International Journal of Bio-Science and Bio-Technology
Vol. 5, No. 3, June, 2013

Indirect Measurement of Central Aortic Pressure using Carotid and Radial Pulses

Jae Joong Im[1], Ran Wei[2], Young Chul Lim[1], Chan Song Hwang[1],
Hee Sun Kim[3] and Moo Yong Rhee[4]

[1]*Division of Electronic Engineering, Chonbuk National University, Jeonju, Korea*
[2]*School of Electronics and Information Engineering,*
Tianjin Polytechnic University, Xiqing, Tianjin, China
[3] *UnC Co., Ltd., JeonJu, Korea*
[4]*Cardiovascular Center, Dongguk University College of Medicine,*
Ilsan Hospital, Goyang, Korea

lyc951@nate.com

Abstract

Aortic blood pressure is more meaningful than brachial blood pressures for clinical diagnosis, and ambulatory blood pressure monitoring is better predictor for the outcomes than clinical blood pressure monitoring. However, there are few devices which provide continuous central blood pressures and arterial stiffness noninvasively. In this study, pressure sensors were developed to detect two radial and one carotid pulse waveforms. Central aortic pulse, two radial pulses and carotid pulse were recorded simultaneously during surgery. Parameters were extracted and the relationships among them were examined. Standard deviations for radial and carotid pulse pressures were all within the range of ±5 mmHg for every experimental setup. Augmentation index from aortic pulse showed much lower value than that from the radial sites, and the values of averaged augmentation index showed different trends, which might be caused by the different force applied to the pressure sensor on the carotid artery. The observed correlation, not only between the RADI SBP and estimated SBP, but also between the pulse pressure measured by the RADI pressure wire and estimated pulse pressure, proved the usefulness of the estimated central blood pressure obtained from the radial pressure pulse waveform using the ARX model.

Keywords: *Aortic pulse, Blood pressure, Pressure sensor, Carotid pulse, Radial Pulse*

1. Introduction

With the increased longevity of modern societies the relationship between vascular aging and cardiovascular disease has assumed major importance. Especially, increased arterial stiffness is influenced by functional as well as structural changes and may predict vascular damage before the onset of any clinical symptoms. Early researchers used pulse contour analysis of peripheral pressure waveforms to obtain information about arterial stiffness. Pressure waveform at various body sites is a composite of the forward-going and reflected waveforms. However, the relationship between the aortic pressure and peripheral pressure is not well established yet. Such relationship is clinically important because it is central aortic, and not peripheral, pressure waveform which determines left ventricular workload. Therefore, extraction of the parameters from the pressure waveform for central aorta, rather than for peripheral artery may provide better prediction of cardiovascular risk [1-3].

It has been demonstrated that pulse contour analysis is one of the techniques which is simple, reproducible, and known as a good marker of systemic arterial stiffness [2-5]. Pulse waveforms recorded in any arterial site are the combination of both the forward and reflected pulse waves. The forward wave is dependent on the elastic properties of the aorta, whereas the reflected waves from the periphery is dependent on the stiffness of entire arterial tree including travel time from the heart to the periphery and the distance to the major reflecting sites [6]. Therefore, it is documented that the central aortic pressure value is the one which determines left ventricular workload and provides better prediction for cardiovascular disease [7]. However, it is difficult to obtain central aortic pressure waveforms noninvasively. Establishment of transfer function is a solution, and there have been many studies performed for various types of transfer functions, which estimates central pressure waveform from the radial pressure waveforms.

The standard method for central aortic blood pressure measurement uses invasive procedure by inserting catheter in clinical environment. It is used only when necessary because of complexity and involving many risks. Several methods for estimating central pulse waveform were developed by applying transfer function to the radial pulse waveform [8-9]. However, since the relationship between the aortic pressure and peripheral pressure is not well established yet, accuracy of noninvasive central blood pressure measurement devices using peripheral arterial pulse waveforms needs to be improved.

Brachial or radial arteries are the common sites for noninvasive blood pressure measurement. Various methods were being used for peripheral blood pressure measurement, and it is worth noting that the systolic blood pressure and pulse pressure are amplified as the pressure waveforms move from the aorta to the periphery [10-11]. Difference of systolic blood pressure between aorta and radial artery is amounting to 20 mmHg or more but the diastolic pressure does not vary significantly [12-13]. Moreover, ambulatory blood pressure monitoring (ABPM), which provides 24-hour continuous blood pressure values is a better predictor of outcome than clinical blood pressure monitoring (CBPM) [14]. Almost all of the conventional ABPM devices provide blood pressure values by employing an inflatable cuff, which is uncomfortable and inconvenient for long time monitoring. Recently developed ABPM devices are still using traditional inflatable cuff for the calibration of pressure pulse from radial artery [15].

Objective of the study was to develop pressure sensors to detect radial pulses from the wrist and one carotid pulse waveform. Central aortic pulse waveforms were recorded invasively under the clinical setting. Then, meaningful parameters from the waveforms were extracted and analyzed for comparison. Also, transfer function for estimating central aortic pressure waves from radial arterial pulse was established. Then, algorithm for extracting accurate points from pulse contour was established. Finally, compare the previous studies and developed algorithm which obtained AIx form peripheral pressure.

2. Methods

Overall experimental design for the study is illustrated in Figure 1. Two radial pulse waveforms and one carotid pulse waveform were obtained from three pressure sensors, and recorded using MP150 (Biopac Systems Inc., CA) system. Central aortic pulses were acquired invasively using RADI pressure wire system (RadiAnalyzer Xpress Measurement System, St. Jude Medical, USA), which is composed of pressure sensor tip wire and recoding subsystems.

Digital signal processing was applied to the waveforms to extract various meaningful parameters for diagnosis. Finally, the correlation studies for the acquired waveforms were performed to provide the relationships.

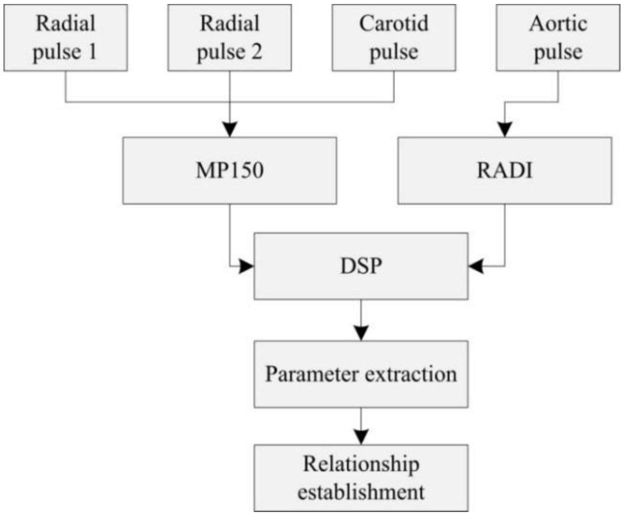


Figure 1. Block diagram for the overall experimental design.

2.1. Sensor design

As shown in Figure 2, piezoresistive pressure sensor was developed for obtaining radial and carotid pulse waveforms. A plastic housing and soft rubber encapsulates each sensor for sensor protection and lossless pressure delivery. The pressure sensor die is sealed by epoxy and senses pressure through gel which is fully filled in the wide hole.

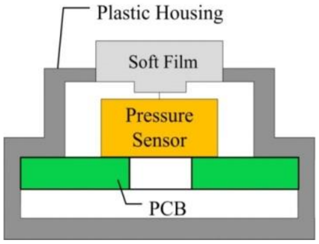
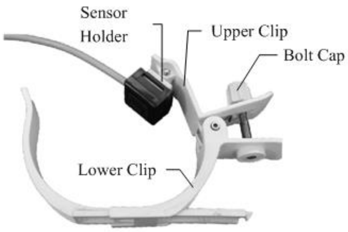


Figure 2. Cross section of the pressure sensor encapsulated inside the plastic housing

Clip and straps were developed for carotid and radial pulse measurements as shown in Figure 3. Carotid pressure sensing module (Figure 3(a)) is composed of sensor holder, upper clip, lower clip and bolt cap. Two straps (Figure 3(b)) were used to fix radial pressure sensors on the wrist over the radial artery. Two sensors were separated and located on the radial artery 2cm apart from each other, and elastic bands with velcro attachment were used to ensure the sensors locating right over the radial artery.



(a) Carotid artery sensor and clip

(b) Radial artery sensors and elastic bands

Figure 3. Fixtures for data collection from carotid artery and radial artery

2.2. Data collection

Clinical experiments were performed at the Cardiovascular Center, Dongguk University College of Medicine, Ilsan Hospital, Korea. Figure 4 shows an example of the pressure pulse waveforms obtained from the aorta using RADI pressure wire system.

Two radial sensors and one carotid sensor were placed before the surgery. Before inserting RADI pressure wire into the aorta, pulse waveforms from both left and right sides of the body were acquired for twenty seconds. After RADI pressure wire insertion, the aortic pulse waveforms, one carotid and two radial pulse waveforms were recorded simultaneously for twenty seconds from the left side of the body. Then, the carotid/radial pulse waveforms and aortic pulse waveforms from the right side of the body were recorded under the same condition. Finally, both left and right sides of carotid/radial pulse waveforms were acquired again after RADI pressure wire had been withdrew.

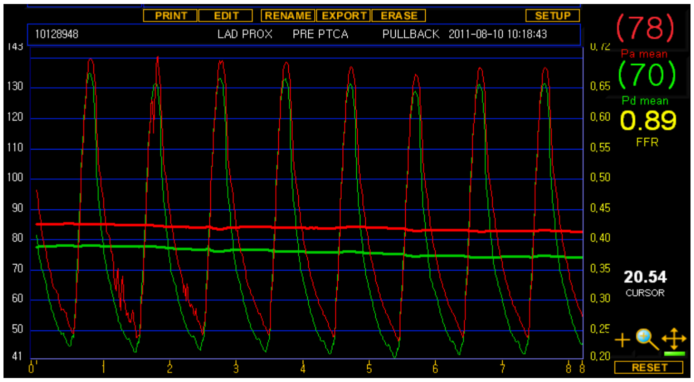


Figure 4. The RADI Pressure wire output (central aortic waveform).

2.3. Data conditioning and transfer function

Pre-processing of the acquired signals was performed prior to the application for establishing transfer function as input and output. It includes 20Hz low pass filter, trend removal, and normalization for removing unwanted noises and trends included in the raw data. Furthermore, brachial blood pressure was measured and used to adjust the radial pressure pulses into the unit of mmHg. It is achieved by setting brachial blood pressure, diastolic values of the radial pulse, and pulse pressure to the same values.

Chen and Fetics performed for establishing forward-going and inverse ARX (autoregressive exogenous) modeled generalized transfer function and Fourier transformed transfer function using central pressure waveform obtained from Millar catheter and radial pulse waveform. They showed that the results based on Fourier transform give the lower accuracy than others.

In this study, order of the ARX model was set at 10th order based on the FPE (Final Prediction Error) method by analyzing relationship between the order size and prediction errors.

$$A(q)y(n) = q^{-k}B(q)u(n) + e(n) = B(q)u(n-k) + e(n)$$

$$TF_{ARX} = \frac{B(q)}{A(q)} = \frac{b_1 q^{-1} + \ldots + b_{nb} q^{-nb}}{1 + a_1 q^{-1} + \ldots + a_{na} q^{-nb}}$$

2.4. Data analysis

Various meaningful parameters from radial artery and central aorta were extracted and analyzed. Since the values of diastolic blood pressure between aorta and peripheral arteries are almost same, the brachial diastolic blood pressure is used to calibrate and compensate for the radial pulse waveform obtained from developed pressure sensor.

Figure 5 represents the parameters extracted from radial pulse waveforms. Several researches have documented that the pulse pressures (PP), and augmentation index (AIx) derived from radial pulse waveform are the most important values for clinical diagnosis. Augmentation index, which depends on ventricular ejection, the timing of reflected waves, may be useful in identifying patients who might benefit from treatment for reducing arterial stiffness. Radial AIx was calculated as P2/P1 × 100%.

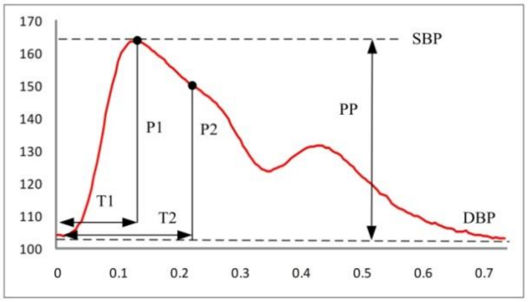


Figure 5. Feature extraction from radial pulse waveform.

Since the carotid pulse is considered same as the central pulse, same parameters were extracted from both central aortic pulse and carotid pulse waveforms. Descriptions of the parameters from both central and carotid pulse waveform are illustrated in Figure 6.

There are critical parameters for central aortic pulse such as central blood pressure, AIx (AP/PP × 100%), and ejection duration (ED).

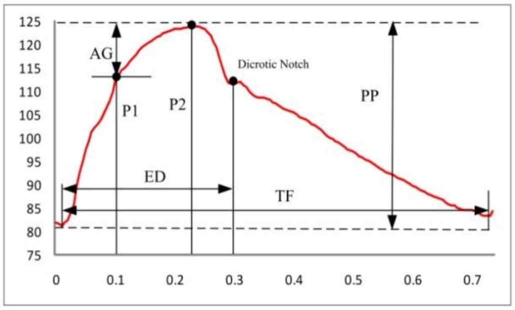


Figure 6. Feature extraction from carotid and central aortic pulse waveform.

3. Results and discussion

Previous studies applied to detect first negative slope zero-crossing 100msec after the 4th derivative. It is obviously clarified that the algorithms between developed by previous studies and this study showed that the -11.5±14.34 point differences and -3.75±1.26 point differences, respectively. As a result, developed algorithm appeared to provide high accuracy for the detection of augmentation point.

Table 1 and 2 are summarized results for comparison among the previous studies by Chen[16] and Fetics[17] and developed algorithm estimated by ITF (individual transfer function) and by GTF (generalized transfer function), respectively. According to the comparison data from the tables, it is clear that estimated parameters extracted from ITF showed higher accuracies than those from GTF. Moreover, developed algorithm showed the minimum AIx deflection when compared with the previous studies.

Table 1. Results for comparison among the previous studies and developed algorithm estimated by ITF

Parameters	Chen[16]	Fetics[17]	Developed Algorithm
SYS_BP (Systolic BP, mmHg)	-0.2±0.9	-0.7±0.8	-2.78±1.08
PP (Pulse Pressure)	-0.2±1.4	-	-2.6±2.31
ED	-	14.7±10.8	13.7±13.8
AIx (% error)	-27±22	-39.5±39.4	5.31±17

Table 2. Results for comparison among the previous studies and developed algorithm estimated by GTF

Parameters	Chen[16]	Fetics[17]	Developed Algorithm
SYS_BP (Systolic BP, mmHg)	0.0±3.7	0.4±2.9	-4.75±3.86
PP (Pulse Pressure)	0.2±3.8	-	-5.29±3.16
ED	-	19.8±24.8	19.3±20
AIx (% error)	-30±45	-50±232	13.04±27.26

According to the experimental protocol, aortic pulse waveforms, carotid pulse waveforms and radial pulse waveforms from two different sites were acquired in clinical environment. Central aortic pulse waveform was used as a reference for evaluating carotid and radial pulse waveforms obtained by developed pressure sensors. Twenty-second of pulse waveforms under three different clinical setups (before RADI insertion, during RADI insertion and after RADI withdrawal) were acquired and analyzed to extract meaningful parameters.

Averaged parameter values of both PP and AI for the two radial sensors are shown in Table 3. It was found that standard deviations for the values of radial pulse pressure from both sensor1 and sensor2 were within the range of ±5 mmHg for every experimental setup. Also, it was notices that the parameter values for the pulses from two different radial sites (sensor1 and sensor2) were different because of the direction of blood flow from the heart. As expected, PP from aorta showed lower values than that from the radial sites. The values from two radial sites were almost similar regardless of inserting or withdrawing of RADI pressure wire. AI from aortic pulse showed much lower value than that from the radial sites as expected.

Table 3. Summary of the averaged parameter values for radial and aortic pulses

	PP (mmHg)	AI (%)	Period
Radial 1	42.5 ± 3.5	91.6± 4.4	Before RADI insertion
	42.8 ± 2.2	91.9± 1.0	During RADI insertion
	52.5 ± 1.9	90.5± 1.0	After RADI withdrawal
Radial 2	47.4±3.0	86.8± 1.3	Before RADI insertion
	48.2± 2.9	88.1± 0.9	During RADI insertion
	52.7± 1.9	88.8± 1.4	After RADI withdrawal
Aorta	43.1 ± 4.6	43.0 ± 3.8	

Since the carotid pulse waveform is usually considered same as the aortic pulse waveform, averaged values of the parameters from central and carotid pulses during RADI wire insertion were compared to find relationship and the resulting values are summarized in Table 4. Among those parameters shown in Table 4, PP, P2, and AG, which are important since they reveal the reproducibility of the acquired signal, were closely examined. Pulse pressure of carotid pulse normally shows higher value than that of central pulse, however, the results showed that the carotid pulse pressure was lower than central pulse pressure. It probably was caused by the different force applied to the pressure sensor on the carotid artery.

The values of averaged augmentation index show different trends and large standard deviation for all three clinical setups. It probably was caused by the different force applied to the pressure sensor on the carotid artery. However, since the outcome shows the consistent results, it is promising for continuing detailed study with enough number of patients.

Table 4. Summary of the averaged parameter values for carotid and aortic pulses

Parameter (Unit)	Aorta	Left carotid	Right carotid
PP (mmHg)	43.1 ± 4.6	39.7 ± 4.0	38.8 ± 5.0
T1 (msec)	66.3 ± 5.1	101.1 ± 21.0	95.6 ± 17.5
T2 (msec)	196.6 ± 25.6	170.6 ± 34.0	179.9 ± 33.6
TF (msec)	699.8 ± 28.1	666.2 ± 55.6	702.1 ± 42.3
P1 (mmHg)	108.7 ± 3.6	149.1 ± 5.9	144.0 ± 8.2
P2 (mmHg)	127.3 ± 4.4	152.9 ± 6.0	150.3 ± 7.2
AG (mmHg)	18.6 ± 1.4	3.8 ± 2.6	6.3 ± 2.9
AIx (%)	43.0 ± 3.8	9.6 ± 6.3	17.1 ± 8.6
ED (msec)	274.7 ± 24.8	306.6 ± 12.5	307.7 ± 31.3

4. Conclusions

Among various types of blood pressure device, there exit problems of accuracies and convenience for monitoring. Therefore, the study was performed for the development of blood pressure monitoring device which provides 24-hour continuous blood pressure values without using inflatable cuff. It also is necessary to provide central aortic blood pressure and aortic stiffness noninvasively. Once the peripheral pulse waveforms were obtained accurately from various arterial sites, the central aortic pressure waveforms could be compared with those pulse waveforms.

Pressure sensors for obtaining accurate pulse waves from the radial and carotid artery using piezoresistive pressure sensor were developed, and the sensor were sensitive enough to provide accurate arterial pulses. Differences of the parameter values extracted from two different radial arterial sites revealed the similar patterns for both right and left sides as expected. It suggests the possibility of using two radial sensors for applying adequate forces to the artery based on the comparison of outputs form the two sensors.

Parameter values for pulse pressure extracted from different sites show that the carotid pulse pressure values were lower and radial pulse pressure values were greater than central pulse pressure values. The reason for this suggests necessities for the modification of calibration process using diastolic pressure values of central pulse waveform. Parameter values for augmentation index extracted from different sites showed that the values for carotid and radial arteries are lower and higher than that of central pulse waveform, respectively.

It was concluded that once the peripheral pulse waveforms were obtained accurately from various sites, the central aortic pressure waveforms could be derived. Many types of central pressure waveforms were synthesized for the purpose of evaluation, however, since the physiological signal varies a lot from person to person, further in-depth studies are necessary to the accuracy of the parameter extraction process.

Further research will be focused on finalizing pressure sensors with the use of air pumps for controlling applying forces to the two pressure sensors on the radial artery. Additional clinical experiments will also be performed with enough data collection for analysis. Moreover, estimation of central aortic pressure waveform from radial artery pulse waves using transfer function will be performed, and direct comparison of pulse waveforms between central aortic pulse and carotid pulse will also be performed. Results of this study could be used as a valuable data for developing 24-hour continuous blood pressure monitoring device without using inflatable cuff for early diagnosis of cardiovascular diseases.

References

[1] I. B. Wilkinson, H. MacCallum, L. Flint, J. R. Cockcroft, D. E. Newby and D. J. Webb, "The influence of heart rate on augmentation index and central arterial pressure in humans", The Journal of Physiology, vol. 525, no. 1, **(2000),** pp. 263-270.

[2] M. F. O'Rourke and D. E. Gallagher, "Pluse wave analysis", Journal of Hypertension, vol. 14, no. 5, **(1996),** pp. 147-157.

[3] R. P. Kelly, S. C. Millasseau, J. M. Ritter and P. J. Chowienczyk, "Vasoactive Drugs Influence Aortic Augmentation Index Independently of Pulse-Wave Velocity in Healthy Men", Hypertension, vol. 37, **(2001),** pp. 1429-1433.

[4] K. S. Tyrrell, A. Newman, E. M. Simonsick, R. Havlik, M. Pahor, E. Lakatta, H. Spurgeon and P. Vaitkevicius, "Aortic stiffness is associated with visceral adiposity in older adults enrolled in the study of health, aging, and body composition", Hypertension, vol. 38, **(2001),** pp. 429-433.

[5] P. Boutouyrie, A. I. Tropeano, R. Asmar, I. Gautier, A. Benetos, P. Lacolley and S. Laurent, "Aortic stiffness is an independent predictor of primary coronary events in hypertensive patients", Hypertension, vol. 39, **(2002),** pp. 10-15.

[6] O. B. Robert, L. M. Douglas, P. Z. Douglas and L. Peter, "M. F. Braunwald's Heart Disease: A Textbook of Cardiovascular Medicine", 2-Volume Set (Google eBook), Elsevier Health Sciences **(2011).**

[7] A. D. Protogerou, T. G. TPapaioannou, J. Blacher, C. M. Papamichael, J. P. Lekakis and M. E. Safar, "Central blood pressures: do we need them in the management of cardiovascular disease? Is it a feasible therapeutic target?", Journal of Hypertension, vol. 25, no. 2, **(2007)**, pp. 265-272.

[8] S. Wassertheurer, J. Kropf, T. Weber, M. Van der Giet, J. Baulmann, M. Ammer, B. Hametner, C. C. Mayer, B. Eber and D. Magometschnigg, "A new oscillometric method for pulse wave analysis: comparison with a common tonometric method", Journal of Human Hypertension, vol. 24, no. 8, **(2010)**, pp. 498-504.

[9] K. Takazawa, H. Kobayashi, I. Kojima, A. Aizawa, M. Kinoh, Y. Sugo, M. Shimizu, Y. Miyawaki, N. Tanaka, A. Yamashina and A. Avolio, "Estimation of central aortic systolic pressure using late systolic inflection of radial artery pulse and its application to vasodilator therapy", Journal of Hypertension, vol. 30, no. 5, **(2012)**, pp. 908-916.

[10] J. Topouchian, R. E. Feghali, B. Pannier, S. Wang, F. Zhao, K. Smetana, K. Teo and R. Asmar, "Arterial stiffness and pharmacological interventions-the Transcend Arterial Stiffness Substudy (TRANS study)", Vascular Health and Risk Management, vol. 3, no. 4, **(2007),** pp. 381-387.

[11] F. U. Mattace-Raso, T. J. van der Cammen, A. Hofman, N. M. van popele, M. L. Bos, M. A. D. H. Schalekamp, R. Asmar, R. S. Reneman, A. P. G. Hoeks, M. M. B. Breteler and J. C. M. Witteman, "Arterial stiffness and risk of coronary heart disease and stroke: the Rotterdam Study", Circulation, vol. 113, **(2006),** pp. 657-663.

[12] G. M. London and B. Pannier, "Arterial functions: how to interpret the complex physiology", Nephrology Dialysis Transplantation, vol. 25, no. 12, **(2010)**, pp. 3815-3823.

[13] D. Hejtmánková, R. Dvořák, M. Drahanský and F. Orság, "A new method of finger veins detection", Journal of Bio Science and Bio-Technology, vol. 1, no. 1, **(2009)**, pp. 11-16.

[14] E. O'Brien, "Twenty-four-hour ambulatory blood pressure measurement in clinical practice and research: a critical review of a technique in need of implementation", Journal of Internal Medicine, vol. 269, no. 5, **(2011)**, pp. 478-495.

[15] D. Nair, S. Y. Tan, H. W. Gan, S. F. Lim, J. Tan, M. Zhu, H. Gao, N. H. Chua, W. L. Peh and K. H. Mak, "The use of ambulatory tonometric radial arterial wave capture to measure ambulatory blood pressure: the validation of a novel wrist-bound device in adults", Journal of Human Hypertension, vol. 22, no. 3, **(2008)**, pp. 220-222.

[16] C. H. Chen, E. Nevo, B. Fetics, P. H. pak, F. C. P. Yin, W. L. Maughan and D. A. Kass, "Estimation of central aortic pressure waveform by mathematical transformation of radial tonometry pressure", Circulation, vol. 95, **(1997),** pp. 1827-1836.

[17] B. Fetics, E. Nevo, C. H. Chen and D. A. Kass, "Parametric model derivation of transfer function for noninvasive estimation of aortic pressure by radial tonometry", IEEE Transactions on Biomedical Engineering**,** vol. 46, **(1999),** pp. 698-706.

Authors

Jae Joong Im

· 1983: Department of Electronic Engineering, Konkuk University, Korea (bachelor's)
· 1988: Department of Biomedical Engineering, Texas A & M University, USA (Master)
· 1991: Department of Biomedical Engineering, Texas A & M University, USA (Ph.D.)
· 1992 - 1998: Department of Biomedical Engineering, Inje University, Korea, Assistant professor
· 1998 - present: Division of Electronic Engineering, Chonbuk National University, Korea, Professor

Ran Wei

· 2004 : School of Electronics and Information Engineering, South-Central University for Nationalities, China. (Bachelor’s)
· 2008 : Division of Electronic Engineering, Chonbuk National University, Korea (Master)
· 2012 : Division of Electronic Engineering, Chonbuk National University, Korea (Ph.D.)
· 2012 – present : School of Electronics and Information Engineering, Tianjin Polytechnic University, China, Lecturer

Young Chul Lim

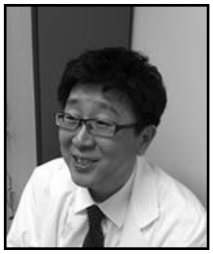
· 2012: Division of Electronic Engineering, Chonbuk National University, Korea (bachelor's)
· 2012 - present: Division of Electronic Engineering, Chonbuk National University, Korea (Master Course)

Chang Song Hawng

· 2012: Division of Electronic Engineering, Chonbuk National University, Korea (bachelor's)
· 2012 - present: Division of Electronic Engineering, Chonbuk National University, Korea (Master Course)

Hee Sun Kim

· 1997 : Department of Control and Instrumentation Engineering, Chonbuk National University, Korea (bachelor's)
· 1999 : Intelligent Control, Chonbuk National University, Korea (Master)
· 2006 : Intelligent Home Network, Chonbuk National University, Korea (Ph.D.)
· 2008 : Chonbuk National University, Post-Doc
· 2008 - present: UnC Co., Ltd., JeonJu, Korea, CEO



Moo Yong Rhee

· 1988: College of Medicine, Seoul National University, Korea (bachelor's)
· 1990: Department of Internal Medicine, Seoul National University, Korea (Master)
· 1995: Department of Internal Medicine, College of Medicine, ChungbukNational University, Korea (Ph.D.)
· 1998 - 1999: Department of Internal Medicine, College of Medicine, Dankook University, Korea, Instructor
· 2000 - 2003: Department of Internal Medicine, College of Medicine, Dankook University, Korea, Assistant Professor
· 2004 - 2005: Department of Internal Medicine, College of Medicine, Dankook University, Korea, Associate Professor
· 2005 - 2008: Department of Internal Medicine, College of Medicine, Dongguk University, Korea, Associate Professor
· 2009 - Present: Department of Internal Medicine, College of Medicine, Dongguk University, Korea, Professor, Director of Cardiovascular Center, Dongguk University Ilsan Hospital