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Technical note

Pulse pressure waveform estimation using distension profiling with contactless optical probe

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ABSTRACT

The pulse pressure waveform has, for long, been known as a fundamental biomedical signal and its analysis is recognized as a non-invasive, simple, and resourceful technique for the assessment of arterial vessels condition observed in several diseases. In the current paper, waveforms from non-invasive optical probe that measures carotid artery distension profiles are compared with the waveforms of the pulse pressure acquired by intra-arterial catheter invasive measurement in the ascending aorta. Measurements were performed in a study population of 16 patients who had undergone cardiac catheterization. The hemodynamic parameters: area under the curve (AUC), the area during systole (AS) and the area during diastole (AD), their ratio (AD/AS) and the ejection time index (ETI), from invasive and non-invasive measurements were compared. The results show that the pressure waveforms obtained by the two methods are similar, with 13% of mean value of the root mean square error (RMSE). Moreover, the correlation coefficient demonstrates the strong correlation. The comparison between the AUCs allows the assessment of the differences between the phases of the cardiac cycle. In the systolic period the waveforms are almost equal, evidencing greatest clinical relevance during this period. Slight differences are found in diastole, probably due to the structural arterial differences. The optical probe has lower variability than the invasive system (13% vs 16%). This study validates the capability of acquiring the arterial pulse waveform with a non-invasive method, using a non-contact optical probe at the carotid site with residual differences from the aortic invasive measurements.

1. Introduction

The profile of the arterial pressure pulse shows the result of the ventricular blood ejection over the arterial system, modulated by its mechanical properties. The load on the ventricle during ejection can be described by the systolic blood pressure. The arterial pressure wave travels from the central aorta to the peripheral arteries and several changes occur. The pulse pressure wave progressively steepens and increases in amplitude, while it loses the sharpness of the dicrotic notch [1].

Another effect that contributes to the pulse pressure profile is the time of arrival of the reflected pressure wave in the arterial system, during the cardiac cycle. This will depends on the pulse wave velocity (PWV) and the distance from the individual reflecting sites. One must note that the reflected waves of the most peripheral reflecting sites will arrive earlier at the larger peripheral arteries than at the central aorta [2]. The pulse pressure waveform, measured at the aortic site, is expected to be very similar to the waveform acquired in the carotid vessel (despite their proximity) but not equal, due to their different mechanical behaviour that results from the differences in the structural properties of the vessel walls [3,4].

The arterial pulse waveform is affected by changes in the peripheral circulation or alterations in the cardiac operation. Thus, the pulse wave analysis (PWA) could provide a better understanding of the risk factors, as well as help in establishing the extent of cardiovascular diseases, diagnosis and monitoring of the therapies effects [5–8].

Direct blood pressure monitoring with an arterial catheter is currently considered to be the most accurate method, but its invasive nature has several disadvantages. Great efforts have been made in the development of new techniques for non-invasive detection

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[7]. However, all of them establish direct contact with the patient's tissues at the artery site, which may distort the waveform. Then, the clinical application of a non-invasive and non-contact method can overcome practical and technical limitations inherent to the currently used methods such as arterial applanation tonometry, ultrasound and plethysmography. They require contact of the probe with the patient skin and compress the artery throughout an entire cardiac cycle, so the Bernoulli effect distorts the shape of the pulse curve [9,10].

For instance, in the tonometry the probe needs to be placed over the widest pulsation area, and requires support from solid structures such as the bone. For this reason, it is difficult to make valid measurements with tonometry over the carotid artery, since it is involved in soft tissues [11]. Moreover, arterial tonometry must be used with great caution in patients with carotid atherosclerotic plaques. Any risk of rupture attributable to the high external pressure, imposed by probe, should be avoided [12]. Therefore, the contactless technique is obviously safer in this aspect. Several patients also feel quite a discomfort during carotid applanation tonometry, especially when their pulsation is not easily assessed (i.e. obese patients).

In the current study, an optical non-contact probe developed for measuring the distension waveform of the carotid artery is compared with the pulse pressure waveform acquired by an intra-arterial catheter in the ascending aorta, during cardiac catheterization procedures, in order to validate the new optical device. This work was carried out with the aid of the Hemodynamic team from the Cardiology Unit of the Centro Hospitalar e Universitário de Coimbra (CHUC) and designed to determine the correlation between the two waveforms and analyse the differences obtained from PWA parameters, based on the time intervals of the cardiac cycle and the corresponding areas in the arterial pulse waveform of 16 subjects who had undergone cardiac catheterization [13,14].

2. Methods

2.1. Description of the optical system

The optical probe was designed to assess the arterial pulse wave profile at the carotid site, based on the optical reflectance fluctuations of the skin surface during the underlying pulse wave propagation [15].

The carotid artery is the natural probing site for the pulse waveform measurement due to the heart proximity and because it is easily accessible, i.e. it is close to the skin surface. The blood pressure wave travels across the arterial tree in a compliant way, forcing the blood vessels to distend elastically, according to the pressure wave profile, and causing a visible distension effect. This distension can be used to generate an optical signal correlated with the passing blood pressure wave. Several studies have shown that the distension waveform and the pressure waveform have an analogous wave contour and, therefore, can reciprocally be used for pulse wave analysis [16–18].

The functional structure of the optical probes allows the emission of the light and the detection of the reflected beam light. The box containing the optical probe, in an ergonomic configuration, ensures a non-contact signal acquisition at the artery site, by keeping a 3 mm distance between the probe and the skin surface. The obtained signals were digitized with a 16-bit resolution data acquisition system (NI, USB6210®) at a sampling rate of 20 kHz and stored for offline analysis using Matlab® tools.

Previously, a comparison test was carried out between an ultrasound image system GE *Vivid e*® (30 Hz), as a source of reference data, and the optical sensors that allow a higher resolution (20 kHz), adequate to feed feature extraction algorithms [16]. The clinical use of these optical probes includes vast applications, as they provide enough resolution for features extraction with higher accuracy, and they are an inexpensive and a non-invasive diagnostic method for the detection and monitoring of the pressure wave profile.

Table 1
Main characteristics of the volunteers.

Characteristics	Value
n, Males/females	16 (12/4)
Age, years	65.2 ± 12.3
Height, cm	163.3 ± 6.0
Weight, kg	72.3 ± 7.0
BMI, kg/m^2	27.1 ± 2.6

Values are numbers or means ±SD.BMI indicates the body mass index (weight/height^2).

A larger study was performed in 131 young subjects and the results showed that the use of this new technique is a trustworthy method to determine PWV and PWA parameters using dedicated algorithms [19,20].

Previous studies have proved the good reproducibility of arterial pulse waveform acquired with the optical technique in 13 patients by 2 senior operators. The results show small Standard Deviation of Measurement (SEM) values for heart rate (operator A: SEM = 1.47, operator B: SEM = 1.79), Augmentation Index (operator A: SEM = 1.70, operator B: SEM = 1.89) and ETI (operator A: SEM = 1.96, operator B: SEM = 2.27) [21].

2.2. Study population

The characteristics of the volunteered population in this study are presented in Table 1. This is a preliminary study for correlation of the two measures and not a statistical study. This is a prospective study. Similar studies of this kind present a sample of the same magnitude [14,22,23].

2.3. Study protocol

Measurements were performed in a study population of 16 patients, with a cardiovascular pathology, who had undergone cardiac catheterization. In all cases, simultaneous invasive (in the aortic root) and non-invasive measurements were performed. The study protocol was approved by the ethical committee of the CHUC.

Subjects were allowed to rest 15 min in the supine position at a temperature-controlled environment before the angiography proceeds. Each exam procedure consisted in the acquisition of a set of cardiac cycles at the carotid artery for 5 min with the optical system. The measurements were taken by a senior physician who had been trained to operate the optical probe device.

After the optical signal acquisition, the arterial catheter was used to monitor the blood pressure during the surgery and it was positioned to record the pulse pressure at the aorta site. In these tests a 6-Fr Judkins right catheter was used that was connected to a pressure transducer using a saline infusion system. After flushing and calibration the transducer, the hemodynamic polygraph was set to 200 mmHg/10 cm sensitivity and at a 100 mm/s registry speed. The used system was a Siemens® *Artis Zee* with AXIOM Sensis hemodynamic recording system. For waveform analysis data were resampled for 10 s at 200 Hz to cover, at least, two respiratory cycles.

2.4. Hemodynamic measurements

To compare the waveforms acquired with the two systems with different amplitudes and time duration, it is convenient to normalize both over amplitude and time. After this process, the dicrotic