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Radial pulse rate estimation from brightness-mode ultrasound imaging

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Abstract: Cardiovascular disease is a global concern with a high economic burden that needs to be controlled. Predictors of cardiovascular disease include blood pressure. There is a drive to evaluate these predictors through continuous non-invasive methods, which often requires custom devices to achieve the measurements. To reduce reliance on custom devices, we developed, verified, and validated an algorithm to measure the dynamic cross-sectional area of the radial artery and estimate the pulse rate from brightness-mode ultrasound imaging. The algorithm was implemented using Python and MATLAB®, and verified using a simulated environment with known parameters. It was validated using radial artery ultrasound scans, where pulse rate estimation was confirmed using continuous non-invasive arterial pressure monitoring as the control. The algorithm was verified to measure the area at >99 % accuracy with a difference in pixel value between artery and background >20 when considering a complex signal. The pulse rate estimate was exact. The accuracy of area measurement decreased when applied to ultrasound scans. However, the algorithm still estimated the pulse rate within the error margin, compared to the control, for five out of six subjects thus validating the algorithm. This demonstrates the possibility of measuring physiological factors without the need of custom devices. With further development, this algorithm could incorporate colour doppler information such that arterial pressure could be determined using a medical ultrasound device.

Keywords: algorithm development, CNAP, image processing, physiological phenomena, verification and validation.

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1 Introduction

Cardiovascular disease is a major global concern with an economic burden of disease of approximately €155 billion in the European Union in 2021 [1]. There is a need for a deeper understanding of vascular mechanics and a more advanced assessment of the health of the cardiovascular system.

The motion of the arterial wall has been considered important in assessing the health of the cardiovascular system. Cinthio et al. [2] propose a broad cardiovascular mechanical scenario to evaluate this motion using parameters such as blood pressure, arterial diameter change, and arterial stiffness. Accurate cardiovascular monitoring also requires a proper understanding of the measurement location and physiological factors. Siaron et al. [3] demonstrated the dependency of the blood pressure estimation into measurement sites such as the arm and wrist. Loh et al. [4] presented the influence of physiological parameters such as gender, hypertension and age on the radial artery size.

There is a distinct benefit to monitoring these phenomena continuously, which has led to the development of new techniques [5]. Zhou et al. [6] presented the clinical validation of a wearable ultrasound-based sensor solution for continuous non-invasive blood pressure monitoring. Another such example is presented by Wang et al. [7] where they combine brightness-mode ultrasound and colour doppler to achieve the pressure measurement.

Therefore, to determine radial pressure from ultrasound scans, it is important to assess both the cross-sectional area of the radial artery and the flow rate through the artery over time. The flow rate can be visualised with ultrasound using colour doppler [8]. We hypothesise that the change in the cross-sectional area of the artery can be used to identify the pulse rate. The purpose of this paper is to present, verify, and validate an algorithm that can measure the cross-sectional area of

the radial artery from brightness-mode ultrasound scans, and relate the change over time to the pulse rate.

2 Materials and methods

2.1 Algorithm design

An algorithm to measure the cross-sectional area of a radial artery and to estimate the pulse rate was developed using Python (v3.12) and several additional libraries [9], as well as MATLAB® (The MathWorks, Inc., Natick, MA, USA). The algorithm comprises three stages: data loading and cleaning; area measurement; and pulse rate estimation, as detailed in Figure 1.

The data loader and cleaner stage was developed using Python libraries `zipfile`, `os`, and `pandas` (v2.0). The data loader extracted time, heart rate, and event information from the continuous non-invasive arterial pressure (CNAP) data for each subject. The data was segmented into 60-second packets starting from each custom event. Any empty rows or rows with "NaN" were removed. A data dictionary was created for each subject, with the subject number as the key, and the corresponding data was stored in a data frame for import to the next stage of the algorithm.

The area measurement stage was developed using Python libraries `OpenCV` (v4.8), `NumPy` (v1.26), `matplotlib`, `scipy.signal`, and `pandas`. First, the user selected the desired region of interest. Then for each frame in the input video, the image was converted to grayscale, converted to a binary image using global thresholding with a threshold level of 15, before the colours were inverted. Any continuous contours were identified. In the situation where there was more than one visible contour in the region of interest, the largest contour was assumed to be the radial artery and the area was computed from this.

To reduce noise, the time-series area data were subjected to a 4th order bandpass Butterworth filter with a lowpass frequency of 0.5 Hz and a highpass frequency of 4 Hz. The outputs at this point were stored in a `.csv` file. To estimate the pulse rate, peaks above the average area and separated by at least 0.64 seconds were identified and indexed. The pulse rate was computed using the time interval between identified peaks, with a rolling window of width 5.

2.2 Algorithm verification

To verify the presented algorithm, a video to simulate arterial expansion and contraction was generated using `OpenCV` and `NumPy`. The simulated artery had an amplitude of 5 and a fixed pulse rate of 50 beats per minute (BPM). The video was 15 seconds long and was stored in `.MP4` format. The true cross-sectional area of the simulated artery was stored for each frame of the video. The artery itself was defined as black (pixel value of 0), and the background could be varied from white (pixel value of 255) down to a pixel value of 15, corresponding to the threshold used for the algorithm.

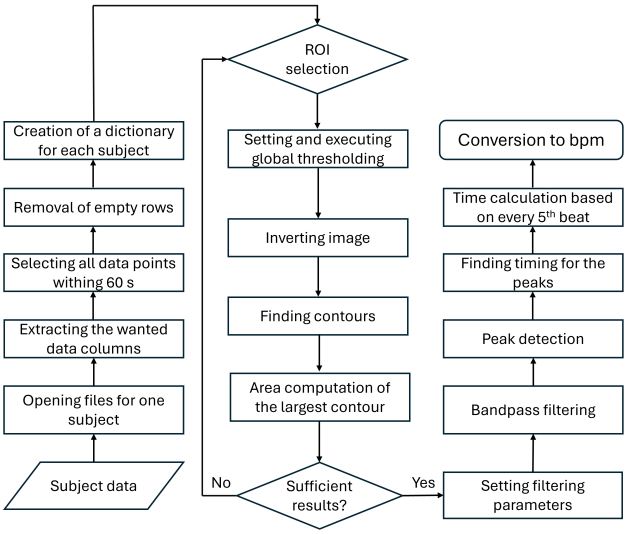

Fig. 1: Flow diagram of the presented algorithm that loads and cleans the data, allowing for user selection of the region of interest before processing the video to compute the area over time, and finally filter the output to remove noise before performing peak detection to estimate the pulse rate.

2.3 Validation experiments

Ultrasound imaging of the radial artery on the left wrist, demonstrated in Figure 2, was performed to validate the presented algorithm. This was accomplished using a L18–5 linear probe of a HOLOGIC® SuperSonic™ MACH 30 ultrasound imaging platform (Hologic, Inc., Marlborough, MA, USA). The probe was positioned transverse to the radial artery at the level of the proximal palmar fold and held in position using a custom-made fixation device. Positioning and recording was performed by a single operator throughout the experiments. Positioning commenced during the auto-calibration process of the CNAP device.

The ultrasound device was operated in vascular (upper extremity arterial) pulsed brightness mode with a penetration depth of 15 mm relative to the probe surface, an indicated mechanical index of 0.6, and an indicated thermal index of 0.0. A 60-second prospective video was captured for each subject in this study.

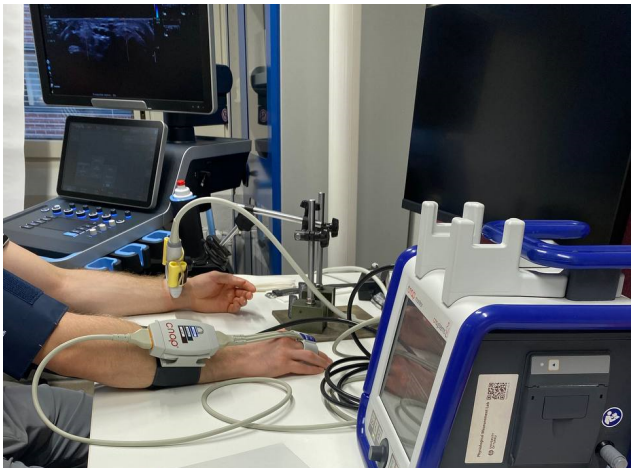

Fig. 2: Setup of the validation experiments. The ultrasound probe was oriented transverse to the radial artery of the left wrist, held in position using a custom-made fixation device. The CNAP device was affixed to the proximal phalanges of the index and middle fingers of the right hand.

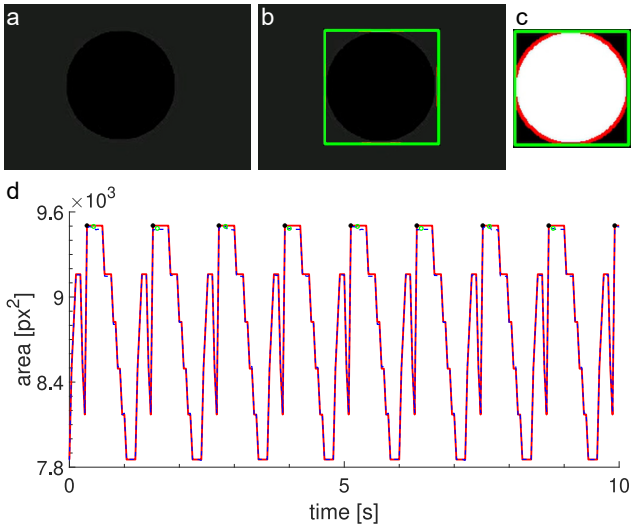

Fig. 3: First frame from the verification video with a background pixel value of 30 and artery pixel value of 0 (a), with the region of interest marked (b). The measured contour is superimposed in red on the output of the algorithm after thresholding and inverting the region of interest (c), from which the area is computed. The change of the area over time (d) is shown for the measured (– –) and true (—) areas. The peaks detected from the measured and true areas are shown as black dots and green circles respectively.

To provide a control measurement for pulse rate, a CNAP® Monitor 500 HD V1.4 device (CNSystems Medizintechnik GmbH, Graz, Austria) was affixed to the proximal phalanges of the index and middle fingers of the right hand, demonstrated in Figure 2. For each participant, a single operator turned the device on and captured the required patient data while the device was auto-calibrating. Once the CNAP device had completed its auto-calibration, the CNAP operator started the signal recording.

To allow for the ultrasound and CNAP data to be synchronised during processing, an event was incorporated into the CNAP data by button press when the ultrasound recording began. This was coordinated between the ultrasound and CNAP operators. Data from six subjects were captured for inclusion in this study.

3 Results and discussion

Figure 3 shows the verification environment and the contour detection process yielded by the algorithm after selection of a region of interest. The measured area was observed to closely track the true changes of the simulation artery, even when an intentionally complex signal was used. The average percentage error was 0.13 % when the difference between the pixel values of the simulated artery and background was 30. When the pixel value difference was higher, resulting in a higher contrast between the background and the simulated artery, the error was the same or less. At pixel value differences lower than 30 the error started increasing, yet the algorithm still yielded >99 % accuracy when the difference was >20. At a pixel value difference of 20 the average percentage error was 1.29 %. Despite this error, the calculation of the pulse rate was accurate, as seen in Table 1. This verifies that the presented algorithm performs as intended.

Analysis of the ultrasound scans of the radial arteries of the test subjects, a representative example shown in Figure 4, was not as accurate when computing the area compared to the verification environment. As seen in Figure 4c), the identified contour includes the bordering vessels, which introduces an inherent error when computing the area. This limits the validity of the algorithm for the purposes of area measurement.

When evaluating the estimated pulse rate for each of the test subjects, there was sufficient change in the measured area to allow for accurate peak detection, as seen in Table 1. In five of the 60-second experiments, the algorithm-estimated pulse rate was the same or within the margins of standard deviation compared to the control. The standard deviation of the pulse rate yielded by the algorithm was higher than that of the control. The algorithm underestimated the average pulse rate in the 60-second experiment for three of the subjects. This was not due to the chosen 0.64 seconds separation between peaks in the pulse rate estimation stage. Resting heart rates typically vary between 50–90 BPM [10], and the measurement limit for the chosen separation is 93 BPM. It is clear from the control data that all subjects had a pulse rate below the limit. We attrib-

Tab. 1: Summary of the measured pulse rate, in beats per minute (BPM), for the presented algorithm compared to the control in the simulated environment and the ultrasound analysis of the 6 subjects. The control pulse rate in the simulated environment was the preprogrammed rate, and for the ultrasound analysis it was the pulse rate measured from the CNAP device over the same period.

		Algorithm	Control
Verification environment		50 ± 0 BPM	50 ± 0 BPM
Ultrasound analysis	S1	55 ± 4 BPM	54 ± 2 BPM
	S2	54 ± 5 BPM	54 ± 1 BPM
	S3	60 ± 7 BPM	65 ± 4 BPM
	S4	61 ± 4 BPM	62 ± 2 BPM
	S5	61 ± 6 BPM	69 ± 1 BPM
	S6	56 ± 6 BPM	63 ± 5 BPM

ute the higher standard deviation and understatement of pulse rate to insufficient visualised area change, stemming from the inaccurate contour identified.

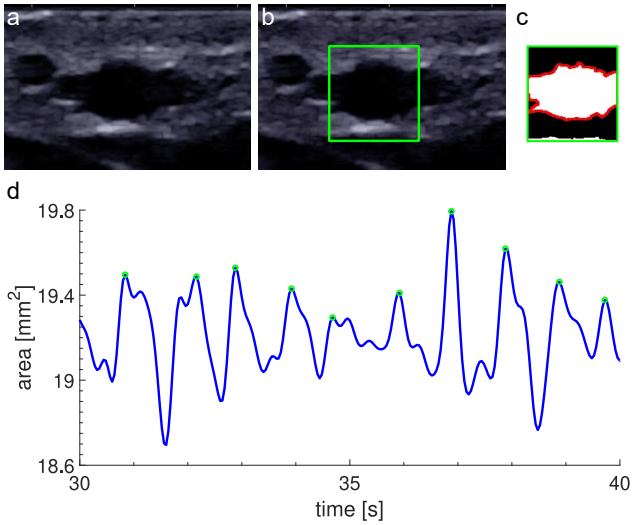

Fig. 4: First frame from the ultrasound scan of test subject 4 (a), with the region of interest marked (b). The measured contour is superimposed in red on the output of the algorithm after thresholding and inverting the region of interest (c), from which the area is computed. The change of the area over time (d) is shown for the measured area (—) with the peaks detected marked as green circles.

4 Conclusions

An algorithm to measure cross-sectional area of the radial artery and estimate pulse rate data from brightness-mode ultrasound scans was presented, verified, and validated. The algorithm achieved >99% area measurement accuracy under simulated conditions where the difference in pixel value between the background and artery was >20, and was exact in estimating pulse rate. The accuracy of the area measurement decreased when applied to ultrasound brightness-mode scans, but the algorithm was still able to estimate the pulse rate within the error margin for five of six subjects. With some refinement and further development, this algorithm could incorporate colour doppler information such that arterial pressure can be determined using a medical ultrasound device.

Author Statement

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