

Consideration of Invasion, Intrusion, and Consciousness in Biomedical Sensing with Uncertainty

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Abstract— Both burden of human and performance of sensing technology should be carefully considered in bioinstrumentation. The article proposes the ideas of invasion, intrusion, and consciousness in biomedical sensing to improve its comfort and performance. Consideration of the three concepts is very important to realize burden-reduction of human. They also save sensing accuracy when sensing targets and sensor heads are influenced by invasion, intrusion, or consciousness during sensing. Realizing noninvasive, nonintrusive, and unconscious sensing requires solutions against uncertainty in sensory signals and estimation models. Sensory signals from these sensing methods might superimpose various types of signals besides target one. Target signals would be appropriately extracted by the causal analysis-based model. Case studies were investigated by considering the method and experimental results were reported in the article.

Keywords—component; Biomedical sensing, Fuzzy Logic, Noninvasive, Nonintrusive, Unconscious, Uncertainty information processing, Causal Analysis, Hierarchical Knowledge Representation

I. INTRODUCTION

There have been noticed many kinds of problems related to our healthy, social, and environmental issues during the new decades of 21st century. Among them, aging society will make rapid progress especially in advanced nations. Medical crisis has also become clear. Environmental issues centering global warming would have some impacts on our live body. Through these rapid changes close to our daily life and health, it has been much more important for us to know about our human body by bioinstrumentation than ever.

For instance, metabolic syndrome which is caused by life style habit has been immediately paid attention to. Even though the cause would be individual's life style, the result is quite serious from obesity through hypertension and diabetes to cardiovascular events like brain and cardiac infraction and complication [1][2]. The most important and effective against the disease is to change the life style of diet, exercise, and sleep. However, it is very hard for the patients and the preliminary

group of the disease to change their life styles which have been continued for a long time. In order to change the life style, it is effective for them to notice the status of their body condition based on the measurements of their vital signs and life styles. Continuation of the measurements would be the key to success in changing lifestyle habit. For this reason, bioinstrumentation and lifestyle measurement without invasion, intrusion and consciousness in daily life would be required besides the indices such as Electrocardiograph (ECG) and blood pressure (BP) sensed in the medical field.

In the article, the importance of idea of invasion, intrusion, and consciousness in bioinstrumentation is studied and discussed. The realized biomedical sensing methods which consider the idea are introduced and surveyed for considering the uncertainty in the sensing methods.

The rest of the article is organized as follows; Section II studies the bioinstrumentation from the views of invasion, intrusion, and consciousness. Section III introduces the biomedical sensing methods which are for visceral fat estimation and heart rate monitoring as the case studies. The methods employ the causal analysis with hierarchical knowledge against uncertainty which is caused by restrictions of reducing invasion, intrusion, and consciousness. Discussions follow the introductions and experimental results. Section IV concludes the article with summaries.

II. RELATIONSHIP BETWEEN LIVING BODY AND SENSING

Physical and mental pain and restraint of patients should be eliminated or minimized during bioinstrumentation with accurate sensing results. It is the motif of reducing invasion, intrusion, and consciousness. Fig. 1 shows the overview of bioinstrumentation. Various types of sensory signals from the living body are obtained via sensory head. The signals are accumulated into the database to put them to practical use of medical and healthcare by feeding back some effects the patients. Besides them, the database is used in the medical science and engineering to develop the new evidences and the new solutions.

In this section, invasion, intrusion, and consciousness in biomedical sensing are studied and discussed from the views of both human burden and technology performance. Invasion has been studied more than intrusion and consciousness so far. However, latter two issues are also important idea to provide different meanings and values from invasion to realize comfortable and accurate biomedical sensing method.

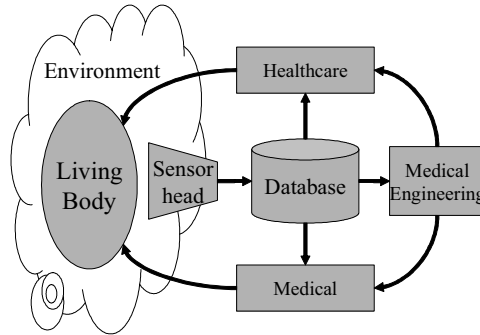


Figure 1. Overview of Bioinstrumentation

A. Invasion

Invasion levels can be defined by distance between sensory head and sensing target or location of them. According to [3], there are five invasion level of biomedical sensing as follows;

1. A catheter is inserted into body to send transmitter to a sensor head.
2. A sensor head is implanted to send sensory signals via fixed line.
3. A sensor head is implanted to send sensory signals via wireless communication.
4. A sensor head is contacted on skin of the body to detect signals.
5. A sensor head is not contacted on skin of the body to detect signals.

As mentioned above, the invasion levels are defined by the positional relationship between sensory head and live body. Even though the invasion level is low according to the definitions above, a CT scan that is non contact sensing requires X-ray exposure which is serious invasive. This case should be treated as high invasion. Thus, definition could be changed according to the development of sensing technology and consideration of influence to human body.

Compared with invasion, intrusion and consciousness sensing are new ideas in biomedical but important for both of sensing accuracy and human comfort.

B. Intrusion

Nonintrusion is important idea for sensing daily life activity. ECG and BP are very important physical indices used in medical and healthcare. The indices can be measured in just in hospital and clinic. It is strongly required to monitor for 24 hours to detect defect condition of body in daily life. However, it is impossible to monitor ECG in daily life in the case of

using ordinary ECG equipment. A Holter electrocardiographic monitor has been realized for gathering the ECG signals and an ambulatory blood pressure monitor for accumulating blood pressure signals for 24 hours. Although the equipment could be used for sensing live body, it is far from non-intrusion. The user has to use contacted sensory head and to carry on the equipment. There has not been clearly defined but some levels would be discussed on intrusion.

C. Consciousness

Consciousness or realization to be sensed would have some influence to the sensing signals. White coat hypertension and masked hypertension [4] are examples for understating the importance of unconsciousness sensing. Not just for these serious cases, other examples can be easily pointed out with considering consciousness such as video and image sensing. Long and continuous sensing for 24 hours requires unconsciousness. Besides them, unconsciousness helps for users not to forget the measurement.

Through these definitions and observations on invasion, intrusion, and unconsciousness, some discussions on influences to patients and live bodies and to measurements.

D. To Living Body

It is strongly required to reduce and to eliminate burden, pain, and damage both physically and mentally to live bodies and patients. According to the definitions of invasion level, the level is decided by distance and location between sensor head and body. However, even though X-ray CT scan is non contact sensing, it gives serious impact of X-ray exposure on a living body. Implant sensing requires surgery whose invasion level is quite high, but intrusion is very low when the sensor could be used for a long time without any invasion. Additionally, a patient who is implanted a sensor into could feel unconscious with the sensor. As these discussions, invasion is not the only perfect prerequisite in biomedical sensing. Intrusion and consciousness should be also considered for realizing the effective and efficient bioinstrumentation.

E. To Measurements

Sensing performance would be generally sophisticated according to higher invasion level. However, invasion sometimes brings negative results in sensing. Contact between a sensor head and live body makes energy exchange among them to possibly cause unstable sensing. For example, huge sensor head of clinical thermometer realizes good fitting with body however it takes body temperature. Like the examples pointed out in intrusion section, it would be very hard to keep the ideal situation of the patient such as in daily life activities with high intrusion. Besides, unconscious sensing might bring good results with the sensing performance as discussed in consciousness section.

F. Uncertainty

Realization of biomedical sensing without invasion, intrusion, and consciousness would bring some uncertainty in the sensing mechanism. Sensor signals superimpose not just target but other kinds or noises. Besides extraction of target

signal, it is also required to compose causal structures which explain sensing principles well.

The article proposes causal analysis method against the problems to be solved discussed above. Causality plays an important role for solving the uncertainty discussed above because it is the basis of human's understandings and also machine could handle with it; i.e., it is transparent among humans and machines mutually. It brings powerful solution which improves observability and controllability of the target system.

III. CASE STUDIES

In this section, two applications to biomedical sensing with considering the sensing issues described in the previous section are described.

A. Visceral Fat Area Estimation

Entering the 21st century, declining birthrate and a growing proportion of elderly people have developed into more serious social problems especially in advanced nations. Not only solving the problem of labor power reduction but also extending healthy life expectancy is the important challenge which should be socially addressed. In terms of the issues, primary prophylaxis has been recognized as an important activity to prevent life style related diseases. Currently, the waist circumference and blood sugar, neutral fat or quantities of cholesterol in the blood are measured for the primary screening whether the person is metabolic syndrome at the medical checkup. Generally, it has been clarified that over-accumulation of visceral fat causes several life-style related diseases. X-ray CT or MRI is currently the gold standard in medical field but it causes serious invasion of X-ray exposure. An accurate and safe measurement of the visceral fat accumulation status is desired in medical field. In responding to the invasion problem, simple, accurate, and safe equipment of visceral fat estimation has been proposed based on bioelectrical impedance analysis (BIA) [5-7, 14] with considering low invasion. As shown in Fig. 2 and 3, body compositions depend on individuals and have complicated mixture. A patient in Fig. 2 accumulates much visceral fat and low subcutaneous one. On the other hand, we can see much subcutaneous fat and low visceral one in Fig. 3.

1) Measurement Principles and sensing

There are three types of composition which are visceral fat, subcutaneous fat, and lean body. Lean body is not fat and internal organs, muscles, and bones. Each area can be calculated by image processing technology applied to the image of cross sectional area gotten by a CT scan or an MRI as shown in Fig. 2.

Visceral fat area can be calculated by (1) which is the measurement principle of VF.

$$VFA = CSA - SFA - LBA \quad (1)$$

where VFA is visceral fat area, CSA all cross sectional area, SFA subcutaneous area, and LBA lean body area. In the sensing, two types of bioelectrical impedance and the abdominal shape

at umbilical level are measured. As in (1), each area of CSA , SFA , and LBA will derive VFA . The strategy of the measurement is as follows;

1. CSA could have high correlation with the abdominal shape information.
2. SFA could be estimated by the abdominal shape and the internal abdominal impedance.
3. LBA could have inverse correlation with the total body impedance.

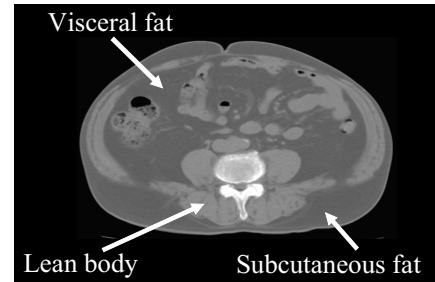


Figure 2. Cross sectional area image at umbilical level

Firstly, let us consider about the abdominal shape information. In a medical checkup, waist circumference is used to diagnose metabolic syndrome. However, it brings less information about the abdominal shape. The shape estimation performance could be improved by using the measurements of the width a and the depth b at abdominal level as shown in Fig. 3, instead of waist circumference. These variables are used in calculating CSA and SFA .

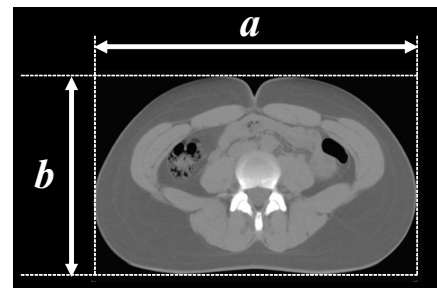


Figure 3. Body shape measurement

In order to measure the total body impedance, the electrodes for turning on electricity are placed on the back of both hands and the instep of both feet with the subjects lying on their back. Eight electrodes for the measurement are placed on surroundings of the waist circumference at umbilical level. These electrodes are placed on the trunk, paired in intervals of 9 cm, centered at the umbilicus with $250 \mu A$ with $50 kHz$. The total body impedance can be obtained as Z_T . Regarding the abdominal surface impedance, the eight electrodes are classified into groups of four. In each group, the electricity is impressed using one electrode, and the impedances of the abdominal surface are obtained by the other electrode as Z_S .

2) Causal Structure Design

Fig. 4 illustrates the causality of VFA estimation considering the relationship between the sensory variables and the measurement principle. The left and the right are the sensory variables and the principle measurement respectively. According to the causal structure, we prepare the variables which are the candidates for constructing the causality. By using the selected variables, multi linear regression was employed to acquire the estimation model. In this step, we carefully considered about nature of the model without over-fitting, multicollinearity, and some other difficulties; especially keeping the notion of the measurement principle. We finally derived the estimation model denoted by the equation (2).

$$\tilde{A}_{VF4} = \alpha_1 a + \alpha_2 b^2 + \alpha_3 Z_S \sqrt{a^2 + b^2} + \alpha_4 / Z_T + \varepsilon \quad (2)$$

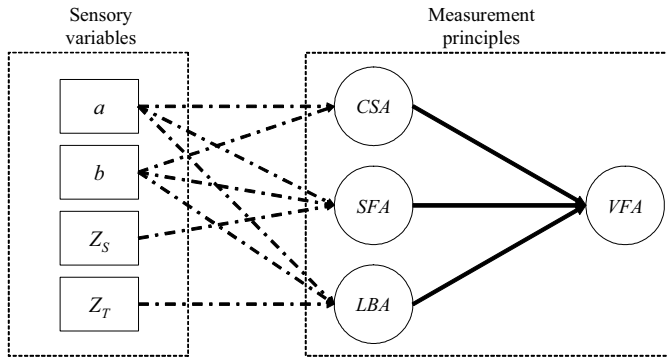


Figure 4. Causality between the sensory variables and the measurement principle

In order to extract the causality for estimating VFA, we designed the following development steps;

1. Preparation of variables according to the measurement principles
2. Selection of the variables by applying AIC and VIF on the sample dataset

In the first step, we prepared the candidates of the variables as possible as used in the estimation equation. The idea here is that the candidates should bring some information about VFA estimation and be understandable from the point view of the measurement principles shown in the Fig. 4. The prepared variables are listed in the table 1.

The second step is the suitable variables selection as a set of them. We employed two different criteria to realize the legitimate model for VFA estimation. Our consideration was to realize both promised performance and transparency according to the measurement principle. The first is the accuracy and simplification of the model without over-fitting to the sample dataset. The second is multicollinearity which causes some difficulties in the estimation results. The problem is caused by an almost linear relationship among dependent variables in the regression model. Akaike Information Criterion (AIC) [8] and Variance Inflation Factor (VIF) [9] are the employed criteria for former and later considerations. The criteria are given by the (3) and (4), respectively.

$$AIC = n \log(2\pi\hat{\sigma}_e^2) + \frac{1}{\hat{\sigma}_e^2} \sum_{i=1}^n \{y - (\alpha_1 x_1 + \dots + \alpha_m x_m + \varepsilon)\}^2 + 2(m+2) \quad (3)$$

where m and n is the numbers of independent variables and data respectively, y a dependent variable, $x_i (i = 1, 2, \dots, m)$ independent variables, $\alpha_i (i = 1, 2, \dots, m)$ coefficient terms, ε error term, $\hat{\sigma}_e$ the standard deviation of estimation errors.

$$VIF_i = 1/(1 - R_i^2) \quad (4)$$

where R_i is the multiple correlation coefficient between the independent variable $x_i (i = 1, 2, \dots, n)$ and the rest of $(n-1)$ variables.

3) Experimental Dataset

We designed the experimental data set by using the three variables of gender, age, and waist circumference which is substituted to for VFA because it could not be used in the recruiting phase. The number of subject is 180 (90 males + 90 females) who were 22 to 80 years old (mean is 49.95) and had from 65.8 to 120 cm of their waist circumferences (the mean 90.09). All of the subjects are measured by both the proposed method and a CT scan as reference values.

4) Experimental Results and Discussions

The results were as follows; the correlation coefficient 0.88, the errors mean -1.38, and the errors standard deviation 27.28. The scatter diagrams of the proposed instrument and the CT scan and waist circumferences and the CT scan are shown in Fig. 5 and 6, respectively. The correlation coefficient between waist circumferences and CT scans is 0.77.

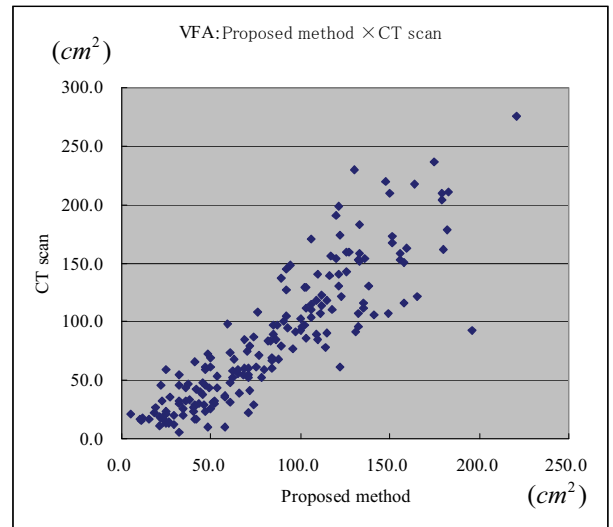


Figure 5. VFA: the proposed method vs. CT scan

As the results, visceral fat areas estimated by the proposed method achieved high correlation with ones by the CT scan. Waist circumference which is used in a medical checkup works

well but the estimation accuracy is lower than the proposed method. Besides, it cannot differentiate VF from subcutaneous one and lean body in principle. According to the scatter diagrams, the method estimates stably from small to huge size of visceral fat volume. Difference plot shown in Fig. 7 would also suggest this nature but is has a tendency of slightly lower estimation as VF goes large. The correlation coefficients of females' VFA and males' are 0.913 and 0.862 respectively. The difference between them is statistically non significance ($p = 0.114$).

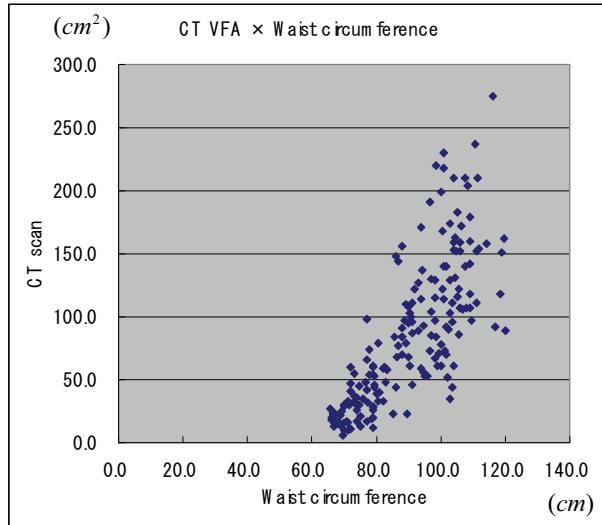


Figure 6. Waist circumference vs. CT scan

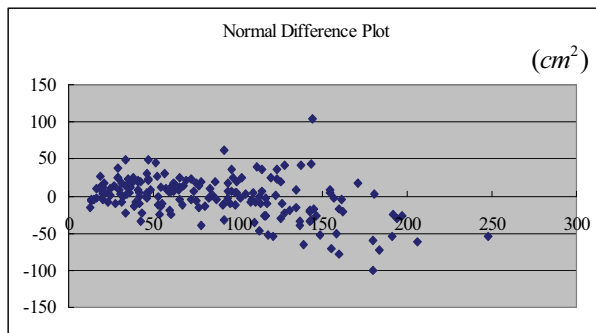


Figure 7. Normal difference plot

B. Heart Rate Estimation

Among vital-signals, heart rate (HR) provides important information of humans' health transit [10] such as an early stage of cardiac disease. It would be pretty important for us to continuously measure our heart rate to know the changes in our daily life. In addition, the variability of heart rate transit provides information of autonomic nerve activity [11]. Through these discussions, it might be clarified that continuous heart rate monitoring in daily life is quite important.

Currently, in a medical domain, an electrocardiography (ECG) is the gold standard system for measuring heart rate transit correctly. However, ECG requires subjects to be put electrodes on and is high intrusive. It is strongly preferred to be sensed in daily life without invasion, intrusion, and unconsciousness. In response to the requirements, heart rate monitoring equipment by using an air pressure sensor (APS) has been developed [11-13].

1) System Configuration

The equipment measures body pressure variability via an air pressure sensor, and extracts heart rate variability from the obtained pressure variability. Fig. 8 shows the system architecture of the equipment. Heart beats are detected and the heart rate variability is calculated by using detected heart beat intervals.

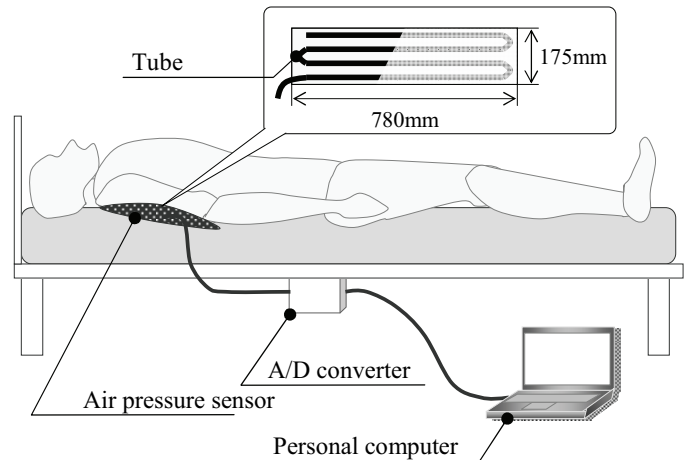


Figure 8. Heart rate extraction equipment

2) Causal Structure Transformation

Heart rate will be estimated as follows; heart beat locations which are R-waves are decided from the changes of the signal caused by heart beat, R-R interval can be calculated by using the R-waves, then heart rate is calculated by using R-R intervals. The causality is designed by considering the similarity between electrocardiograms and air pressure sensors.

Firstly, the conceptual causality by using ECG was designed as shown in Fig. 9. ECG extracts R-waves τ_R from the electrical change caused by heart rate HR and calculate heart rate from their RR intervals τ_{RR} .

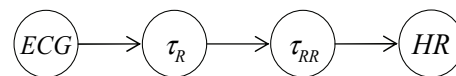


Figure 9. The conceptual causality for HR extraction via ECG

In the next step, the causality was divided into two parts. Because the process of calculating heart rate from RR interval τ_{RR} can be generalized, it was considered as independent causality, which allows the decomposition of the causality as shown in Fig. 10.

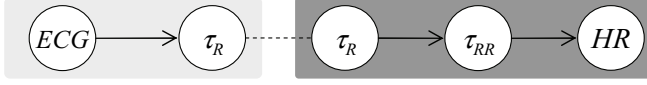


Figure 10. Decomposition of conceptual causality for ECG

Then, the original causality should be modified according to the development equipment. The aforementioned heart rate extraction equipment using an air pressure sensor measures pressure change caused by body movement MV and respiration RSP as well as heart beat HB . The conceptual causality considering the nature is depicted as shown in Fig. 11, which indicates that only HB is extracted from the pressure change, and HR is calculated by τ_{RR} in the same manner as ECG.

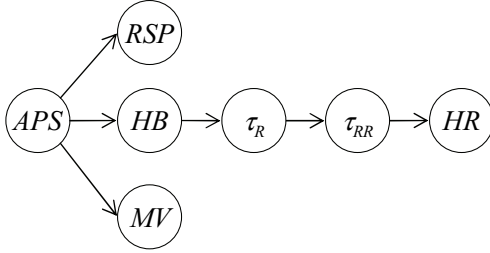


Figure 11. The conceptual causality for HR extraction via APS

The causality shown in Fig. 11 will be decomposed to the partial causalities as shown in Fig. 12 because in the structure, the process of calculating HR from τ_{RR} can be generalized. That is, the causality modification caused by the equipment replacement is limited to the process of extracting τ_R from the air pressure sensor.

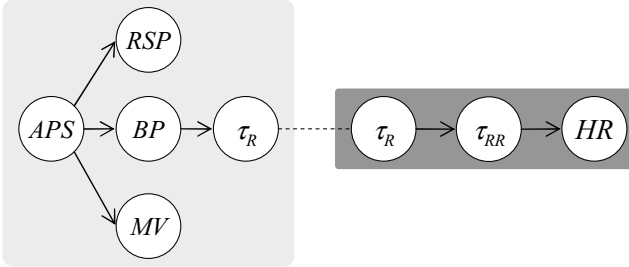


Figure 12. Decomposition of conceptual causality for HR extraction equipment via APS

As shown in Fig.12, τ_R should be extracted according to the changes of waves from the signals which superimpose not only BP , but RSP and MV . It is difficult to determine the precise position of R-waves τ_R by autocorrelation function and peak detection method. We developed formulate knowledge about heart beat by using fuzzy logic [12-14]. In the method, moving averages of pressure changes are calculated and smoothened. Then, the fuzzy logic based on the knowledge

about τ_{RR} is applied to the smoothened pressure changes to extract BP .

3) Experimental Dataset

In the study, we use the dataset which is obtained from seven healthy male subjects by concurrently measuring pressure changes in body with the equipment shown in Fig 8 and the electrocardiogram from an ECG.

4) Experimental Results and Discussions

In this experiment, we compare the method with autocorrelation functions and peak detection and one with fuzzy logic. TABLE I shows correlations between heart rate changes that obtained from the ECG and those that obtained from the heart rate extraction equipment with an air pressure sensor.

The result indicates that the method with fuzzy logic achieved higher performance for all of the subjects. In particular, the correlation to ECG for the subject E is 0.991, which is extremely high. The improvement of the performance is realized by conducting minimum arrangement via consideration for sensors' characteristics based on experts' knowledge.

TABLE I. HR EXTRACTION PERFORMANCE VIA APS

Subjects	Attributes		Correlation coefficient	
	Height [cm]	Weight [kg]	Developed method	AC function
A	175	76	0.973	0.703
B	171	68	0.807	0.389
C	165	50	0.754	0.621
D	171	56	0.872	0.699
E	180	92	0.972	0.658
F	172	55	0.844	0.677
G	170	62	0.737	0.346
Mean	172	65.6	0.851	0.585

C. Discussions on both studies

In the case of visceral fat estimation, the sensing requires intrusion but invasion level is quite low compared with X-ray CT scan which is used in medical field as the gold standard. According to the causality development, the method used knowledge and statistical approach for realizing good performance.

As the case in heart rate estimation, it realizes noninvasive, nonintrusive, and unconscious sensing for heart rate monitoring of body on the bed. The method requires highly sophisticated signal extraction from multiple superimposed original sensory data.

Both cases prove that the causal analysis with hierarchical knowledge and causal analysis method works well against uncertainty in biomedical sensing.

IV. SUMMARIES AND CONCLUSIONS

This article discusses the importance of the ideas of intrusion and consciousness besides invasion in biomedical sensing. The problems to be solved in such noninvasive, nonintrusive, and unconscious sensing is to extract target signals and estimation model from uncertainty information.

Hierarchical knowledge and causal analysis methods are studied and applied to the two biomedical sensing case studies of visceral fat estimation and heart rate monitoring. The former considers noninvasive but intrusive and conscious and the latter realized noninvasive, nonintrusive, and unconscious biomedical sensing. Uncertainties in the both applications are investigated with the knowledge and causal analysis. The article has discussed on the ideas of invasion, intrusion, and consciousness in the biomedical sensing with considering uncertainty and provided the case studies and their experimental results. Biomedical sensing methods would be more sophisticated by considering the notions of the three points in the future.

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