to be 5 Hz.

CPU

The on-board CPU controls all the operations of the ring sensor, raging from the sequence control of LED lighting and data acquisition to the conversion of analogue data to digital signals in the RS-232 format for wireless transmission. A PIC16C711 microprocessor from Microchip was selected because of its unique design for low power consumption. It consumes less than 25 μA for 32 kHz clock frequency in the normal operation mode and almost no power consumption in the sleep mode. This CPU has 4 channels of embedded A/D converter, 13 channels of digital I/O line. It has 1 KB of EPROM that is good enough to store the whole code needed for computation.

Battery

One critical problem that is practically important is interference between the RF transmitter and the other part of the circuit. Since the RF transmitter uses on-off keying, the current drawn to the RF transmitter goes up and down as the output is switched between on and off. This incurs a serious fluctuation in the battery voltage and causes interference with the rest of the circuit, particularly the analog op-amps. To resolve this problem, two separate batteries were used for the prototype ring sensor: one for the RF transmitter alone and the other is for the CPU, LEDs, and op-amps. Button-type thin lithium batteries from Duracell were selected. The RF transmitter is powered with a DL2016 battery of 75 mAh rated-capacity and the CPU-LED circuit with DL2032 battery of 220 mAh rated-capacity. Both batteries have an output voltage of 3 volts.

PACKAGING

Figure 5 shows a prototype of the isolating ring sensor. Details of this design are:

- A miniaturized sensor unit is attached to the inner ring whose mass is almost negligible. This sensor unit is a small circuit board (5mm × 5mm × 0.8mm) that contains two light emitting diodes and a photodetector. As we use point-based light emitting diodes and a subminiature photodetector, this sensor unit weighs only 0.79 grams.

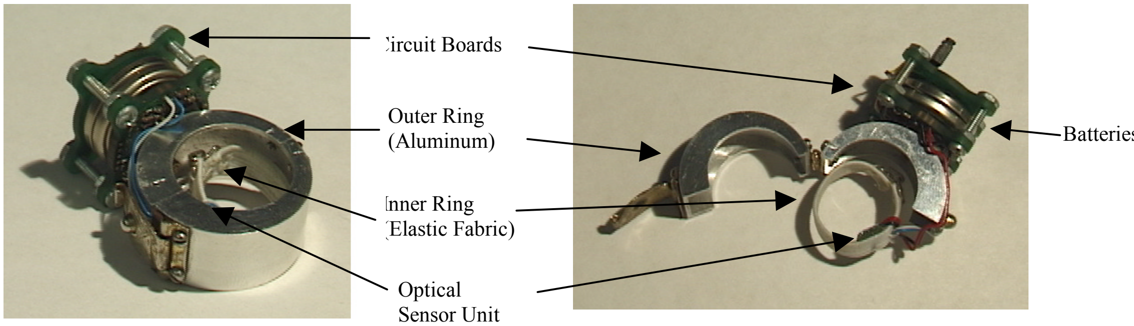


Figure 5 : Isolating ring sensor designed for motion artifact minimization

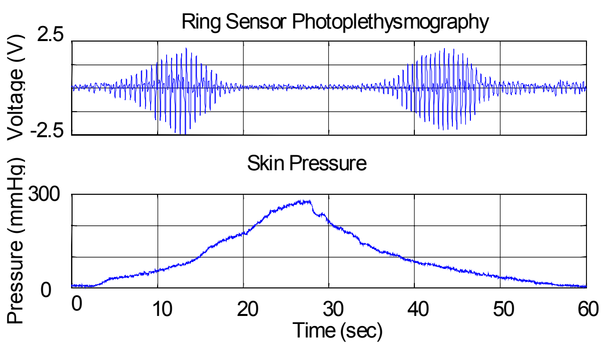


Figure 6 : Experiment of pulsation amplitude and skin pressure

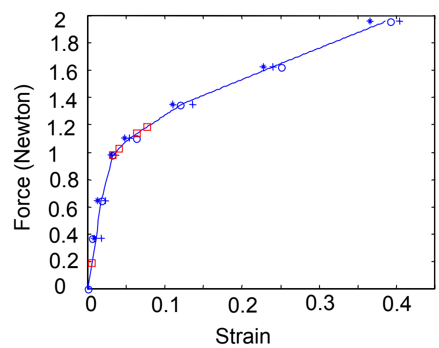


Figure 7 : Experiment of tension-strain characteristics of inner ring band

- The main circuit board and batteries, which are heavy and bulky in comparison to the sensor unit, sit on the outer ring. The main circuitry consists of many small elements, most of which are in a surface mount or bare die form. Although the size and weight of the components used are generally small and light, the total mass of this circuit board is not negligible, 3.68 grams. In addition, the button type batteries used for providing power to the circuitry are relatively heavy, 6.31 grams. These components sit on the surface of the outer ring facing outward. The outer ring is made of aluminum; a block of aluminum was machined to a hollow ring as shown in Figure 3, and all the parts other than the sensor unit were fixed to the outer ring.
- The inner ring floats inside the outer ring. When a patient wears the ring, both rings are put on the same finger. Since the outer ring covers the inner ring, the external force is born by the outer ring and does not directly act on the inner ring. Although the outer ring may be dislocated due to the external force, the sensor unit on the inner ring can be held stably, since there is no direct mechanical connection between the two rings except for a few thin wires. The two rings are mechanically decoupled.

EXPERIMENT

The prototype ring sensor is now evaluated experimentally. There are several issues that need experimental verification and evaluation.

Adjustment of Inner Ring Tension and Skin Pressure

The inner ring must hold the sensor unit securely and stably with an appropriate pressure against the finger skin. It is known that pressurizing the tissue increases the pulsation amplitude of blood vessels and thereby provides a better signal to noise ratio. However, as the skin pressure increases, the possibility of necrosis and blood occlusion increases. As mentioned previously, the pressure with which the sensor unit is attached to the skin must be tuned to a proper level by making a trade-off between these two conflicting requirements.

Figure 6 shows experiments of the skin pressure v.s. pulsation amplitude. The sensor unit of the inner ring was placed near a digital artery in order to obtain a large pulsation signal. The subject was a 29 year old healthy male. A micro pressure gage was attached to the inner ring to measure the pressure with which the sensor unit is placed against the finger skin. The pressure was gradually increased up to *300 mmHg*, and then gradually decreased. The pulsation amplitude measured by the ring sensor changed in accordance with the skin pressure. It increased until the skin pressure reached the *100 mmHg* level, and then decreased. At around *180 mmHg*, the blood vessels completely collapsed and thereby the pulsation disappeared. Although there is no published data as to the maximum allowable pressure for the finger base, literature [7] suggests that the pressure less than *90 mmHg* causes no long-term circulation problem. We chose the skin pressure to be 75 mmHg, for which the amplitude is about 50 % of the maximum pulsation. This amplitude is large enough to accurately measure the beat-to-beat pulsation.

The inner ring must apply this pressure and maintain the desired level despite disturbances. The thickness of the finger base, however, varies for various reasons. The inner ring must therefore have some compliance to accommodate the pressure in the face of variation in the finger conditions. To this end, a polyester braided elastic band (70% polyester, 30% rubber, from Rhode Island Textile Company) was used for the prototype inner ring. This has been used for underwear in the apparel industry, and proven to be comfortable to wear. This material

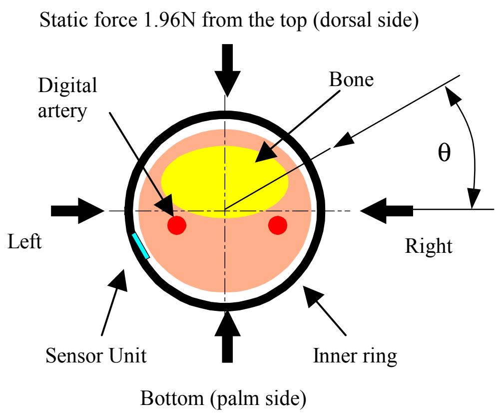


Figure 8 : Static force experiment

has a unique nonlinear elasticity: the spring constant is high for small strain, while it becomes very low beyond a certain limit. Therefore, it allows the inner ring to keep the tension almost constant despite a wide range of finger diameter change.

Figure 7 shows the experiment of the tension-strain characteristics of the polyester braided elastic band. Note that the slope is steep up to 4% of strain, i.e. high Young's modulus. Beyond this limit, the slope lowers to 1/15 of the initial steep slope. Therefore, in this range of large strain, the tension of the inner ring does not vary much, even though the finger diameter varies. In other words, the sensitivity of the inner ring tension to the finger diameter change is very low. The pressure applied to the skin surface is given by

$$P = \frac{2T}{Dw}$$

where P is skin pressure, T the tension, D the diameter of the elastic band, and w the width of the inner ring, i.e. the elastic band. Combining the tension-strain characteristics in Figure 7 and the above equation, the skin pressure can be obtained based on the unsprung length of the inner ring belt and the finger diameter. This skin pressure showed a good agreement with actual measurements using the micro pressure gage.

Comparison between the Isolating Ring and a Non-Isolating Ring

To demonstrate the effectiveness of the new isolating ring sensor, several tests were conducted. First, a force was applied to the outer ring from various directions (see Figure 8), and the pulse waveforms were measured with the isolating ring sensor, and were compared with that of the conventional single body ring sensor. Figure 9 shows the resultant waveforms taken from the same 29 year old, healthy male. The top two waveforms captured by the single body ring sensor show a significant influence of the external load. Particularly when the force is applied from the direction of $\theta = 0$ degree, i.e. the opposite side of the optical sensor unit, the signal was totally destroyed due to an air gap created between the sensor unit and the skin. In this case, the optical sensor is open to the air and strong ambient light dominated the measurement. The isolating ring sensor, on the other hand, shows stable measurements despite external loads, as shown by the bottom two waveforms in the figure. The sensitivity to external loads is an order-of-magnitude lower with respect to the amplitude of the detected pulse, compared with the single body ring sensor.

Figure 10 shows experiments of acceleration disturbance. Pulse waveforms were recorded while the finger was shaken. As indicated along the horizontal axis, the finger was shaken for 10 seconds and kept stationary for the following 10 seconds. The process was repeated for different accelerations. The top two waveforms were taken by the single body ring sensor under vertical ($\theta = 90$ degrees) and horizontal ($\theta = 0$ degree) accelerations, respectively. Note that the waveforms are very susceptive to acceleration. The bottom two waveforms captured by the isolating ring sensor show much lower sensitivity. Even under high acceleration, the isolating ring sensor can correctly capture the basic pulse frequency.

Benchmarking

The new ring sensor was benchmarked with other FDA-approved devices. An electrocardiogram (EKG) from AD Instruments Pty, Ltd. (NSW, Australia) and a standard fingertip photoplethysmograph from IBS Corp. (MA, USA, FDA-approved) were used for benchmarking. The three devices were attached to a subject at the same time, and data were recorded simultaneously. The fingertip PPG was attached to the tip of the middle finger of the right hand, while the ring sensor was to the base of the middle finger of the left hand. The EKG probes were attached to the standard three points of the body.

Two benchmarking tests were conducted. First, the FFT power spectrum of the ring sensor waveform was compared with those of EKG and the fingertip PPG. Second, the heart rate obtained from the ring sensor signal was compared with those of EKG and the fingertip PPG. Both benchmarking tests were repeated for different conditions with respect to external loads and skin pressure.

Waveform Power Spectrum

Figure 11 shows the waveforms of the three devices recorded simultaneously and their FFT power spectra. The subject was the same 29-year old healthy male. The FFT power spectra were computed for the waveform data recorded for 10 seconds, i.e. approximately 16 pulses. The first peak frequencies of the three spectra are exactly the same, *1.50 Hz*, while the second peak around *3 Hz* is within *1.6* percent of variation. There is no significant difference between the fingertip PPG and the ring sensor power spectra.

The ring sensor must work despite interference due to contact with the environment surface, as discussed previously. To verify that the ring sensor can function properly even under static loads, the benchmarking test was repeated with external forces applied to the ring body. Figure 12 shows the waveforms and power spectra of the ring sensor with a static force of 1.96 N applied to the outer ring from different directions. The EKG and fingertip PPG data are shown for comparison. Note that no external load was applied to the EKG and fingertip PPG, although some variations are apparent in these data[1]. While the amplitude of the ring sensor signal varied depending on the external load, the first and the second peak frequencies in the power spectra remained the same. The ring sensor's peak frequencies have no significant difference from those of the EKG and fingertip PPG, although the static load was applied to the ring sensor.

The skin pressure used for the above experiments was 75 mmHg, an acceptable pressure that won't incur local ischemia, as discussed previously. To evaluate robustness of measurement in relation to skin pressure, experiments were repeated for a low skin pressure. Figure 13 shows waveforms and power spectra of the ring sensor when the skin pressure was lowered to 11 mmHg. The ring sensor still shows a

[1] This kind of variation in EKG and fingertip PPG measurements is common.

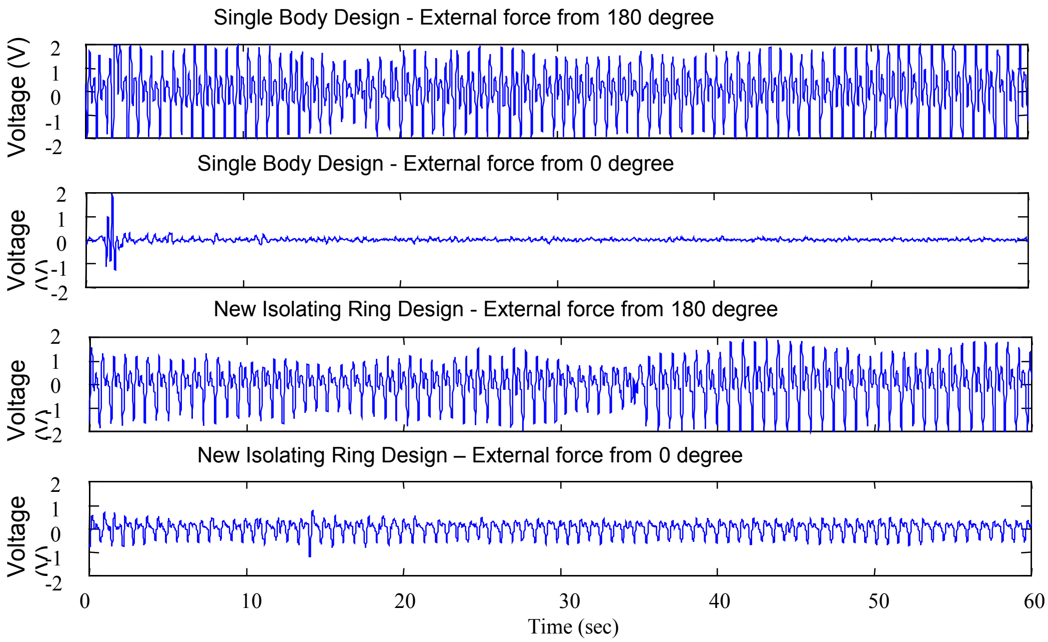


Figure 9 : Comparison between the ring sensor of single body design and the isolating ring sensor under external static force. The initial contact pressure of isolating ring was 75 mmHg.

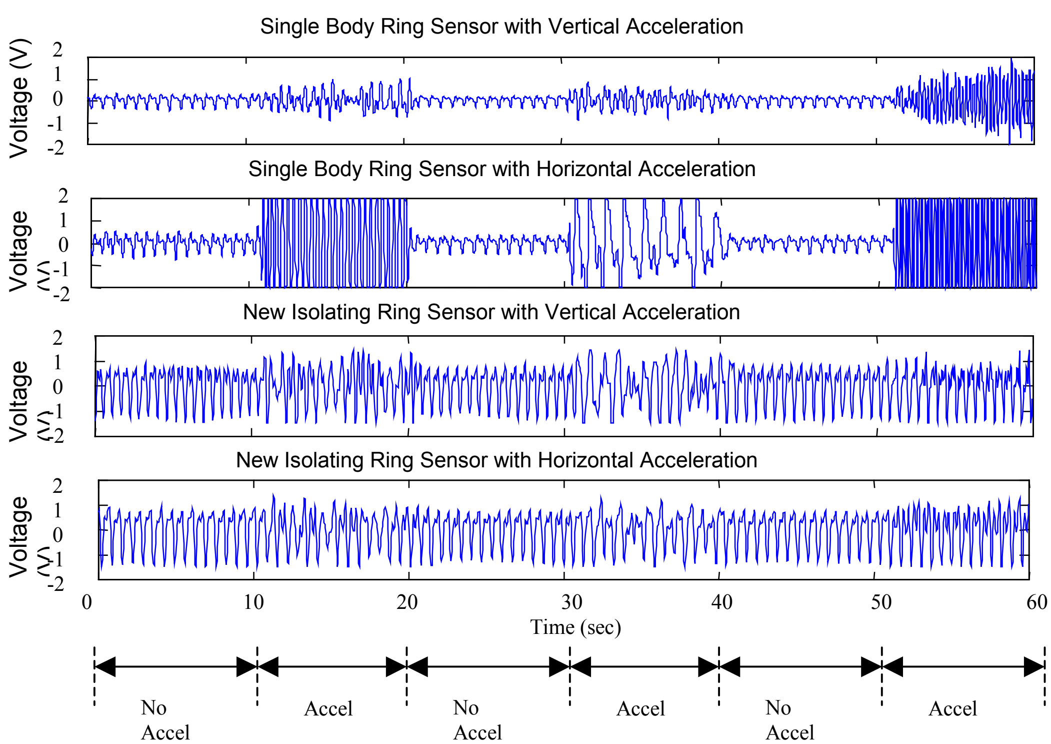


Figure 10 : Comparison between the ring sensor of single body design and the isolating ring sensor under acceleration. The initial contact pressure of isolating ring was 75 mmHg.

consistent result with regard to the first peak frequency, although the static load of 1.96 N was applied from two directions. However, the waveforms were completely distorted when the hand was shaken. Distorted waveforms similar to the ones in the top two plots of Figure 10 were obtained in this case. Therefore, waveforms tend to be susceptive to hand motion, as the skin pressure is lowered. As long as the ring sensor is used under stationary conditions, however, the skin pressure can be lower than 75 mmHg.

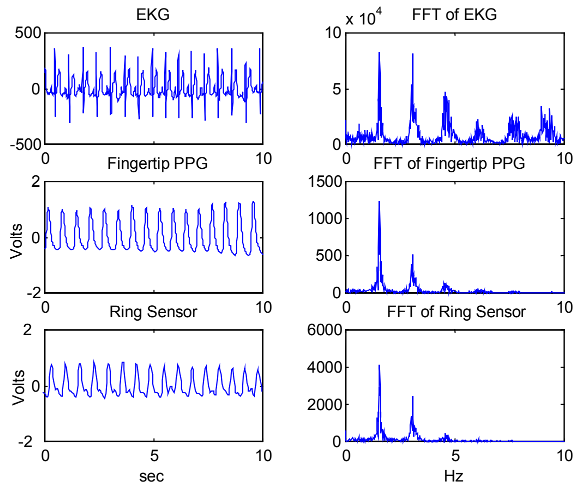
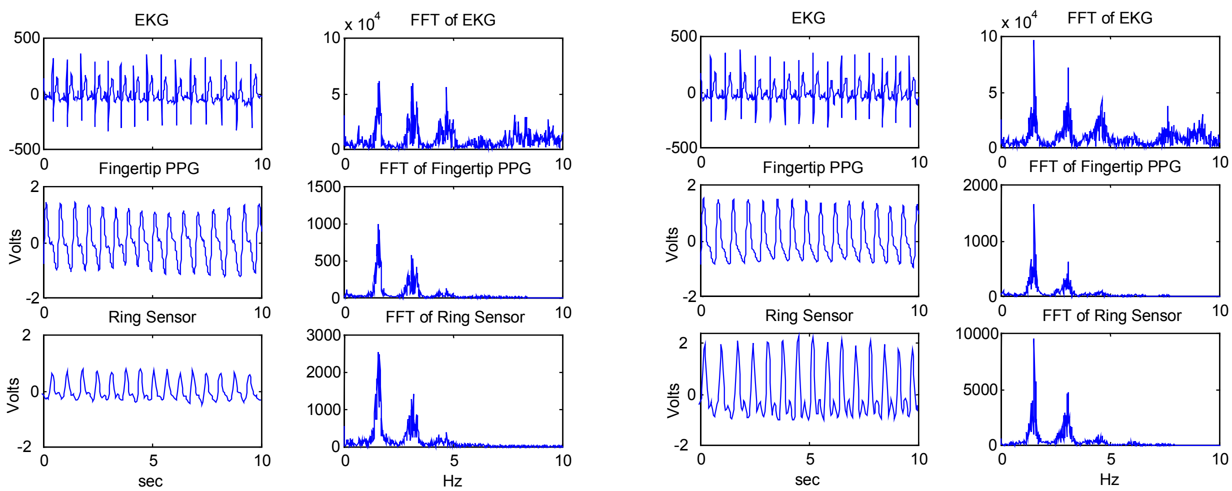
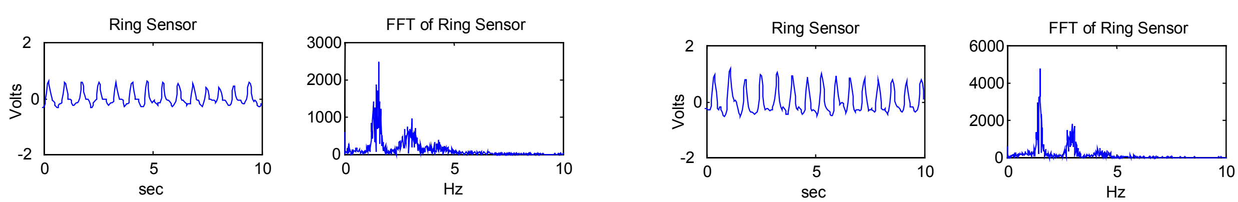


Figure 11 : No external static force with skin pressure of 75 mmHg. "Fingertip PPG" is the photoplethysmograph at the fingertip using FDA-approved device (IBS Corp).



(a) Force from θ = 0 degree

Figure 12 : Static force experiment with 75 mmHg skin pre
fingertip using FDA-approved device (IBS Corp).



(a) Force from θ = 0 degree

(b) Force from θ = 180 degree

Figure 13 : Static force experiment with 11 mmHg skin pressure.

Heart Rate Monitoring Tests

The consistent detection of the first peak frequency demonstrated in the above experiments implies that the ring sensor can be used as a beat-to-beat heart rate sensor. Figure 14 shows the beat-to-beat heart rate measured for the same subject when a light cardiac load was applied. The heart rate was determined by detecting the base point in each pulse and measuring the interval between adjacent base points. For benchmarking, the EKG and fingertip PPG data were simultaneously recorded, and the heart rate was extracted from each signal in the standard manner of beat-sampling technique [8]. The

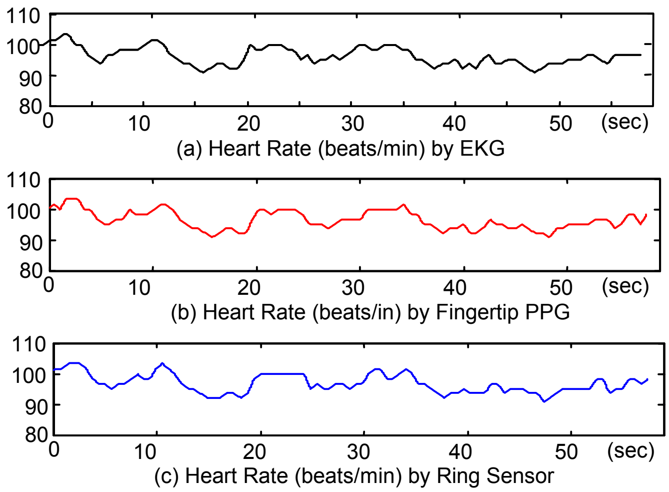


Figure 14 : Heart rate monitored by EKG, Fingertip PPG device, the Ring Sensor

experiment was conducted for 60 seconds. The variation of heart rate has close correlation with that of the EKG and fingertip PPG. Table 1 shows the root mean square errors of the beat-to-beat heart rate, compared with the EKG and fingertip PPG. For a skin pressure of 75 mmHg, the difference between the ring sensor and EKG is 1.23 beats per minute, while that with the fingertip PPG is 1.22 beats per minute. For comparison, the table also shows the root mean square error between the EKG and fingertip PPG. The discrepancy between the ring sensor and the other two is as small as that of the EKG and fingertip PPG. When the skin pressure was lowered to 11 mmHg or increased to 146 mmHg, the discrepancy tends to increase. Nevertheless, the error is as small as 1.6 beats per minute. These results clearly show that the ring sensor's accuracy is comparable to those FDA-approved devices and that the ring sensor can function even under static load and acceleration with a proper skin pressure.

Contact pressure	EKG and Ring Sensor	Fingertip PPG and Ring Sensor	EKG and Fingertip PPG
11 mmHg	1.44	1.39	0.83
75 mmHg	1.23	1.22	0.77
137mmHg	1.41	1.27	0.96
146mmHg	1.60	1.54	0.94

Table 1 : RMS error (beats/min) of the heart rates from the ring sensor compared with those from EKG and fingertip PPG device

CONCLUSION

An artifact-resistive design of ring sensors has been presented. The main results of this paper are:

- The isolating ring design developed in this paper decouples the optical sensor unit from other components, and allows the sensor unit to be shielded from external static loads and the ambient lighting. The new ring design also attenuates the influence of finger acceleration, since the heavy components are mechanically decoupled from the sensor unit. This allowed us to hold the sensor unit with a small skin pressure, so that the circulation at the finger may not be obstructed.
- A prototype ring sensor has been designed, built, and tested. Experiments have verified that the ring sensor can detect beat-to-beat pulsation in the face of interfering force and acceleration acting on the ring body.
- The prototype ring sensor has been benchmarked with FDA-approved PPG and EKG. The FFT spectral analysis has revealed that the ring sensor is comparable to the FDA-approved devices with regard to the first and second peak frequencies of the power spectra. Furthermore, the ring sensor is comparable to those devices for the measurement of beat-to-beat pulse variation. The discrepancy is less than 1.23 pulses per minute.

These experimental data and benchmarking tests have demonstrated that the ring sensor can be used as a wearable sensor for long-term, continual monitoring of patients in the home and other environments.

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