International Journal of Innovative Technology and Exploring Engineering (IJITEE)
ISSN: 2278-3075 (Online), Volume-9, Issue-7, May 2020

Wave Detection of Acceleration Plethysmogram Based on a Closed-Loop Feedback Mechanism

Jae Mok Ahn, Jeom Keun Kim

***Abstract*: Acceleration plethysmogram (APG), which corresponds to the second derivative of the photoplethysmogram (PPG) is a noninvasive method for investigating arterial wall thickness and predicting cardiovascular diseases. To perform an APG wave analysis, five inflection points of the APG waveform (a, b, c, d, and e waves) must be successfully obtained. However, an abrupt change in PPG amplitude due to various physiological conditions and patient's movement has made it very difficult to detect the five waves of the APG waveform in real time. Therefore, to resolve this problem, two stabilization methods for PPG and APG amplitudes were proposed based on a closed-loop feedback amplitude control mechanism. The regulation of PPG amplitude was rapidly carried out in four cardiac cycles by controlling the driving current to a light emitting diode (LED) through pulse width modulation (PWM). Two predetermined amplitude levels were applied to adjust the 1st and the 2nd derivatives of the PPG simultaneously when the wave detection algorithm failed to detect even one of five waves. Forty measurements of the APG signal on an index fingertip were performed to verify a closed-loop feedback amplitude control mechanism (CLFACM). The values of the t statistic (statistical significance) for the a, b, c, d, and e wave groups were 1.08292 (p=0.2855), 0.19607 (p=0.8456), 0.28955 (p=0.7737), 0.39467 (p=0.69467), and 0.50973 (p=0.6131), respectively. To identify waves of extreme values away from normality, the coefficient of kurtosis was obtained; the smallest value was obtained for the d wave (0.07335), and the largest value was obtained for the e wave (3.9456). The results suggested that the in-group waves did not significantly differ. The CLFACM played an important role in increasing the success rate of accurately detecting five waves from the APG signal.*

***Keywords*: Acceleration plethysmogram, arterial wall thickness, photoplethysmogram, closed-loop feedback control, pulse width modulation, physiological condition.**

I. INTRODUCTION

Aging is linked to structural changes of the arterial wall of blood vessels [1, 2]. Arterial wall thickness and stiffness increase with age [3]. Increased arterial wall thickness indicates that cardiovascular related disease may be related to arterial stiffness [4]. The changes in blood volume of the microvascular bed of tissue during the cardiac cycle are depicted using a photoplethysmogram (PPG) waveform that consists of a pulsatile ("AC") physiological waveform and a slowly varying ("DC") waveform as shown in Fig. 1. The minimal and the maximal variations in PPG amplitude in one cardiac cycle correspond to changes in blood volume and vascular structure. The PPG signal consisting of the AC and DC waveforms is widely accepted in various clinical applications because it can provide vascular information about the cardiovascular system [5]. A typical PPG system contains a light source that emits light to a tissue and a photodetector that measures the reflected or transmitted light from the tissue. The amount of transmitted light obtained by the photodetector placed on the opposite of a light emitting diode (LED) on a fingertip is proportional to the blood volume variations in the microvascular bed of tissue [6]. Most common PPG sensors use an infrared LED (IR-LED) as the light source because it penetrates more deeply into tissue; however, IR-LED is vulnerable to body movement. A red LED (R-LED) is used here because it penetrates moderately into tissue and can provide a PPG waveform that is more accurate compared with that from IR-LED. The 2nd derivative of the PPG signal with respect to $\Delta t = 2$ ms, which is called the acceleration plethysmogram (APG), makes it possible to extract clinical information regarding arterial status [7, 8]. The APG waveform replaces the PPG waveform to stabilize the baseline and intensify the five components of the waveform compared with that derived from the PPG waveform. For an APG waveform analysis, every inflection point must be obtained from the baseline, with the points greater than the baseline being positive and the points lower than the baseline being negative. Accurately detecting the peak values of each reflection (wave) plays a critical role in evaluating vascular elasticity or screening for arteriosclerotic illness [9, 10]. Although the detection methodology for the a, b, c, d, and e waves from the APG waveform is not fully established, APG signals may be useful in clinical areas. For instance, their use has been considered for the aging field to obtain vascular information about atherosclerosis, which is a disease in which plaque builds up inside the arteries. Unfortunately, the physiological sampling waveforms include signal artifacts, such as motion artifacts, electronic noises, signal distortion, sensor issues, and random noises, as well as amplitude variations. These problems come with APG waveforms even after careful filtering of the raw signal, i.e., PPG. For this reason, an automatic control mechanism for amplitude stabilization of both PPG and APG signals is needed to improve the reliability of the vascular indicators computed from APG data. In [11], the authors proposed a digital IIR methodology based on the use of an optimal sampling frequency of 1 kHz in combination with an analog Sallen-Key second-order active low-pass filter for removing motion artifacts from PPG signals.

Revised Manuscript Received on May 30, 2020.
***** Correspondence Author
Jse Mok Ahn*, School of Software, Hallym University, Chuncheon-si, Gangwon-do, South Korea. Email: ajm@hallym.ac.kr
Jeom Keun Kim, School of Software, Hallym University, Chuncheon-si, Gangwon-do, South Korea. Email: jkim@hallym.ac.kr

In [12], vascular diseases were assessed according to the vascular aging index obtained by analyzing five waves. The PPG amplitude is largely affected by changes of the blood volume inside blood vessels due to many physiological conditions, such as aging speed, circulatory conditions, and breathing. In addition, the shape and amplitude of PPG signals differ from subject to subject in even the same age group and from position to position such as supine or prone. Therefore, in this study, an amplitude-controlled algorithm for APG and PPG signals, which is called a closed-loop feedback amplitude control mechanism (CLFACM), is proposed to accurately obtain components of the APG wave, and amplifies even low amplitude PPG signals rapidly to a certain level and then maintains the amplitudes of the 1st and 2nd derivatives of the PPG at a predetermined level.

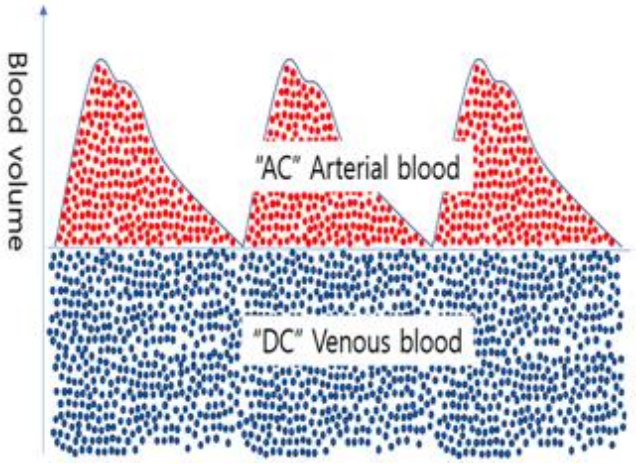

Fig. 1. PPG signal corresponding to a change in arterial blood volume on a finger bed.

II. STABILIZATION OF PPG SIGNALS

PPG is an optical measurement technology that can be used to detect blood volume changes on the finger bed. Inside a fingertip sensor, an R-LED and a photodiode are placed on two opposite sides and facing each other. The PPG's waveform represents the peripheral pulse corresponding to skin blood volume pulsation, which is synchronized to the heartbeat. However, the PPG is weak and noisy, including the dynamic range of its amplitude. Furthermore, the baseline of the signal largely drifts even during rest or when emotional change takes place. Therefore, proper amplification and drift removal with a filtering circuit are needed for stabilization of the PPG signal. Therefore, a circuit topology for stabilizing the PPG amplitude based on closed-loop feedback control and the remove Gaussian noise and drift was developed as shown in Fig. 2. At the first stage in which the optical sensor is applied, a fingertip is illuminated by the R-LED when it is plugged into the sensor. The intensity of the transmitted light is dependent on the blood perfusion and regulated by controlling the input current to the R-LED through a pulse width modulation (PWM) signal, which is based on a microcontroller (MSP430F6638, Texas Instrument Inc., USA). The PWM signal is generated in real time while monitoring changes in the amplitude of a PPG signal, and then the PWM-controlled PPG signal is input to the microcontroller again, which is called the PPG-CLFAM. The duty cycle of the PWM is automatically increased or decreased according to changes in the PPG amplitude. The PPG-CLFACM maintains the desired PPG amplitude, which results in an improvement of APG wave detection. Fig. 3 shows the activation of the peak detection algorithm when the PPG signal is stabilized by the CLFACM. At the first stage, a PNP transistor is added to regulate the driving current by the PWM. The PWM module is locked when the PPG amplitude approaches close to a target level with an error range of ±10% in four cardiac cycles. A peak detection algorithm unlocks the PWM module above or under the specified error range. The purpose of the PPG-CLFACM is to maintain an optimal signal amplitude at the final output, despite continuous changes in the signal amplitude at the output of the fourth stage.

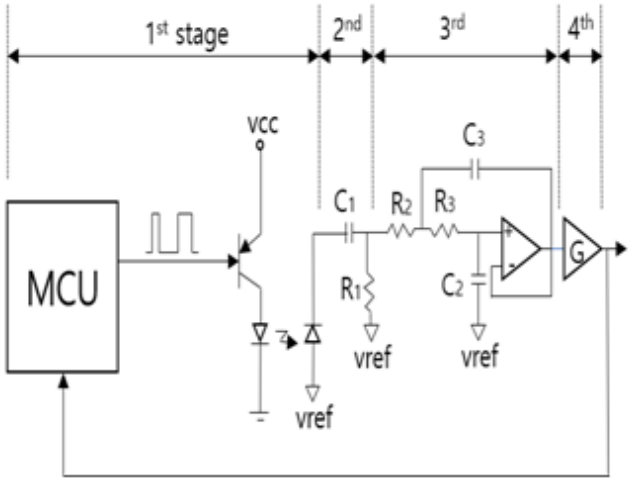

Fig. 2. Circuit topology for the PPG-CLFACM and removal of drift and noise.

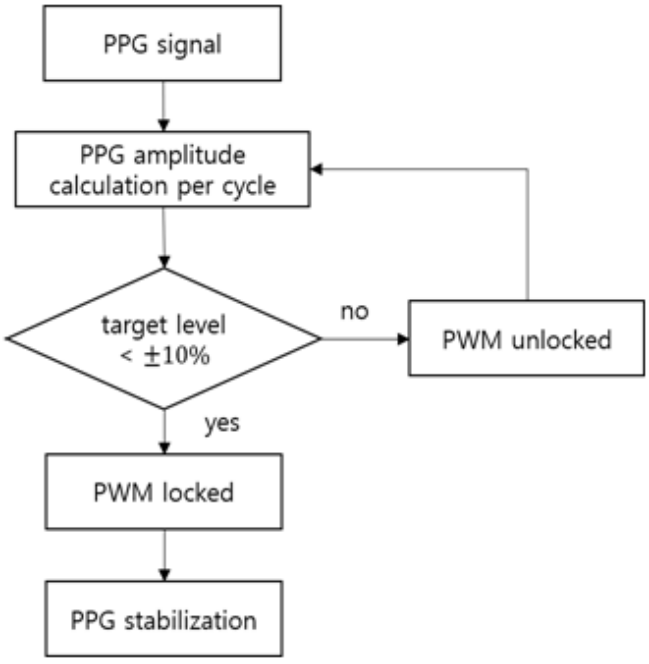

Fig. 3. Feedback process for the stabilization of the PPG signal.

At the second stage, an analog high-pass filter was used to eliminate a drifting baseline with very low frequency below 0.3 Hz from a higher frequency signal. At the third stage, the low-pass filter using the Sallen-Key architecture was designed as an active filter with a unit gain to attenuate the noise inherent in the PPG waveform.

The transfer function for the entire circuit, which is the product of two separate transfer functions except for the output gain amplification at the fourth stage, is as follows:

$$H(s) = \frac{sR_1C_1}{1+sR_1C_1} \times \frac{1}{1+sC_2(R_2+R_3)+s^2R_2R_3C_2C_3} \quad (1)$$

Fig. 4 shows the frequency response of the transfer function in (1). The PPG recording over a short-term period was obtained from the index finger site using HRV analyzer (TAS9VIEW/Canopy9 RSA, IEMBIO Ltd., Chuncheon-si, South Korea), and it was used to apply all of the proposed algorithms.

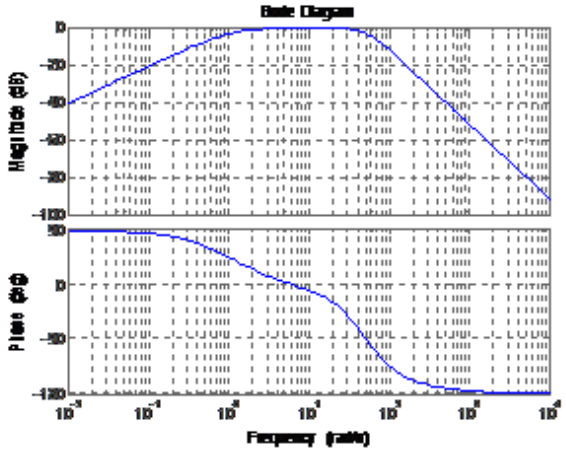

Fig. 4. Frequency response for a sequential combination of a 1st order passive high-pass filter and 2nd order active Sallen-Key low-pass filter.

III. STABILIZATION OF THE APG SIGNAL

The characteristics of the APG waveform provide clinical information about arterial stiffness, which is associated with cardiovascular risk factors and atherosclerosis, based on the vascular status [13]. The extraction of five inflection points (a, b, c, d, and e waves) of the APG wave per cardiac cycle depends on whether vascular stiffness or arteriosclerotic illness has occurred. The PPG waveform can detect each one reflection wave over both systolic period and diastolic period, whereas the APG waveform can detect four systolic reflection waves (a, b, c, and d waves) and one diastolic reflection wave (e wave) [5]. To increase the success rate of accurately five waves from the APG, multiple methods have been studied, such as wavelet transform and linear model comparison [9, 14, 15]. Our study stabilized the APG amplitude based on the CLFACM (APG-CLFACM) to facilitate wave detection in terms of variation and noise before applying a wave detection algorithm. The PPG amplitude was already stabilized by controlling the input current into an R-LED through the PWM at the beginning stage of a photodetector. However, variation in the APG amplitude may remain large due to a variety of situations. Therefore, an auto gain control mechanism based on the microprocessor, namely, APG-CLFACM, was introduced for adjusting both the first and second derivative amplitudes. Fig. 5 shows the flow chart depicting how the APG-CLFACM implements a proper wave detection algorithm. Two predetermined amplitude levels were used to simultaneously adjust the 1st derivative first, and then the 2nd derivative of the PPG only when the wave detection algorithm failed to detect one of the five inflection points. The output of the APG amplitude is fed to the derivatives of the PPG amplitude to compare the signal to a predetermined level to identify errors between two consecutive amplitudes. This APG-CLFACM process continues until the error range approaches a predetermined level.

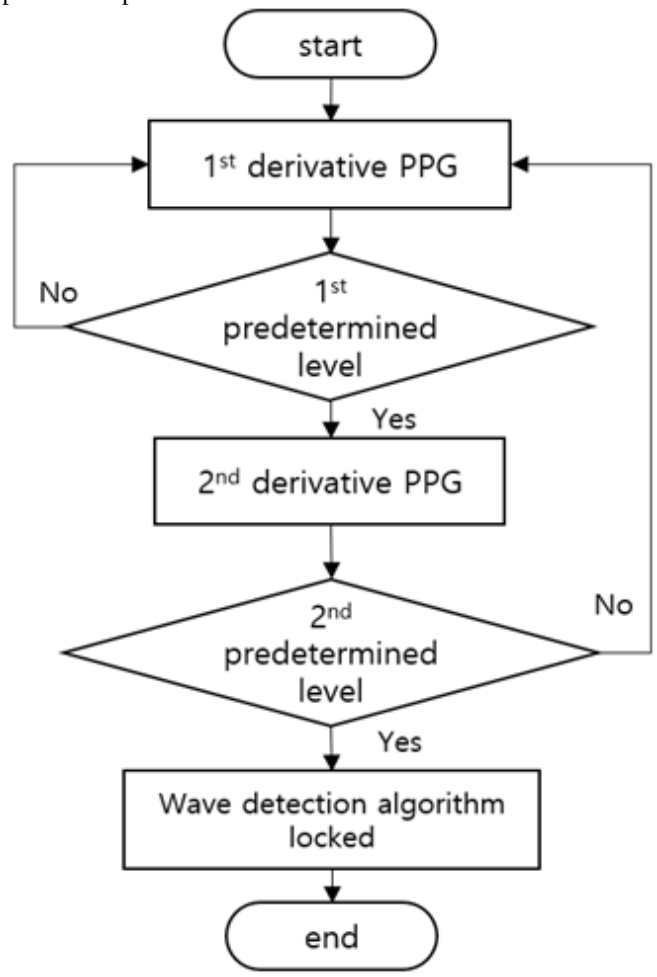

Fig. 5. Flow chart for the APG wave detection algorithm with two predetermined levels based on the APG-CLFACM.

The internal gain controller is locked when the APG amplitude enters a predetermined level with an error range of ±10%, whereas the internal gain controller is unlocked above or under an error range of ±10%. The wave detection algorithm in the on-chip is performed to extract five waves if such a lock situation is met. Fig. 6 illustrates two predetermined levels for controlling the amplitudes of the 1st derivative and the 2nd derivative of the PPG signal based on the APG-CLFACM.

IV. STATISTICAL ANALYSIS

Statistical analyses were performed using a statistics software program (MedCalc, Ostend, Belgium) to investigate the repeatability and reliability of the five waves of the APG waveform over 40 measurements. The coefficient of skewness was calculated to determine whether the data distribution has a skewness near zero. Negative values for the skewness indicate data that are skewed left, and positive values for the skewness indicate data that are skewed right. Skewed left means that the left tail is long relative to the right tail.

The coefficient of kurtosis was calculated to confirm whether the wave data have a standard normal distribution. Negative kurtosis indicates a light tailed distribution, and positive kurtosis indicates a heavy tailed distribution.

If the coefficients of skewness and kurtosis have a value near zero and a negative value, respectively, then the wave detection algorithm based on the CLFACM could be well established. One sample t-test was performed to confirm the statistical significance between the sample mean and the desired value for each wave. It was not important in this study to check the participant's health status because the purpose of the study was to investigate the five waves of the APG waveform that affect vascular status.

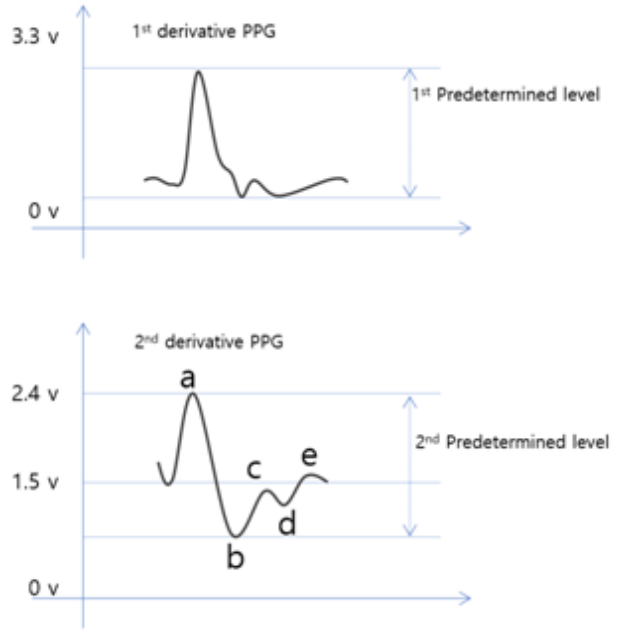

Fig. 6. APG-CLFACM for simultaneously regulating the amplitude on both the 1st derivative and 2nd derivative PPG to extract the five waves of the APG waveform.

V. RESULT AND DISCUSSION

Five waves (a, b, c, d, and e waves) of the APG waveform were measured to predict the vascular status, and the APG aging index was defined as follows [16]:

$$\text{Aging index} = (b - c - d - e) / a \quad (2)$$

Table- I demonstrates that when an optimal wave detection algorithm that includes the PPG-CLFACM and APG-CLFACM was applied, the five waves indices were statistically analyzed. The unit of all waves is mV because the microcontroller detected discrete values by 12-bit analog to digital conversion to convert an analog voltage of 0 V to 2.5 V ranges. The a wave has a clear peak at the systolic rise of the blood pressure compared to the other waves. For the a wave, the relative standard deviation (RSD) and standard error of the mean (REM) were 0.0200 (2%) and 2.8626, respectively. The a wave of the APG shown in Fig. 6 includes a signal component at higher frequency (approximately 40 Hz). Therefore, the cutoff frequency of the low-pass filter for APG signals was limited to 50 Hz. The identification of higher frequencies similar to the a wave requires a more precise detection algorithm. The standard deviation (SD) of the a wave was 18.1048, which was the lowest value compared to the other waves. The coefficient of skewness (-1.0522, p=0.0084) indicated that the data distribution was skewed left and deviated from normality. However, the coefficient of skewness of the d wave had a positive value that was closest to zero at 0.5859 (p=0.1133), meaning that the data distribution was skewed right and did not deviate significantly from normality. The RSD and REM of the d wave data were -0.1367 (-13.67%) and 4.6875, respectively. The detection capability of the d wave was not high because of the relatively high RSD, and the coefficient of skewness for the d wave had the lowest value near zero. The distinguishing feature of the d wave group (n=40) was the standard normal distribution with a wider domain. Based on a one-sample t test, the t value of the a and d waves with a significance level of 95% were 1.08292 (p=0.2855) and 0.39467 (p=0.6952), respectively, as displayed in Table- II. The peaks of the a and b waves were positive if they were above the baseline and negative if they were under the baseline. The b wave is the first minimum after the a wave. The ratio of the two waves, b/a, was correlated with arterial distensibility and could be used to evaluate atherosclerosis [17]. Therefore, the amplitudes and contours of the a and b waves, or the value of b/a of the APG waveform should be significantly considered. The coefficients of skewness and kurtosis for the b wave were 1.0367 (p=0.0092) and 0.3820 (p=0.4662), respectively, and the D'Agostino Pearson test for normal distribution obtained a value of p=0.0259. Kurtosis identifies whether the tails of a given distribution contain extreme values, and the distribution of the b wave data has heavier tails, which is called a leptokurtic distribution because the coefficient of kurtosis is higher than zero. An assessment of the stiffness of the elastic arteries may be affected by extreme b wave values. The coefficients of kurtosis for the c, d, and e waves were -0.4653 (p=0.5553), 0.07335 (p=0.7400), and 3.9456 (p=0.0032), respectively. The highest coefficient of kurtosis was found for the e wave; however, the e wave does not significantly reflect the distensibility of peripheral arteries. The values of the t statistic with statistical significance for the a, b, c, d, and e waves were 1.08292 (p=0.2855), 0.19607 (p=0.8456), 0.28955 (p=0.7737), 0.39467 (p=0.69467), and 0.50973 (p=0.6131), respectively. The smallest t statistic with the highest p value was found for the b wave, meaning that the b wave group is very similar.

Table- I. Statistical analysis of a normal distribution for five waves (a, b, c, d, and e waves) of the APG waveform.

	a	b	c	d	e
n	40	40	40	40	40
Min.	858	-686	-405	-265	156
Max.	920	-639	-249	-140	218
Mean	903	-674.58	-308.08	-216.85	196.00
Median	904	-678	-296	-218	202
SD	18.1048	13.7092	42.0472	29.6462	12.4076
Coefficient of skewness	-1.0522 p = 0.0084	1.0367 p = 0.0092	-0.7170 p = 0.0573	0.5859 p = 0.1133	-1.5581 p = 0.0004

Coefficient of kurtosis	0.3565 p = 0.4848	0.3820 p = 0.4662	-0.4653 p = 0.5553	0.07335 p = 0.7400	3.9456 p = 0.0032
D'Agostino-pearson test for normal distribution	p = 0.0244	p = 0.0259	p = 0.1380	p = 0.2701	p < 0.0001

Table- II. Statistical analysis of one sample t-test for five waves (a, b, c, d, and e waves) of the APG waveform.

	a	b	c	d	e
Test value	900	-675	-310	-215	195
Difference	3.1000	0.4250	1.9250	-1.8500	1.0000
95% CI	-2.6902 ~ 8.8902	-3.9594 ~ 4.8094	-11.5224 ~ 15.3724	-11.3313 ~ 7.6313	-2.9681 ~ 4.9681
DF	39	39	39	39	39
t Statistic	1.08292	0.19607	0.28955	0.39467	0.50973
Significance level	p = 0.2855	p = 0.8456	p = 0.7737	p = 0.6952	p = 0.6131

VI. CONCLUSION

The newly developed detection algorithm based on the CLFACM presented certain detection errors because of several factors, such as an abrupt irregular heartbeat, very low PPG amplitude less than 10 mV, and body' movement. Two stabilization methodologies were applied so that APG wave indices could be detected and used for clinical application and wearable devices. A detection algorithm for the APG waveform that simultaneously regulates the 1st derivative and the 2nd derivative PPG amplitude, which is called the APG-CLFACM, has not been previously studied in the literature. A PPG stabilization algorithm was developed with a preamplifier circuit with an active low-pass Sallen-Key topology. However, a very low amplitude close to 10 mV was amplified to the predetermined level, although stabilization delays of approximately 11 seconds was observed. A slight difference was observed between in-groups for the c and d waves because the two waves are positioned closely to each other in the APG signal. The wave with the greatest impact among the five waves for assessing the aging index or atherosclerosis is the b wave. The b wave data showed the highest statistical significance compared with the other waves. The five-wave pattern we obtained by the CLFACM has the potential for clinical application as a biological marker for atherosclerosis that is associated with the elastic properties of blood vessels.

ACKNOWLEDGMENT

This work was supported by the Hallym University Research Fund (HRF-202004-019).

REFERENCES

1. B. Jani, C. Rajkumar, "Ageing and vascular ageing," *Postgraduate Medical Journal*, 2006, vol. 82, no. 968, pp. 357-362.
2. M.A. Lim, R.R. Townsend, "Arterial compliance in the elderly: its effect on blood pressure measurement and cardiovascular outcomes," *Clinics in Geriatric Medicine*, 2009, vol. 25, no. 2, pp. 191-205.
3. Zhongjie Sun, "Aging, arterial stiffness and hypertension," *Hypertension*, 2015, vol. 65, no. 2, pp.252-256.
4. R.S. Vasan, M.I. Short, T.J. Niiranen, V. Xanthakis, C. DeCarli, S. Cheng, S. Seshadri, F.F. Mitchell, "Interrelations between arterial stiffness, target organ damage, and cardiovascular disease outcomes," *Journal of the American Heart Association*, 2019, vol. 8, no. 14, pp. e012141.
5. Mohamed Elgendi, "On the analysis of fingertip photoplethysmogram signals," *Current Cardiology Reviews*, 2012, vol. 8, no. 1, pp. 14-25.
6. T.Y. Abay, P.A. Kyriacou, "Photoplethysmography for blood volumes and oxygenation changes during intermittent vascular occlusions," *Journal of Clninical Monitoring and Computing*, 2018, vol. 32, no. 3, pp. 447-455.
7. T. Oh-I, T. Okuda, H. Shimazu, A. Watanabe, "An experimental study of vascular dynamics by an acceleration plethysmogram using artificial circulation devices," *Life Sciences*, 2002, vol. 71, no. 14, pp. 1655-1666.
8. L.A. Bortolotto, J. Blacher, T. Kondo, K. Takazawa, M.E. Safar, "Assessment of vascular aging and atherosclerosis in hypertensive subjects: Second derivative of photoplethysmogram versus pulse wave velocity," *American Journal of Hypertension*, 2000, vol. 13, no. 2, pp. 165-171.
9. J.M. Ahn, "Wave detection in acceleration plethysmogram," *Healthcare Information Research*, 2015, vol. 21, no. 2, pp. 111-117.
10. K.S. Hong, K.T. Park, J.M. Ahn, "Aging index using photoplethysmography for a healthcare device: comparison with Brachial-Ankle pulse wave velocity," *Healthcare Information Research*, 2015, vol. 21, no. 1, pp. 30-34.
11. J.K. Kim, J.M. Ahn, "Digital IIR filters for heart rate variability; a comparison between Butterworth and Elliptic filters," *International Journal of Scientific and Technology Research*, 2019, vol. 8, no. 12, pp. 3509-3513.
12. K. Kohara, Y. Tabara, A. Oshiumi, Y. Miyawaki, T. Kobayashi, T. Miki, "Radial augmentation index: a useful and easily obtainable parameter for vascular aging," *American Journal of Hypertension*, 2004, vol. 18, no. S1, pp. 11S-14S.
13. G.F. Mitchell, H. Parise, E.J. Benjamin, M.G. Larson, M.J. Keyes, J.A. Vita, R.S. Vasan, D. Levy, "Changes in arterial stiffness and wave reflection with advancing age in healthy men and women: the Framingham Heart Study," *Hypertension*, 2004, vol. 43, no. 6, pp. 1239-45.
14. A. Biswas, M.S. Roy, R. Gupta, "Motion artifact reduction from finger photoplethysmogram using discrete wavelet transform," *Recent Trends in Signal and Image Processing*, 2018, pp. 89-98.
15. Suyi Li, Shanqing Jiang, Shan Jiang, Jiang Wu, Wenji Xiong, Shu Diao, "A hybrid wavelet-based method for the peak detection of photoplethysmogram signals," *Computational and Mathematical Methods in Medicine*, 2017, vol. 2017, Article ID 9468503.
16. K. Takazawa, N. Tanaka, M. Fujita, O. Matsuoka, T. Saiki, M. Aikawa, S. Tamura, C. Ibukiyama, "Assessment of vasoactive agents and vascular aging by the second derivative of photoplethysmogram waveform," *Hypertension*, 1998, vol. 32, pp. 365-370.
17. A. Suzuki, K. Yamakawa, H. Fujinuma, H. Sudo, K. Ogawa, "Relation between elastic artery and distensibility," *Japanese Journal of Applied Physiology*, 1990, vol. 20, pp. 113-23.

AUTHORS PROFILE

Jae Mok Ahn received the B.E. degree in electronics engineering and Ph.D. degree in biomedical engineering from Seoul National University, Seoul, South Korea. Since Spring 1998, he has been a faculty member at the department of electronics engineering, school of software, Hallym University. He is currently engaged in research on improving healthcare system, bio-signal analysis, heart rate variability, and acceleration plethysmogram. He has developed a pulse analyzer that provides the judgment of a vascular status and activity of autonomic nervous system for healthcare system. He is a member of the Korean Society for Biomedical Engineering.

Jeom Keun Kim received the B.E. degree in control and instrumentation engineering and Ph.D. degree in mechatronics from Seoul National University, Seoul, South Korea. Since Spring 1994, he has been a faculty member at the department of electronics engineering, school of software, Hallym University. His research interests include motor control, smart farm control system, spirometer, healthcare communication, and signal processing techniques. In particular, he has developed a smart spirometry that gives information related to lung capacity, with a newly detection system of slight changes in air pressure flowing in and out through a mouthpiece being introduced.