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Application of a Textile-based Inductive Sensor for the Vital Sign Monitoring

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Abstract – In this study, we developed a feasible structure of a textile-based inductive sensor using a machine embroidery method, and applied it to a non-contact type vital sign sensing device based on the principle of magnetic-induced conductivity. The mechanical heart activity signals acquired through the inductive sensor embroidered with conductive textile on fabric were compared with the Lead II ECG signals and with respiration signals, which were simultaneously measured in every case with five subjects. The analysis result showed that the locations of the R-peak in the ECG signal were highly associated with sharp peaks in the signals obtained through the textile-based inductive sensor (r=0.9681). Based on the results, we determined the feasibility of the developed textile-based inductive sensor as a measurement device for the heart rate and respiration characteristics.

Keywords: Magnetic-induced conductivity sensing method, Inductive sensor, Textile-based sensor, Vital sign monitoring, Heart rate sensing, Respiration sensing, Ubiquitous health care system

1. Introduction

Generally, physical health can be confirmed through medical instruments such as electrocardiogram (ECG), electroencephalogram (EEG), electrooculogram (EOG) and electromyogram (EMG) at a hospital [1, 2]. Although these apparatuses obtain accurate vital signs from the human body, they still have some weaknesses, including their lack of inability to monitor health conditions continuously on a daily basis.

In recent years, the concepts of personal health care and well-being throughout life have attracted new attention. In this context, people require smart equipment that enables more convenient use of the health care systems [2, 3]. Responding to these needs, there have been various studies of ubiquitous healthcare monitoring systems for daily use. Similar interests have also emerged in the field of wearable monitoring systems, in which revolutionary smart textile applications have been developed to assist with ubiquitous health care. Various wearable devices have been integrated with sensors to detect signals such as the heart rate, body temperature, respiration, blood pressure, motion, acceleration, and blood glucose level [4].

In the field of wearable monitoring system, devices for the daily monitoring of vital signs developed thus far can be categorized into two types, contact-type and noncontact-type sensing systems [5, 6]. While research on contact-type sensors has generally been conducted based on the principle of electrical resistance or piezoelectricity, investigations of noncontact-type sensors have mostly focused on the capacitive methods [5-8]. In research on noncontact type sensing, the magnetic-induced sensing method has recently emerged [9-12].

In this study, we aim to examine preliminarily the feasibility of a noncontact sensor which use a conductive textile material for the measurement of vital signs and, whose functions work on the basis of the magnetic-induced conductivity sensing principle.

2. The Principles of Heart Activity Based on Magnetic Induction

The principles of the measurements of vital signs using a coil-shaped inductive sensor, for the purpose of this study, are explained below:

An AC current flow in a coil-shaped sensor, with a magnetic field $\vec{H}$ along its axis can be produced to create magnetic flux ϕ_E. If a coil is placed near living tissue which is considered as diamagnetic water [13], the ϕ_E flux inside the living tissue changes over time. According to Faraday's law of induction [14, 15], ϕ_E creates a secondary circular current, i.e., an eddy current i_{eddy} in the living tissue. This eddy current would create a secondary flux ϕ_I that would affect the loading on the net magnetic flux of the coil and, thus its impedance. Also, the eddy current density $\vec{J}$ in living tissue is governed by a diffusion

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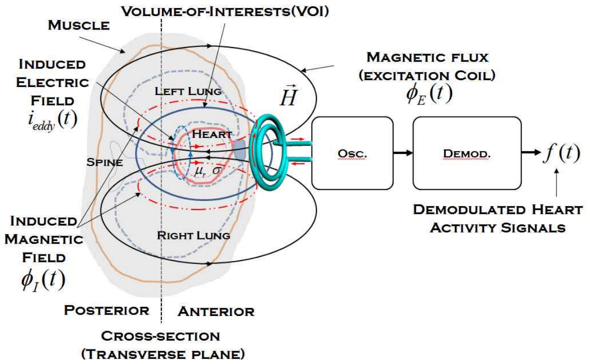


Fig. 1. The basic principle of a magnetic-induced conductivity measurement system [18].

Equation [16] for the current density $\vec{J}$, as expressed by Eq. (1).

$$\nabla^2 \vec{J} = \sigma\mu \frac{\partial \vec{J}}{\partial t}, \tag{1}$$

Here, σ is the electrical conductivity, and μ is the permeability of a living tissue specimen. From (1), it is evident that the eddy current induced by an external time-varying magnetic field depends on the magnetic characteristics, especially on the electrical conductivity, of the living tissue (Fig. 1) [17].

3. Development of a Textile-based Inductive Sensor for the Measurement of Vital Signs

3.1 Conductive materials for a textile-based inductive sensor

The conductive textile material used for the coil-shaped inductive sensor developed in this study requires optimization, including the appropriate conductivity, suitable flexibility, and proper durability.

To be specific, silver-plated nickel yarn can scarcely withstand friction and tension during the fabrication processes such as embroidery, due to its insufficient flexibility and durability. In contrast, due to the polymer structure of polyester, the polyester yarn has appropriate mechanical properties, allowing it to undergo the subsequent fabrication process. Hence, in this study, the unsuitable properties of metal yarn were offset by a yarn treatment which combined a metal ply with polyester ply. The resulting hybrid yarn created by this combination was found to have sufficient mechanical properties to withstand the fabrication processes used here.

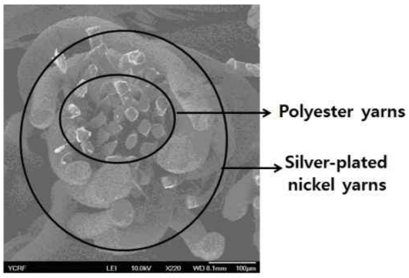


Fig. 2. SEM photo of the cross-section of the conductive yarn

Following the method of a previous study [12], for the conductive material of the textile-based sensor, a type of polyester-metal hybrid thread was developed through a treatment process. A single strand of the conductive thread consists of nineteen units of yarn. Each unit of yarn in the conductive thread is a combination of two heterogeneous components fabricated by a twisting method, multiple filaments of polyester (75 denier per thickness in single filament) and eight lines of silver-plated nickel yarn, consisting of six lines of 30㎛ yarn and two plies of 50㎛ yarn(Fig. 2). 'Denier' is a unit that represents the fineness of a textile yarn. One denier indicates that one gram of the textile, material is required to realize a yarn length of 9000 meters [19].

The resulting electrical resistance of the conductive thread for the textile electrode produced in this study was 0.23Ω/m.

3.2 The textile-based electrode for the inductive sensor

The basic shape of the textile-based electrode for the inductive sensor in this study is a flat spiral, as inspired from a coil-shaped inductor. Ten turns of a spiral line using the conductive thread were applied to the polyester fabric by means of an embroidery machine (Fig. 3).

The electromagnetic characteristics of the textile inductor were measured by a network analyser (HP8735D, Agilent, U.S.A). Within the frequency bands of interest, 0.5~1.5MHz, its inductance was 2.6±0.3 μH (Fig.3).

As the inductive coil sensor works as a transceiver, the size of the electrode plays a crucial role. Increasing the size of the textile electrode is an effective way to obtain stable heart activity signals. On the other hand, a large textile electrode embedded in a garment tends to have unwanted effects, such as reflecting the influence of motion artifacts during breathing. Taking into consideration the advantages

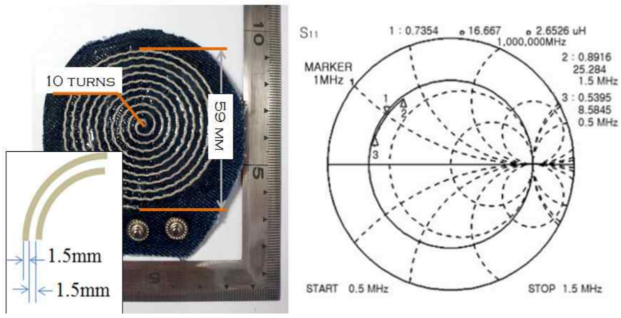


Fig. 3. The embroidered textile-based inductor and its electromagnetic characteristics

and disadvantages of increasing the textile electrode size, the optimized size was set such that the diameter was 5.9 cm.

3.3 Computer simulation of the induced magnetic flux and eddy currents in biological tissues

In order to simulate a change in the magnetic field distribution and induced eddy current with changes in the size of the heart, the three-dimensional model shown in Fig. 4, was used.

The magnetic field simulation was performed using the COMSOL Multiphysics (COMSOL AB, U.S.A), Magnetic field model. The electromagnetic characteristics, i.e., the conductivity, permittivity, and permeability of living tissues around 1MHz, are summarized in Table 1 [10].

Table 1. Electromagnetic characteristics of the Material contents of the simulation parts

	Electric conductivity [S/m]	Relative permittivity	Relative permeability
Coil	3.7e7	1	1
Air	0	1	1
Fat	0.02	100	0.999
Muscle	0.3	900	1
Heart	0.8	1000	1

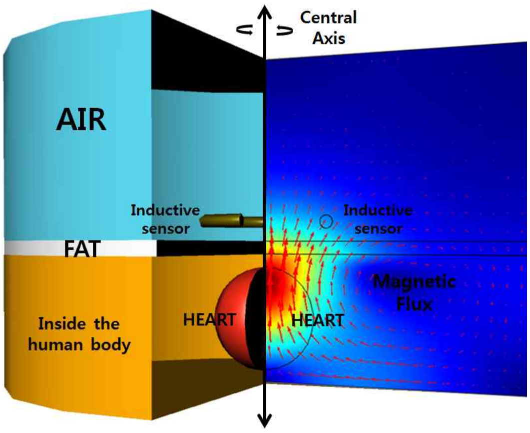


Fig. 4. A simulation of a three-dimensional model of the excitation coil of the sensor.

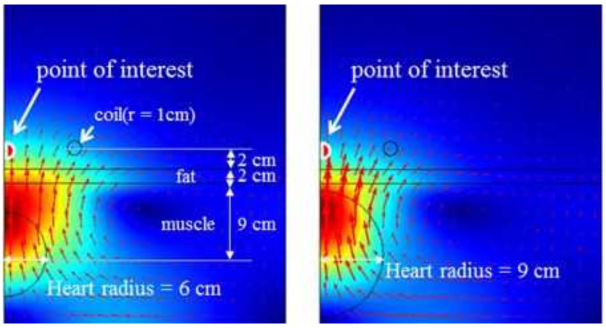


Fig. 5. The changes of the magnetic flux depending on the heart radius

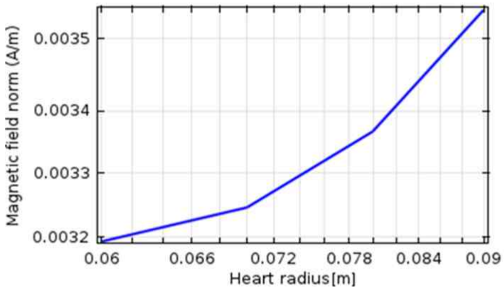


Fig. 6. Magnetic field strength of a point of interest

The simulation consisted of two steps. The first step was to evaluate the induced eddy current by the excitation of an external coil, and the second step was to evaluate the induced magnetic fields by an eddy current. Given that the direction of an induced magnetic field caused by an eddy current is opposite to an excitation magnetic field according to Ampere’s law, the overall magnetic fluxes that were coupled with the external coil were assumed to vary according to the change of the induced magnetic field (Fig. 5).

Fig. 6 shows the induced magnetic fields at the point-of-interest according to a change in the size of the heart. As the size of the heart increased, the induced magnetic fields caused by the eddy current in the heart muscle also increase. Therefore, during cardiac cycles in which the atrium and ventricles of the heart are beating continuously, the induced magnetic fields sensed at a fixed location would be proportional to the movement of living tissues.

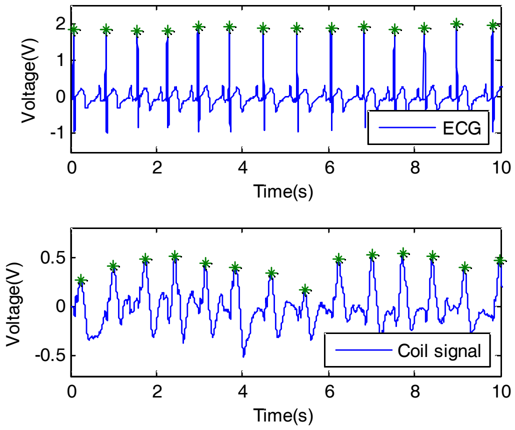
3.4. Experiment

Measurements were taken with five male subjects in their twenties, all of whom were in good health. Each subject was asked to sit in a chair while his heart activity signals were measured. The textile-based inductive sensor developed for this work, was attached onto the surface of the shirt the subject was wearing, over the left chest. In order to check whether the magnetic induction principle was applied, the heart activity signals with the proposed textile based inductive sensor were acquired and compared with the signals from a standard ECG signal (lead II) and respiration signals **(Biopac System.** MP150 MODEL RSPEC-R Wireless Trans metre), which were simultaneously measured in each subject.

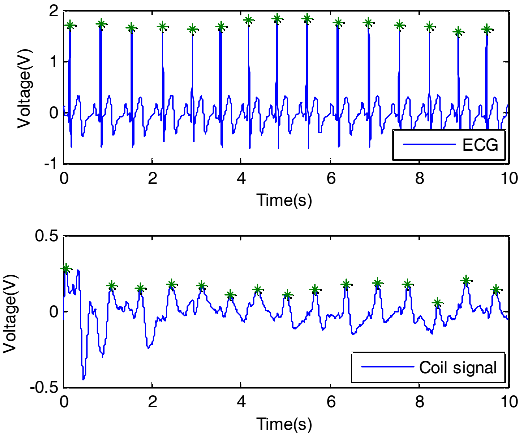
4. Results and Discussion

4.1 Detection of the heart beat using the textile-based inductive sensor

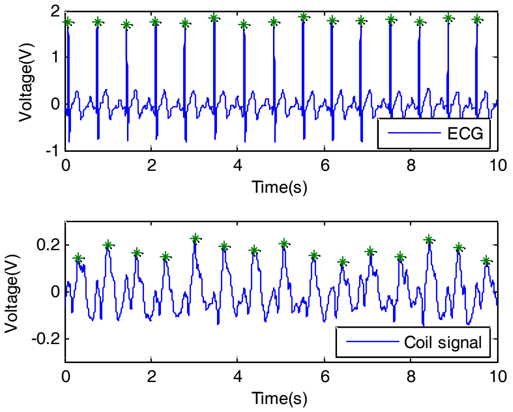
The signals from the textile-based inductive sensor were compared with the R-peaks in the standard lead II ECG signals (Fig. 7).



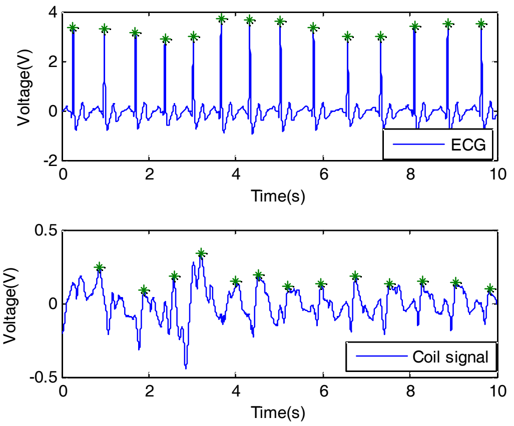
(a) Result of subject 1



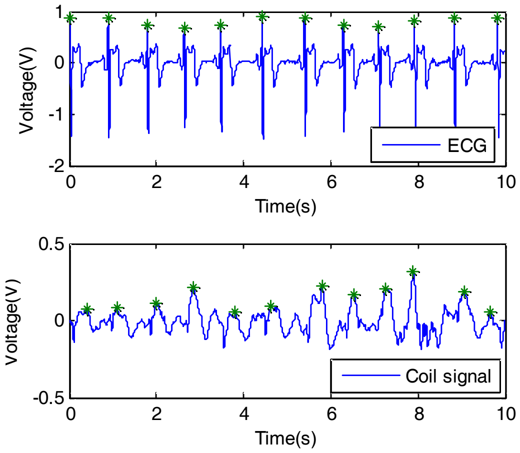
(b) Result of subject 2



(c) Result of subject 3



(d) Result of subject 4



(e) Result of subject 5

* The asterisk on the graph means the peak point.

Fig. 7. The relationship of the peak point between the inductive sensor signals measured on the anterior side and the standard Lead II ECG signals (Subjects 1-5).

From the data obtained in the experiment (Fig. 7), we conjectured that the magnetic-induced conductivity of the heart muscles was reflected in the inductance changes of the textile-based inductive sensor. Although the peaks from the inductive sensor are slightly lagged, the peak-to-peak intervals appear to be associated with the ventricular contraction activity of the heart shown in the ECG. Fig. 7 shows the relationship between the peak-to-peak intervals in the ECG and those in the signals from the inductive sensor.

The tendency of signal lagging from the textile-based sensor, in comparison with the QRS-complex in the ECG, stems from the measurements of the two different physical activities in the heart, in each sensing method. In other words, while ECG represents the electrical activity of the heart, the textile-based sensor in this study represents the mechanical activity, contraction and expansion, of the cardiac muscle, especially the ventricular muscle. Considering that the mechanical activity of the heart is triggered by the electrical activity of the SA node, the time lagging tendency between the ECG and the measured signals in this study could be interpreted to indicate the timely sequences of the heart conduction. This assumption could be verified by results which showed that the waves in the magnitudes of the heart activity signals mostly match the respiration cycle (Fig. 9) [20].

To verify the association between these sets, a regression equation(y=1.050x-0.039) was calculated and a correlation coefficient (r=0.9681) was derived (Fig. 8). On the basis of

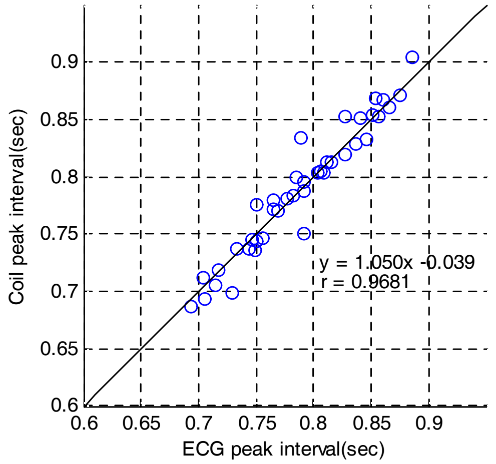


Fig. 8. The correlation between the peak-to-peak intervals in the obtained signals through the inductive sensor and those in the ECG (Subject1).

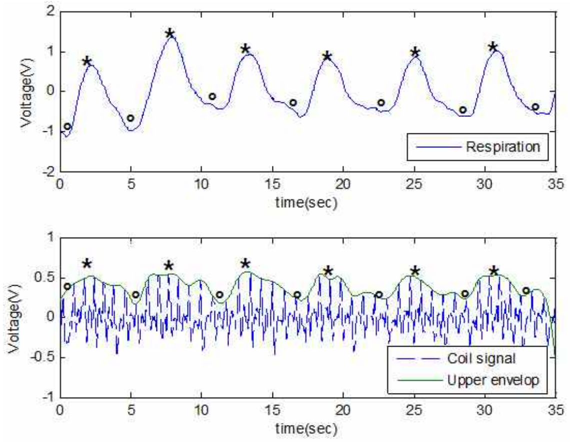
the relationship between the peak-to-peak intervals above, we can infer that the peaks in the signals from the textile inductive sensor indicate the ventricular contractions in the cardiac cycles.

4.2 Respiratory effect on the measured inductive sensor signals

Although we examined the feasibility of the inductive sensor as a heart activity sensor, the results suggest another intriguing phenomenon pertaining to the respiratory effect on the signals from the textile inductive sensor.

Fig. 9 shows the association phenomena between the respiration signals and the enveloped signals from the inductive sensor, which were simultaneously measured on the anterior side of the torso. From Fig. 9, it is inferred that when the subject draws a breath-in, the magnitudes of the heart activity signals tend to enlarge. In contrast, when the subject exhales the magnitudes in the heart activity signals tend to shrink. A similar phenomenon in which thoracic changes by respiration were found to be associated to the magnetic induced measurements of heart activity signals, have been reported in earlier research [11, 21].

The change of the distance between the textile-based inductive sensor and the VOI (i.e., volume of interest) in the heart area is inferred to be the key factor influencing on this phenomenon. The fluctuation in the magnitude of the obtained signal is inferred to have been caused by the change in the distance between the sensor and the heart, due to the following reactions to respiration inside the thorax.



*The asterisk on the graph denotes the breath-in point
*The circle on the graph denotes the breath-out point.

Fig. 9. The association between the respiration signal and the enveloped signals from textile inductive sensor measured on the chest (Subject1).

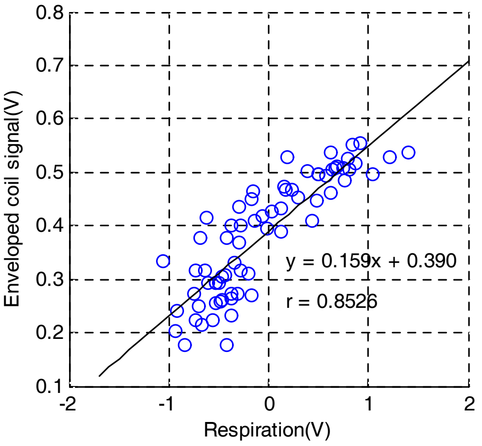


Fig. 10. The correlation between the respiration signal and the envelope of the inductive textile-based coil sensor signals measured on the chest (Subject1).

During inhalation, as the diaphragm contracts it moves to the lower position, while the thorax expands to the triple direction - to the left, right and front. Consequently, the pressure level the inside thorax decreases causing air to rush into the lungs, which causes rapid enlargement of the volume of the lungs [21]. It is inferred that the enlarged lungs push the heart towards the front, which makes the distance between the textile-based inductive sensor and the VOI becomes closer when inhaling, and vice versa during exhaling. This change of the distance results in a change in the conductivity distribution in the VOI, which induces the subsequent fluctuation in the magnetic flux.

This inference enables to explain how and why the waves in the magnitudes of the heart activity signals mostly match the respiratory cycles (Fig. 9).

In order to check the correlation between the respiration signals and the enveloped signals from the textile inductive sensor in this study, a correlation coefficient (r=0.8526) and a regression equation were derived (Fig. 10). On the basis of the relationship above, we hold that the peaks in the signals from the textile inductive sensor indicate its respiratory effects.

Comparing the correlation coefficient between the peak-to-peak intervals in the signals obtained using the inductive sensor and those in the ECG shows a result of about 0.97, while that between the respiration signal and the enveloped signals from textile inductive sensor measured on the chest is about 0.85.

While the reference signals obtained from the electro-resistive respiration sensor detect changes in the abdominal girth, the enveloped signals from the textile-based inductive sensor detect the changes in the thoracic cavity.

This slightly lower correlation coefficient between the respiration signals and the envelops of the inductive coil sensor signals compared to that of the heart activity signal, is likely related to the difference in the sensed parts in the body.

5. Conclusion

In this study, the feasibility of a textile-based inductive sensor for the sensing of vital signals was examined. We observed that the changes in a magnetic-induced eddy-current due to the electrical changes of biological tissues and the motion of the ventricle walls in the heart were apparently reflected in the inductance change of the textile-based inductive sensor. Based on results indicating a high correlation between the measured signals using the proposed method and QRS-peaks in the standard lead II ECG., the feasibility of the device proposed in this study as a heart rate sensor was verified.

In addition, the magnitudes of the signals obtained from the inductive coil sensor, were also found to be influenced by pulmonary activity.

As mentioned previously, this is a preliminary study which sought to examine the feasibility of the textile-based inductive sensor for the measurement of the vital signs. The result of this study is expected to suggest some guidelines for further studies which adopt textile-based inductive sensors for vital sign measurements.

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References

[1] X. F. Teng, Y. T. Zhang, C. Poon, and P. Bonato, “Wearable medical systems for p-health”, Biomedical Engineering, IEEE Reviews, Vol. 1, No. 1, pp. 62-74, Jan. 2008.

[2] A. Lymberis, “Smart wearable systems for personalised health management: Current R and D and future challenges,” Proceedings of the 25th Annual International Conference of the IEEE, 2003, Vol. 4, pp. 3716-3719, 2003

[3] J. J. Rutherford,” Wearable Technology: Health-Care Solutions for a Growing Global Population” IEEE Engineering in Medicine and Biology Magazine, pp. 19-24, May/June 2012

[4] S.T. Doherty and P. Oh,” A Multi-Sensor Monitoring System of Human Physiology and Daily Activities”, Telemedicine and e-Health, Vol. 18 No. 3, pp. 185-192, April. 2012

[5] J.H. Oum, S.E. Lee, D.-W. Kim and S. Hong, “Non-contact heartbeat and respiration detector using capacitive sensor with Colpitts oscillator”, Electronics Letters, Vol. 44 No. 2, January 2008

[6] T. Linz, L. Gourmelon, G. angereis, “Contactless EMG sensors embroidered onto textile”, 4th International Workshop on Wearable and Implantable Body Sensor Networks , IFMBE Proceedings,Vol. 13, pp 29-34, 2007

[7] S.H. Cho, S.M. Koo, J.H. Lee, H.K. Cho, D.H. Kang, H.Y. Song, J.W. Lee, K.H. Lee, Y.J. Lee, “Heart Monitoring garments using textile electrodes for healthcare applications ”,Journal of Medical Systems, Vol.35, No.2, pp. 189-201, 2011.

[8] Y. G. Lim, K. K. Kim, K. S. Park, D. U. Jeong, “ECG Measurement Method during Sleep with Array of Capacitive Electrodes Attached to Bed”, IEEK Fall Conference, Vol. 28, No. 2, pp. 521-524, 2005.

[9] D. Teichmann, J. Foussier, M. Buscher, M. Walter and S. Leonhardt, “Textile Integration of a Magnetic Induction Sensor for Monitoring of Cardiorespiratory Activity”, World Congress on Medical Physics and Biomedical Engineering, IFMBE Proceedings, Vol.39, pp. 1350-1353, 2013

[10] M. Steffen, A. Aleksandrowicz, S. Leonhardt, “Mobile Noncontact Monitoring of Heart and Lung Activity”, IEEE, Transactions on biomedical circuits and systems, Vol. 1, No. 4, pp.250-257, 2007

[11] H. R Koo, Y.J Lee, S.O Gi ,S.N Khang, J.H Lee, J.H Lee, M.G Lim, H..J Park , J.W Lee, “The Effect of Textile-Based Inductive Coil Sensor Positions for Heart Rate Monitoring”, Journal of Medical Systems, Vol.38 No.2, Published online, 2014

[12] S.O GI, Y.J Lee, H.R, Koo, S.A. Khang, H.J Park, K. S. Kim, J.H Lee, J.W Lee, “An Analysis on the Effect of the Shape Features of the Textile Electrode on the Non-contact Type of Sensing of Cardiac Activity Based on the Magnetic-induced Conductivity Principle”, The Transactions of the Korean Institute of Electrical Engineers Vol. 62, No. 6, pp. 803-810, 2013

[13] T. Varpula, “Magnetic-Susceptibility Plethysmography”, Il Nuovo Cimento D, 2th edition, 1983, pp. 624-641

[14] W.H.Hart, J.A.Buck, “Engineering electromagnetics”, McGraw-Hill Science, 8th edition, 2012, pp277-296

[15] D. K. Cheng, "Field and wave electromagnetics", Addison-Wesley, 4th edition, 1989, pp. 307-353

[16] Kriezis, E. E., Tsiboukis, T. D., Panas, S. M., and Tegopoulos, J.H., "Eddy currents: Theory and application", Proceedings of the IEEE., 1992,Vol. 80, Issue.10, pp.1559-1589 Vol.41, pp. 2231-2249, 1996

[17] Gabriel, C., Gabriely, S., and Corthout, E., "The dielectric properties of biological tissues: I. Literature survey", Physics in Medicine and Biology, Vol.41, No. 11, pp. 2231-2249, 1996

[17] Gabriel, C., Gabriely, S., and Corthout, E., "The dielectric properties of biological tissues: I. Literature survey", Physics in Medicine and Biology, Vol. 41, No. 11, PP. 2231-2249, 1996

[18] S.O GI, Y.J Lee, J.H Lee, J.W Lee, "Inductive bio signal detection sensor based on conductive textile", Patent. No.10-2012-0092695, KOREA, Aug.2013

[19] S.R Kim, "Material for fabric", 2011, 3th edition, Kyo moon sa, pp. 245

[20] D. E. Morhrmnan, H.J. Heller, "cardiovascular physiology", 4th edition, McGraw-Hill international companies, 1997, pp.49

[21] www.revisionworld.com/gcse-revision/biology/human-body/breathing-respiratory-system, Accessed on .02. 06. 2014

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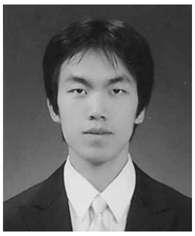

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