New Marker for Vascular Health based on the Poincare Plot Analysis using Acceleration Plethysmogram

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Abstract

Acceleration plethysmogram (APG) has been used to evaluate atherosclerosis in subjects of various ages by extracting five parameters that characterize the morphology of APG. APG is a noninvasive indicator used to identify arterial stiffness and aging. However, reliable evaluation of vascular health is complicated by difficulties in the detection of five parameters in an APG. The paper proposes a new marker, vascular type index (VTI), that evaluates vascular status based on the Poincare plot analysis of APG. The results showed significant age-dependent changes detectable to the Poincare parameters more easily than those detected using a conventional aging index (AI). AI was calculated as \( \frac{(b-c-d-e)}{a} \) is a function comprising the a, b, c, and d peaks in the systole and an e peak in the diastole, while APG VTI is a ratio of standard deviations of the width and length of the Poincare plot. The range of VTI from 4.0 to 9.5 is wider than that of AI (from -1.3 to 0.9) corresponding to various age groups (from 20 to 80 years of age). Therefore, the newly proposed VTI appears to be useful for evaluation of vascular aging because of the wide range of the values that change according to the inflection points of APG. This study suggests that VTI may reflect development of atherosclerosis with aging better than AI.

Keywords: Poincare plot, arterial stiffness, atherosclerosis

INTRODUCTION

Acceleration plethysmogram (APG) is a second derivative of the fingertip photoplethysmogram (PPG) waveform. APG has been widely used as a non-invasive method to assess the pulse wave components and their relation to vascular status, and cardiovascular risk factors [1-3]. PPG waveform is measured by optical detection of the changes in light absorption at the fingertips due to the volume of the blood vessels. PPG waveform reflects fluctuations in blood perfusion within peripheral circulation and is related to vascular health [4]. In arteriosclerosis, the changes in both systolic and diastolic periods of the PPG waveform increase with age. The changes reflecting the presence of atherosclerotic disorders have been estimated using the APG waveform measurements to identify four systolic wave peaks (a, b, c, and d) and a diastolic wave peak (e) [5]. Several studies have shown that these parameters of the APG waveform can be used to provide clinical information on arterial stiffness, arterial compliance, vascular aging, and mental stress related to the autonomic nervous system [6]. In our previous studies, the APG aging index (AI) calculated based on a combination of a, b, c, d, and e wave peaks represents an inflection point in the same phase as the PPG waveform; however, we did not have sufficient range to fully cover all age groups. AI is inherently difficult to use for specific discrimination between vascular types II, III, or IV out of six known vascular stiffness type levels (type I, II, III, IV, V, and VI) as shown in figure 1. In particular, it was difficult to discriminate between type II and III based on the AI values because of the narrow range of AI from -1.3 to 0.9, corresponding to all six types. As a result, the AI of types II and III, corresponding to the ages from 30s to 50s, are expected to vary from approximately -1.0 to -0.7, and the presence of only four steps caused some difficulties in discriminating between these values. To solve this problem, a wide range of AI values is required to assess various vascular stiffness levels according to the age of the subjects. Therefore, the aim of this study was to propose a new marker of a vascular type index (VTI) range wider than suggested previously using the Poincare plot analysis, thereby reducing false determination by removing an ambiguity of the boundary between vascular types II, III, and IV. The newly proposed VTI can replace AI as a marker. The clinical application of the Poincare plot analysis to estimate heart rate variability (HRV) have been identified in a number of publications; however, application of the analysis for the evaluation of vascular health status using the APG signal has not been described to date.
Figure 1. Vascular type based on the traditional aging index (AI) calculated from the changing APG waveform with increasing age and vascular stiffness. It is calculated according to equation $AI = \frac{(b-c-d-e)}{a}$.

ACCELERATION PLETHYSMOGRAM (APG)

APG waveform is generated based on a second derivative of a photoplethysmogram (PPG). Optical PPG measurements were obtained from the index finger. PPG was recorded for 60s, and the APG signal was produced at the same time using a commercial TAS9VIEW (or CANOPY9 RSA) device (IEMBIO Co. Ltd., Chuncheon, Korea) with a derivative algorithm. Characteristics of the medical devices and software were reported earlier [7]. APG consists of four systolic wave peaks and a diastolic wave peak; a, b, c, and d peaks are systolic and an e peak is diastolic as shown in figure 2. The b and d peaks and their relationship to the a peak are specifically correlated with arterial stiffness [7]. Thus, vascular type is determined based on the slope of the b-d peaks as shown in figure 1. Out of five parameter ratios (b/a, c/a, d/a, and e/a), the b/a and d/a ratios are significantly associated with aging, atherosclerosis, the intensity of the wave from reflected peripheral circulation, and arterial distensibility [8]. All five indices comprise the AI equation defined as $AI = \frac{(b-c-d-e)}{a}$; AI is related to diabetes mellitus, hypertension, hypercholesterolemia, and ischemic heart disease [5,9]. The c/a, d/a, and e/a ratios decrease with aging and the d peak reflects the strength of the pulse wave from the peripheral arteries at the fingertips [5]. The magnitude of the negative d peak increases with aging, resulting in a decrease in the d/a ratio correlated to constriction and stiffness in small arteries [10,11]. Additionally, AI was used to estimate blood pressure in a continuous health monitoring system [12]. The number of publications related to the use of APG to assess vascular stiffness has been exponentially increasing over time [13].

Figure 2. Schematic representation of fingertip photoplethysmogram (PPG) waveform (top) and the corresponding second derivative APG waveform (bottom): five peaks (a, b, c, d, and e) are changing with age.
POINCARE PLOT ANALYSIS

In the Poincare APG waveform graph, each data point APG(n) is plotted versus the next data point APG(n+1). The data vector is defined as \( x = (x_0, x_1, x_2, x_3, x_4, x_5, \text{and} x_6) \) with the data size \( N=7 \). The Poincare plot known as a return map will be a plot of the points with coordinates \((x_0, x_1), (x_1, x_2), (x_2, x_3), (x_3, x_4), (x_4, x_5), \text{and} (x_5, x_6)\). This return map provides the variability or fluctuations of the APG signals in time series \( x_n \).

The ellipse fitting method was used to calculate the dimensionless standard deviations (SD) of the distances of the points perpendicular to the axis of the line-of-identity \( (y = -x) \) and the SDs of the distances of the points along the axis of the line-of-identity \( (y = x) \), defined as \( a_{SD1} \) and \( a_{SD2} \), respectively, as shown in figure 3. Indices \( a_{SD1} \) and \( a_{SD2} \) represent the semi-minor (width) and semi-major (length) axes of the ellipse, respectively [14]. The Poincare plot analysis is performed according to the following equations. The APG data vector is defined as \( x = (x_0, x_1, ..., x_N) \). Two auxiliary vectors defined in (1) and (2) are created and all parameters of the Poincare plot are determined as follows:

\[
x^a = (x_0, x_1, ..., x_{N-1})
\]
\[
x^b = (x_1, x_2, ..., x_N)
\]
\[
x^c = \frac{x^a - x^b}{\sqrt{2}}, \quad x^d = \frac{x^a + x^b}{\sqrt{2}}
\]

\[
a_{SD1} = \sqrt{\text{variance}(x^c)}, \quad a_{SD2} = \sqrt{\text{variance}(x^d)}
\]

\[
\text{SD ratio} = \frac{a_{SD2}}{a_{SD1}}
\]
\[
a_S = \pi \times a_{SD1} \times a_{SD2}
\]

The SD ratio defines a new marker, vascular type index (VTI). Area of the ellipse \( a_S \) defines a parameter that reflects total variability. The Poincare plot shown in the left panel in figure 3 corresponds to the normal type II APG waveform and an example of the noisy APG waveform without filtering is shown in the right panel in figure 3. An APG signal without any noise or distortion is required for the Poincare plot analysis.

DATA COLLECTION

Four male subjects (20 to 50 years of age) with potentially different vascular types participated in this study. A professional pulse analyzer with a finger-type sensor of a photoplethysmogram TAS9VIEW (or CANOPY9 RSA) was used to obtain PPG and APG recordings for 60s with the sampling frequency of 100 Hz. The participants were in the supine position in a quiet room and were not allowed to talk or move while multiple measurements were performed. Two subjects were estimated to be at the borderline between types II and III with one measurement corresponding to type II and another measurement corresponding to type III or vice versa. Other subjects were consistently estimated as type I and type IV in multiple measurements. This study did not acquire any information on the health status of the participants including blood pressure and presence of heart diseases, atherosclerosis, or psychological disorders because the aim of the study was to evaluate the possible application of nonlinear geometry by APG-based Poincare plot analysis to define a new aging index. A total of 20 APG and 20 PPG recordings were obtained at five recordings per subject. Four APG datasets including the corresponding PPG datasets were selected to represent four different vascular types I, II, III, and IV. The remaining 16 APG and PPG recordings were excluded from the Poincare plot analysis. However, selection of specific APG recordings was solely based on representation of four different vascular types of arterial stiffness.

AUTO MAGNITUDE CONTROL (AMC)

The magnitude of a PPG depends on the volume of blood ejected from the heart into the peripheral vascular bed per heartbeat, optical absorption of the blood vessels and the blood, and the composition and color of the skin and underlying
tissues [4,15]. The PPG signal is characterized by high fluctuations of the magnitude due to optical properties, including factors listed above. Therefore, implementation of the APG Poincare plot analysis requires that a peak has a constant magnitude because Poincare plot visualization depends on the amplitude of the data vectors in (1) and (2) but does not depend on the data length. An auto magnitude control (AMC) algorithm was developed to ensure that the values of the a peak between 2900 and 3100 (ADC 12bit) are within the optimal range for calculations of the second derivative of APG.

An apgGain counter was used to control the magnitude in the first derivative of PPG and to finally tune the a peak in the second derivative of APG to ensure that the peak is in the optimal range as shown in figure 4(b). The apgGain counter increases or decreases until the a peak of APG approaches a predetermined value and the counter is fixed to fix the magnitude of APG signal locking the window at the moments when the apgGain counter reaches the fixed value. When the window is locked, three complete cycles of APG or PPG signals were used to obtain the Poincare plot data.

**RESULTS**

We analyzed four different types of APG signals corresponding to different vascular stiffness (types I, II, III, and IV). APG signals are the second derivative of the PPG time series that trace the voltage changes with a periodic function corresponding to three complete cycles. Poincare plot analysis was used to distinguish ambiguous vascular type levels based on a conventional AI through extension of an APG 1D dataset into a higher dimensional state space. The analysis is represented by a graph of APG(n+1) on the y-axis versus APG(n) on the x-axis. APG normally consists of a series of wave peaks including the a, b, c, d, and e peaks. The increase in the vascular status level from type I to type IV with aging increases the value of the SD ratio (6.4, 7.1, 7.8, and 8.6, respectively) as shown in figure 5. An increase in the SD ratio (aSD2/aSD1) is due to a decrease in aSD2, which corresponds to the semi-major axis of the ellipse (y=x) in the denominator concomitant to an increase in the type level (619.8, 580.2, 522.2, 471.9, 446.6, respectively). Individual type levels were not significantly different from each other. For example, type I and type II or type II and type III had similar aSD1. The changes in the aSD2 values were more pronounced than the changes in the aSD1 values. The SD ratio reflects the randomness of the
oscillations of the APG waveform in the time series and thus was defined as a newly proposed vascular type index (VTI).

Figure 5. Ellipse fit of the Poincare plot and the index SD ratio (aSD2/aSD1) defined as VTI in the APG waveform: (a) vascular type I, (b) vascular type II, (c) vascular type III, and (d) vascular type IV.

Figure 6 shows the relationships of the SD ratio with different vascular types ranging from I to IV. According to the PPG Poincare plot analysis, the VTI values were higher compared to those in APG; however, the deviation percentage between type II and type III or type III and type IV was lower (1.3 (6.1%), and 1.2 (5.4%)) than those in the case of APG (0.7 (9.0%) and 0.8 (9.3%), respectively). In contrast to APG, the aSD1 values are lower than the aSD2 values, resulting in an increase in the SD ratio.
DISCUSSION

Poincare plot is the geometrical representation of an APG signal time series in a Cartesian plane. Qualitative visualization of the dynamics of the APG waveform is accomplished by fitting an ellipse to the Poincare plot. Two parameters, aSD1 and aSD2, were calculated to describe the geometry and an APG-derived VTI value defined as an SD ratio of aSD2 to aSD1 is proposed for assessment of vascular health or atherosclerosis. We observed that the lowest SD ratio values for APG signal correspond to the healthy vascular status. SD ratios less than 6.5 correspond to vascular type I and SD ratio over 8.0 correspond to vascular type IV. The results presented in this study show a correlation between VTI derived from the nonlinear geometry and the type of vascular stiffness. VTI is a better marker to discriminate between vascular types II and III (or III and IV); this discrimination between various types of vascular status is difficult to perform based on the conventional AI values due to the narrow range of AI. PPG-based Poincare plot analysis had lower variability of VTI by approximately 5% compared to that in the case of the APG-based analysis resulting in the lower changes in the VTI values for PPG versus those for APG. Thus, due to small changes in a traditional AI=(b-c-d-e)/a, the variability index of VTI based on the APG Poincare plot analysis can be considered a better marker for clinical applications and a replacement of conventional AI. Moreover, the fluctuations of variability measurements were high in vascular type I. Thus, division of a vascular type into several classes is possible. Therefore, the APG-based Poincare plot analysis showed better performance than traditional AI and the PPG-based Poincare plot analysis. We conclude that VTI is a better marker for characterization of vascular stiffness levels using the APG-based Poincare plot analysis. In the future, it might be worth to extend the VTI values up to type VI corresponding to high vascular stiffness in those APG datasets that include unhealthy subjects.

CONCLUSIONS

Poincare plot is a nonlinear geometric method that can assist in qualitative and quantitative visualization of 1D data into 2D data. This study is the first to apply the Poincare plot analysis to the APG waveform to assess arterial stiffness, even though this approach has been extensively used to estimate heart rate variability [16,17]. The proposed Vascular Type Index is based on the aSD2 and aSD1 values of the APG-based Poincare plot parameters. The analysis confirms that VTI can measure the variations of the Poincare plot caused by vascular status using an acceleration plethysmogram. VTI has a wider range than that of conventional AI and can be used to easily determine vascular type to bypass calculations of the peak ratios (b/a, c/a, d/a, and e/a) based on the APG waveform. We confirmed that VTI is less sensitive to changes in the transition from one type to another. VTI was found to be effective in the assessment of vascular health according to vascular type assignment. We hope that the first, the third and the fourth derivatives of PPG will be investigated by the Poincare plot analysis. These studies can assist in the development of a new aging index for the evaluation of vascular health.

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REFERENCE


