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Technical note

Non-contact and through-clothing measurement of the heart rate using ultrasound vibrocardiography

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ABSTRACT

We present a novel non-contact system for monitoring the heart rate on human subjects with clothes. Our approach is based on vibrocardiography, and measures locally skin displacements. Vibrocardiography with a laser Doppler vibrometer already allows monitoring of this vital sign, but can only be used on bare skin and requires an expensive piece of equipment. We propose here to use an airborne pulse-Doppler ultrasound system operating in the 20–60 kHz range, and comprised of an emitter focusing the ultrasound pulses on skin and a microphone recording the reflected waves. Our implementation was validated *in vitro* and on two healthy human subjects, using simultaneously laser vibrocardiography and electrocardiography as references. Accurate measurements of the heart rate on clothed skin suggest that our non-contact ultrasonic method could be implemented both inside and outside the clinical environment, and therefore benefit both medical and safety applications.

1. Introduction

Monitoring the heart rate (HR) and its variability is of major importance for medical practice, and presents other safety-oriented applications such as the detection of driver fatigue [1,2]. To measure this vital sign, several conventional methods are used inside and outside the clinical environment: electrocardiography (ECG) or photoplethysmography. These methods provide clinically-relevant measurements but are limited by the need of physical contact. Indeed, physical contact with the skin can cause discomfort to the subject leading to potential physical and psychological burden, and can be inappropriate for specific groups of patients such as infants or patients with cutaneous conditions. To perform contactless measurements, various methods have been investigated and have been recently reviewed [3,4].

Among the most promising approaches, optical vibrocardiography was developed to measure, locally and without physical contact, the heartbeat rate [5,6] but also the respiration rate [7]. The method relies on measurements of the temporal variations in the skin displacement induced by the beating heart and breathing motions. The local measurement, with a Laser Doppler Vibrometer (LDV), allows interrogating different body locations as physicians with a stethoscope. In particular, measurements at the center of the chest wall and above the common carotid arteries were shown to provide complementary cardiovascular information: the HR and its variability [5,8], and the pulse wave velocity [9] – an indicator of the arterial stiffness, respectively. The Laser vibrocardiography (LVCG) measurements were validated by co-registration with conventional techniques [5,7,10] and demonstrated that the skin vibration reports information on cardiac electromechanical events similarly to the ECG [5]. However, the LDV is an expensive piece of equipment that moreover requires the use of non-enclosed laser beams. Furthermore, reported measurements were performed on the naked skin, limiting the usage of LVCG mostly to clinical examination, and for full sensitivity, it may require to place catadioptric paper on the skin [5].

To obtain similar measurements of the local skin vibrations, but with a low-cost system, without the use of hazardous radiations and with the possibility to keep clothes on, we present a new method based on pulse-echo measurements of ultrasound waves, thereby called Ultrasound Vibrocardiography (UVCG). Previous studies have been carried out with a ultrasound Doppler radar but aimed at global measurement on the body vibrations and were only able to detect respiration displacement [11]. Here, we investigate focused airborne ultrasound to restrict the extent of the probed area.

To demonstrate the validity of our approach with and without clothing, we first determined the displacement sensitivity and the accuracy of the measurement of time intervals between similar repetitive events *in vitro* with a controlled shaker. Then, we

Abbreviations: DAQ, Data Acquisition system; ECG, Electrocardiography; HR, Heart Rate; LDV, Laser Doppler Vibrometer; LVCG, Laser vibrocardiography; UVCG, Ultrasound vibrocardiography.

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showed the performance of our UVCG system *in vivo* on human subjects. To compare the performance of our approach with the already validated LVCG method, simultaneous measurements were performed with our UVCG and a commercial LDV. ECG was also used as a reference for *in vivo* measurements.

2. Materials and methods

2.1. Experimental set-up

The experimental setup is presented in Fig. 1. It comprises three measurement systems: the UVCG system developed in this study, and two validation systems: a commercial LDV (OFV 505, Polytech GmbH) and a 3-lead ECG system (AccuSync 42 ECG). The LDV was similar to that used by Scalise et al. [12]. Signals from all three systems were simultaneously acquired using a four-receive-channel data acquisition system (DAQ) at a sampling rate of 500 kS/s (U2542A, Agilent Technologies).

The UVCG system was comprised of separated emitter and receiver. For the emission and focusing of the ultrasound waves on the vibrating surface, a piezoelectric transducer (20-1330, APC International Ltd) was placed at the first focus of an elliptical acoustic mirror (Fig. 1). An emitting channel of the DAQ was used to drive the transducer. The mirror, and its dimensions were chosen so that the f-number at the second focus is 1.1 (Fig. 1), leading to a focal spot with a ~9.5 mm transverse diameter (−3 dB) and a depth of field of 7 cm at 40 kHz. During UVCG measurements, the focused ultrasound waves reflected on the vibrating surface and a microphone (FG-23329, Knowles Electronics) orientated toward the surface received the ultrasound echoes. The vibrating surface was positioned in front of the device. Strict perpendicularity to the system axis was not necessary because of the ultrasound beam divergence after reflection. An electronic preamplifier modified to have a bandwidth of 10–100 kHz was used (modified Velleman electronic kit K2572). Ultrasound emission and reception were synchronized.

The laser beam of the LDV passed through a 5 mm diameter hole in the elliptical mirror to ensure co-focal measurement of the UVCG and the LVCG systems. The velocity range on the laser was set to ±25 mm/s.

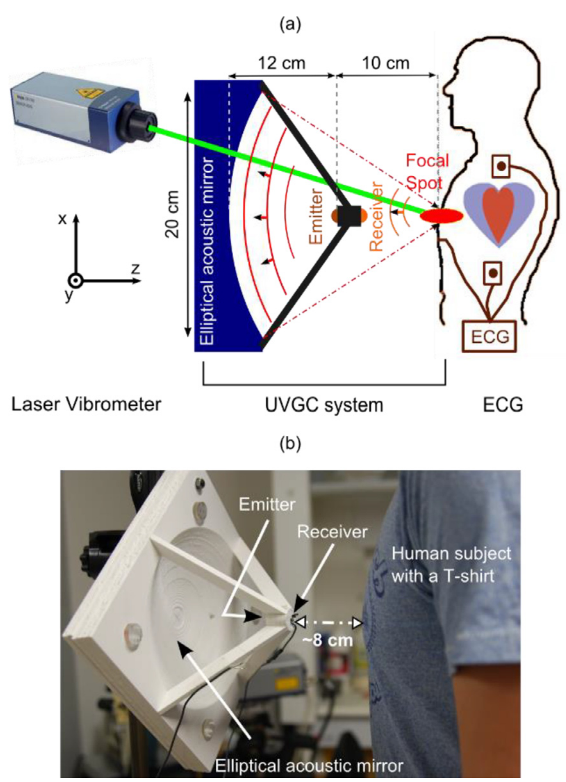

Fig. 1. (a) Schematic drawing of the experimental setup comprised of the UVCG system, a Laser Doppler vibrometer (LDV) and an ECG system. For the UVCG system, the ultrasound waves emitted by an emitter were first reflected on the elliptical acoustic mirror (custom built using PVC slabs, weight ~1 kg), and then focused on the vibrating surface (surface of the human subject here). After being, reflected on the vibrating surface, the waves were recorded by the receiver (microphone). A hole in the elliptical mirror enabled the laser beam of the LDV to probe a measurement point in the ultrasonic focal spot. A Cartesian coordinate system is introduced. (b) Annotated photograph of the UVCG system.

2.2. Acquisition sequence for the UVCG system

The displacement along the z-axis of the portion of the body surface located in the focal zone of the UVCG system was assessed using a pulse-wave Doppler mode. This operation mode was chosen over continuous-wave Doppler because of the multiple reverberations of the ultrasound waves after the first reflection on the surface. Pulse-wave Doppler allows temporal selection of the primary echo, and thereby limits disturbance of the displacement measurement by unwanted secondary echoes. To limit the spatial extend of the focal spot and take advantage of the bandwidth of the emission-reception system, the ultrasound emitter was operated in the frequency band: 20–60 kHz. The ultrasonic wavelength in air at 60 kHz is 5.7 mm, which is several orders of magnitude larger than the expected skin amplitude displacement associated with heartbeats. Therefore, the detection of heartbeat-induced vibrations requires estimating time delays much smaller than the smallest ultrasound period, between echoes corresponding to successive ultrasound pulses. Several methods exist to determine subsample time delays [13,14], but they are sensitive to noise. To increase the signal-to-noise ratio of the echoes, we performed pulse compression. A binary phase shift keying code (BPSK) using a M-sequence [15] was chosen for the good autocorrelation properties of this signal modulation [16]. The BPSK phase-modulated signal was created from an M-sequence of 255 bits and with a carrier frequency of 50 kHz. Each bit was associated with a period of the carrier frequency and a π-phase shift was used. The signals were band-pass filtered (Butterworth filter, order 3, cut-off frequencies 20 kHz and 60 kHz) before being transmitted to the emitter. The modulated signals were sent continuously, setting the pulse repetition frequency of the system to 196 Hz.

The recorded signals were processed post-acquisition. First, pulse compression was performed by cross-correlating the recorded signals with the filtered BPSK phase-modulated signal sent to the emitter. Because the velocity of the skin is negligible compared to the ultrasound velocity, the Doppler frequency shift induced by the reflection on the moving target was determined to be negligible. After pulse compression, the position of the maximum of the cross-correlation, in the time interval corresponding to the primary echo, was estimated using a parabolic approximation [17], and tracked from one pulse to the next. For each pulse, the position of the maximum of the cross correlation corresponds to the time of flight Δt between the emitter and the receiver, and is linearly dependent on the displacement δ_z along the z-axis of the surface (Eq. (1)),

$$\Delta t = t_0 + 2.\delta_z/c \quad (1)$$

with t_0 the time of flight corresponding to a target located at the focal point, and $c = 343$ m/s the ultrasound velocity in air.

After processing the signals corresponding to successive pulses, we obtained a measurement of the displacement δ_z at a sampling rate of 196 Hz. This sampling frequency allows to measure

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