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Extraction of the jugular venous pulse and carotid profile using a cervical contact plethysmography system

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Abstract

The Jugular Venous Pulse (JVP) is considered a reliable parameter for the assessment of Central Venous Pressure (CVP). Here, the functionality of a cervical contact plethysmography system designed for non-invasive and operator-independent acquisition of the JVP signal, is shown. To validate the signal, it was recorded in supine and sitting positions, together with the reference Electrocardiography (ECG), on 26 healthy subjects. In the supine acquired signal, the characteristic JVP waves (a, c, v) and the negative deflections (x, y) are well recognizable. In the sitting recorded signal, the systolic peak b and the d incisura of the Common Carotid Artery (CCA) waveform are recognized. For each signal, we calculated the Fraction of the Cardiac Cycle (ccf) represented by the time intervals between the JVP peaks and the ECG peaks, in the form: ΔtaP, ΔtcR, ΔtxP, ΔtvT, Δtyv, Δtvx, and Δtxa. The same was done for the CCA waveform, in the form: ΔtbS, ΔtbT, Δtdb, ΔtdS, and ΔtdT. This system could mitigate risks and costs associated with central venous catheterization and its potential extends to applications in telemedicine, sports medicine, and space medicine.

Introduction

Cardiovascular Diseases (CVDs) currently represent the leading cause of mortality by the World Health Organization (WHO).[1] This necessitates the development of safe, non-invasive, and cost-effective devices for continuous patient monitoring. Such advancements would optimize the availability of monitoring and improve patient care. The Jugular Venous Pulse (JVP) is a reliable marker for pressure changes in the heart throughout the cardiac cycle.[2] The JVP constitutes a periodic waveform characterized by three ascent peaks and three descent peaks, each corresponding to a distinct cardiac event. The initial rise, termed the "a wave," follows the p wave on the Electrocardiogram (ECG) and reflects atrial contraction propelling blood into the ventricle. This ascent is succeeded by the first descent peak, signifying both atrial relaxation and closure of the tricuspid valve, which separates the atrium from the ventricle. Subsequently, the QRS complex on the ECG marks the onset of ventricular contraction. This event is mirrored in the JVP by the "c wave," a rise caused by the bulging of the tricuspid valve as the right ventricle forcefully ejects blood. As pressure decreases following this ejection, a descent peak, the "x descent," is observed on the JVP waveform. Ventricular repolarization, depicted by the t wave on the ECG, coincides with a rise in the JVP waveform known as the "v wave." This rise represents the right atrium filling to its maximum capacity with blood before the tricuspid valve reopens. The opening of the tricuspid valve triggers a final pressure drop, the “y wave,” as blood flows rapidly into the ventricle. This completes the cycle, and the JVP waveform repeats.[3] The Common Carotid Artery (CCA) arterial pressure waveform can be divided into distinct phases during the cardiac cycle. The systolic phase encompasses two key components: the upstroke (a wave), characterized by a rise in pressure from the diastolic nadir to the systolic peak (b). This initial rise corresponds to ventricular contraction and subsequent blood ejection into the aorta. Following the peak, a downslope (c) ensues, reflecting the decline in pressure as ventricular relaxation commences and blood flow out of the ventricles begins. A characteristic indentation, known as the dicrotic notch (d incisura), interrupts this downslope. The dicrotic notch signifies the closure of the aortic valve, occurring shortly after the onset of diastole. This event marks the end of blood ejection and the return of the pressure waveform to its baseline, the diastolic nadir.

Traditionally, Central Venous Catheterization (CVC) has served as the gold standard for JVP assessment. This invasive procedure necessitates surgical insertion of a catheter into the right internal jugular vein, followed by its advancement towards the right atrium.[4] Due to potential complications, CVC application should be strictly limited to situations of absolute necessity. This study explores a cervical contact plethysmography system as a potential alternative for non-invasive JVP signal acquisition.[5] Ultrasound (US) imaging can be used as an alternative method to assess JVP, but a significant drawback of this technique is its reliance on operator expertise.[6] Employing an automated ultrasound system could overcome this limitation by eliminating operator subjectivity.[7]

Materials and Methods

Experimental protocol

A total of 26 healthy subjects (14 males and 12 females) participated in the study. Their mean age was 25 years (±3 years), mean height was 175 cm (±15 cm), and mean weight was 75 kg (±25 kg). The study was approved by the local Ethics Committee. All participants undergo anatomical evaluation of the neck’s vascular bundle, focusing on the Internal Jugular Vein (IJV) and the CCA, using Doppler ultrasonography. This analysis aims to identify any potential anomalies or pathological conditions that would necessitate subject exclusion, such as IJV entrapment by the omohyoid muscle.[8] For the purpose of validating and precisely identifying the characteristic JVP waves and their corresponding timings, a 3-lead ECG was employed as a reference signal. Following informed consent, subjects autonomously place the device on the neck. Meticulous attention is paid to secure device adherence without compressing surrounding tissues. Compression of superficial cervical venous networks can potentially redistribute venous flow and alter the JVP signal. The plethysmography system placement occurs immediately below the readily identifiable cricoid cartilage (Figure 1). The sensor structure comprises a single-layer dielectric electroactive polymer (ElastiSense Sensor Technology, Aabenraa, Denmark). It has non-stretchable zones at both extremities, facilitating secure attachment. The central region functions as the active zone and exhibits high stretchability. The output signal generated by the film corresponds directly to the elongation experienced by this active zone.[9] Subjects are positioned supine and instructed to maintain silence, avoid swallowing, and strive for stable breathing during signal recording. The recording commences with a series of

Figure 1. Data acquisition setting.

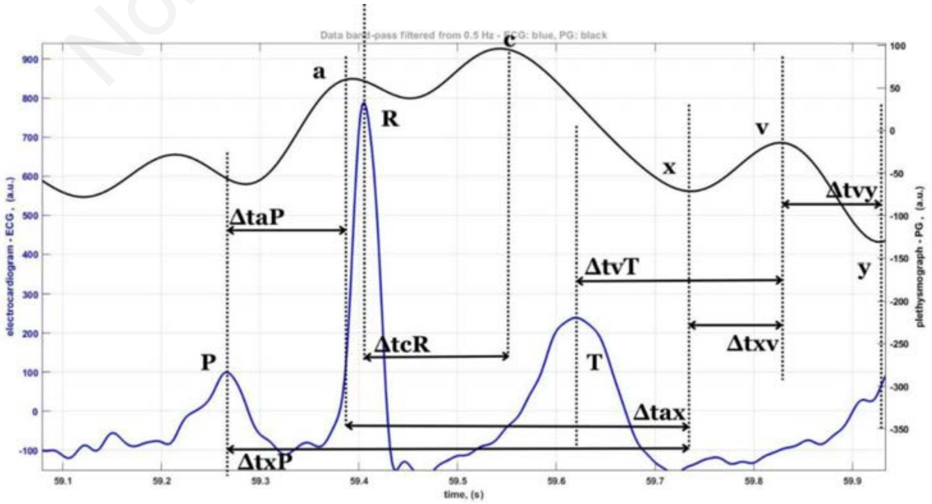

Figure 2. The Jugular Venous Pulse (JVP) signal (black), and the Electrocardiogram (ECG) signal (blue).

head movements performed by the subject: right and left lateral neck rotations, neck extension, and flexion. These maneuvers serve to calibrate device sensitivity. After 15 seconds, subjects execute a maximal inhalation followed by a maximal exhalation. At the end of exhalation, subjects maintain a state of expiratory apnea for 10-15 seconds before resuming normal breathing. This maneuver facilitates the acquisition of a time window free from breathing artifacts. Signal recording lasts for 2 minutes, ensuring the recording of at least four distinct apnea windows. ECG signals are captured synchronously throughout the recording process. The same protocol is repeated with the subject sitting, taking advantage of the shift in venous outflow from the IJVs to the secondary venous pathways, which is associated with complete or partial collapse of the IJVs.[10-14]

Data analysis

Data processing is performed using Matlab software (MathWorks Inc., Natick, USA). The acquired data were post-processed using MATLAB® software version R2022b. Both the plethysmography traces (JVP and CCA waveform) and the ECG signals underwent noise filtering to emphasize cardiac oscillations. The DC component and breathing artifacts were removed from the signals using a high-pass filter with a cut-off frequency of 0.5 Hz for all signals. Subsequently, a low-pass filter was applied to eliminate high-frequency noise: a cut-off frequency of 4.5 Hz was used for the JVP signal and CCA waveform, and a cut-off frequency of 15 Hz was used for the ECG signal. Regarding the FCC value, we first calculated the cardiac cycle period for each participant. The FCC value was then obtained by dividing each selected time difference by the corresponding cardiac cycle period. Following the generation of final graphs, characteristic JVP peaks and CCA waveform peaks are identified. The JVP peaks include the three positive waves (a, c, and v) and the two negative deflections (x and y). The CCA waveform peaks include the systolic peak b and the d incisura. Identification is performed manually by two independent operators for verification purposes. For each cardiac cycle and subject, the Fraction of the Cardiac Cycle (ccf) between JVP peaks and ECG peaks is calculated (ΔtaP, ΔtcR, ΔtxP, ΔtvT). Additionally, time intervals between JVP peaks (Δtvy, Δtxv, Δtax) are also calculated for data analysis (Figure 2). Similarly, time intervals between CCA peaks (Δtdb), and between CCA peaks and ECG peaks (ΔtdT, ΔtdS, ΔtbT, ΔtbS) were calculated (Figure 3).

Results

Signal shape

The shape of signals recorded in supine and sitting positions differs markedly (Figure 4A, B). In the acquired tests, the signals of interest exhibited a faithful correspondence to the JVP and the CCA waveform. All characteristic peaks were observed, including the positive deflections a, c, and v, as well as the negative deflections x and y. Notably, peak a consistently occurred subsequent to peak p of the ECG. Peak c was uniquely present during the systolic phase. Finally, peak v and the negative deflections x and y coincided with the t wave. It was possible to identify the b and d peaks of the CCA. It is noteworthy that peak b occurs during the systolic phase, whereas d incisura manifests within the diastolic phase.

Signal timing

The ccf of each cardiac cycle and for each subject were calculated, after which the mean value and standard deviation of ccf among all subjects were calculated. The data analysis confirmed the periodicity of the waveforms. What emerges is that, for all of the parameters observed and investigated, except for the ΔtbT, the values of the Coefficient of Variations (COV) are below 39%. From this, it can be deduced how the mean values (μ) fairly closely represent the values of the observations. In this way, it was possible to identify a temporal correlation between the ECG and the JVP, in agreement with what is found in the literature.[15] The results are summarized in Table 1.

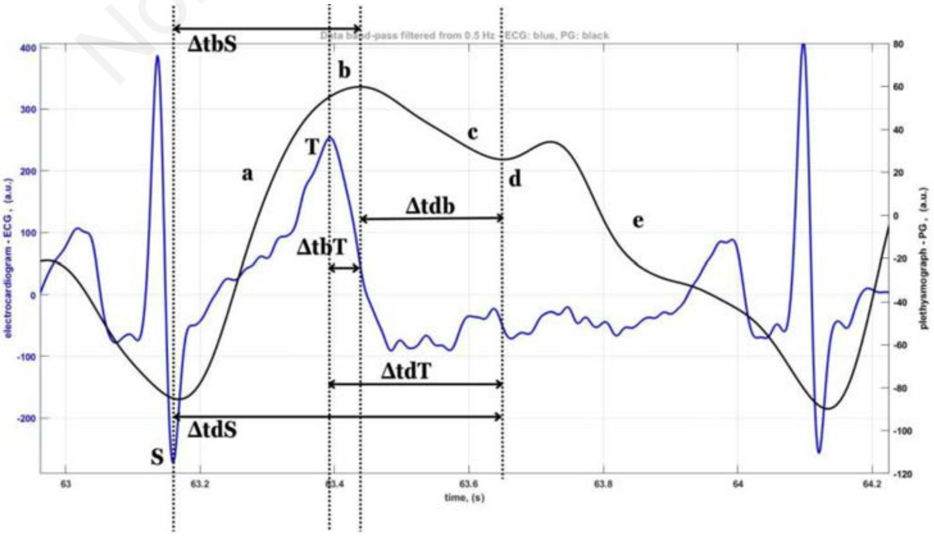

Figure 3. The Common Carotid Artery (CCA) signal (black), and the Electrocardiogram (ECG) signal (blue).

Discussion

This study investigated the feasibility of extracting the JVP waveform from the neck using a cervical contact plethysmography system. The JVP signals were acquired from 26 participants in the supine position. Consequently, the data analysis parameters identified herein may contribute to the further development of this system and facilitate comparisons with alternative methods. Adherence to the experimental protocol proved slightly challenging in a subset of participants, particularly those with a higher Body Mass Index (BMI). This difficulty stemmed from limitations in both achieving optimal sensor positioning and maintaining the required apneic state. Future advancements in device development will focus on two key areas. First, further validation will be conducted by comparing the device's JVP extraction capabilities with established methods.[16-19] Second, JVP signal acquisition will necessitate synchronization with both the arterial signal and the ECG. This study establishes, for the first time, the key attributes of a novel cervical contact plethysmography system for JVP signal acquisition, advancing the state-of-the-art in JVP recording techniques. The proposed method offers a user-friendly and cost-effective solution for non-invasive JVP measurement from the neck. It eliminates the need for expensive equipment or complex infrastructure, unlike alternative approaches. Furthermore, the ease of sensor placement around the neck allows for self-application by the subject, thus increasing user comfort and eliminating the requirement for specialized personnel during JVP assessment. These findings hold significant promise for reducing the risks associated with central venous line catheterization, potentially impacting future CVD clinical diagnosis.[20]

Conclusions

The aim of the study was to validate the JVP signal acquired with the cervical contact plethysmography system. Data analysis from 26 participants identified parameters to inform further system development and comparisons with existing methods. Manual annotation of characteristic a, c, and v waves in the JVP signals, referenced to the ECG, was performed to validate both the observability of JVP waveforms through the device and the feasibility of the proposed method. The calculated time intervals between these key features corroborated the validity of the novel JVP signals and their agreement with established literature, it can be seen that the calculated COV values for ccf are below the 50% cut-off value, as in the article presented by Zamboni *et al.* where JVP was extracted with US.[7] Future directions will focus on system validation against established methods and synchronizing JVP acquisition with both arterial and ECG signals. In conclusion, this research establishes a potentially impactful and user-friendly approach for non-invasive JVP meas-

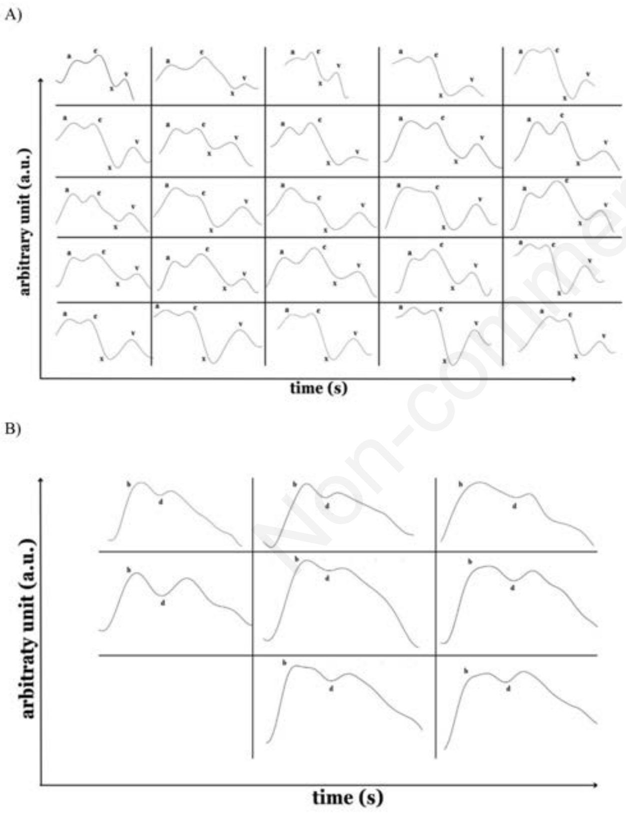

Figure 4. A) Example of a single cycle of Jugular Venous Pulse (JVP) signal extracted from each of the 26 subjects participating in the study. It is interesting to note the wide morphological variability of the signals. **B**) Example of a single Common Carotid Artery (CCA) signal cycle extracted from 8 subjects participating in the study. The y-axis units are arbitrary units because the data are filtered according to the procedure described in Materials and Methods. On the x-axis the units are seconds since these are time intervals.

Table 1. Data analysis: Fraction of the Cardiac Cycle (ccf) values, mean values, Standard Deviation (SD), and coefficient of variations values. The values reported are coherent with those reported by Tavoni,6 in which the Jugular Venous Pulse (JVP) features were extracted using an Ultrasound (US) system.

	ΔtcR	**ΔtaP**	**ΔtxP**	**ΔtvT**	**Δtyv**	**Δtvx**	**Δtxa**
μ (ccf)	0,14	0,10	0,49	0,23	0,14	0,14	0,39
σ (ccf)	0,04	0,04	0,12	0,06	0,03	0,03	0,09
COV	0,29	0,39	0,24	0,26	0,21	0,22	0,23

	ΔtdS	**ΔtdT**	**Δtdb**	**ΔtbS**	**ΔtbT**
μ (ccf)	0,41	0,16	0,15	0,26	0,01
σ (ccf)	0,05	0,04	0,03	0,03	0,03
COV	0,12	0,24	0,21	0,14	2,19

urement. The proposed method eliminates the need for expensive equipment, complex infrastructure, and specialized personnel. This innovation holds promise for safer CVD diagnosis by minimizing risks associated with central venous line catheterization.

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