A portable device to assess underwater changes of cardio dynamic variables by impedance cardiography

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Abstract. Data concerning heart rate (HR), stroke volume (SV), and cardiac output (CO) during dynamic apnoea (DA) were collected from 10 healthy male, elite divers by means of an impedance cardiograph adapted to the underwater environment (C.O.Re., from 2C Technologies Inc, Italy). Three trials were performed by the divers in a 3-m-deep pool with a water temperature of 25°C: 3-minute head-out immersion during normal breathing (A), till exhaustion immersed at the surface (B) and at 3m depth (C). Both B and C conditions did not lead to changes in HR, SV and CO compared to A. Data indicate that typical diving response consisting in a reduction of HR, SV and CO was not present during DA, probably due to sympathetic activation induced by exercise during DA, which partially obscured the effects of the diving response. Moreover, this study highlights the innovative role of our portable, impedance cardiography device, i.e. the C.O.Re., in easily assessing cardiodynamic changes in subjects engaged in exercise schedules including phases of underwater, dynamic apnoea.

Introduction

The assessment of cardiovascular adjustments during underwater apnoea is rendered difficult by the technical limitations related to hemodynamic measurement in the underwater environment. Most of the studies in this field attempted to reproduce conditions similar to real diving in head-out immersed subjects [1], in simulated diving in a pressure chamber [2], and apnoeas with or without face immersion in exercising humans [3]. Furthermore, recently underwater ultrasound cardiac measurements provided exciting new data on heart rate (HR), stroke volume (SV), and cardiac output (CO) responses during diving in humans. In particular, Marabotti and co-workers [4] reported a reduction in HR and SV, and consequently in CO, during underwater, static apnoea. Therefore, this response was interpreted to induce an oxygen-conserving effect as is described in marine animals [5]. However, in the above mentioned studies apnoea was always static because of the impossibility to conduct ultrasound measurements in moving subjects since the ultrasound device was cumbersome. Thus, the only hemodynamic measurements performed during dynamic breath-hold to date were carried out during simulations in a laboratory setting [6]. This research revealed that heart rate (HR) and cardiac output (CO) decreased. The aim of the present investigation was to adapt a impedance cardiography device in such a way of measure the hemodynamic changes due to dynamic apnoea in freely moving subjects in the underwater environment. To this end, a miniaturised, portable impedance cardiograph, which was sealed in a small waterproof container, was developed to assess hemodynamics in the underwater environment. We believed such a measurement would describe better the cardiovascular changes in a situation closer to real apnoea than previous investigations had.

Methods

Subjects. Ten healthy male, elite divers (33.2±3.6 years, 172.4±7.2 cm, and 64.1±6.6 kg) were recruited. All participants received information about the aims and the procedures of the study which was performed according to the Declaration of Helsinki and conformed to Good Publishing Practice in Physiology.

Measurements. All hemodynamic measurements were performed by means of impedance cardiography, a method commonly employed to assess hemodynamic changes in resting and exercising subjects [7, 8, 9, 10]. The impedance method provides reliable, non-invasive data of SV, HR and CO. This technique assumes that, when an electrical current circulates through the thorax, the pulsatile aortic blood flow causes a proportional fluctuation in the electrical conductivity. Given this, changes in thoracic electrical impedance during systole are representative of SV [11]. By measuring several reference points on the impedance waveforms, SV can be estimated by applying the Sramek-Bernstein equation [12].

In detail, VEPT was the volume of electrical participating tissue and was derived using a nomogram from subjects’ sex, height, and weight; \( Z_0 \) was the thorax impedance measured at the end of cardiac diastole [8]; \( dZ/dt_{max} \) is the maximal \( Z_0 \) first derivative value during cardiac systole; VET was the left ventricular ejection time, calculated as the...
interval between the beginning and the minimum of the deflection in dZ/dt trace during systole. In summarising, through impedance traces it was possible to calculate the following parameters: SV, HR, and CO, the later obtained by multiplying SV×HR.

**Instrumentation.** To apply the impedance method during underwater apnoea, a miniaturised Cardiac Output Recorder (C.O.Re., 2C Technologies Inc, Cagliari, Italy) was utilised (Fig.1, panel A).

![Fig. 1. Panel A: the miniaturised impedance cardiograph ("C.O.Re") contained in a waterproof torch for underwater use. Panel B: the C.O.Re is placed inside the torch before diving. Panel C: one of the divers while performing a 3-minute head-out immersion during normal breathing. Panel D: one of divers while executing dynamic apnoea fully immersed at surface.](image)

This device consists of an analogic front-end with a A/D converter. The components of the analogic section are: a sinusoidal current generator at a constant frequency of 65 kHz, an amplifier to assess transthoracic impedance, with a demodulator, which output is connected to the digital section. The digital section consists of a 8 bit microcontroller with a A/D converter (resolution of 10 bit) which converts input signals in serial data. The C.O.Re. was placed in an underwater torch, which was waterproof to a depth of 90m (Fig.1, panel A-B) and was turned on at the beginning of each session(Fig.1, panel B). The C.O.Re. recorded impedance traces throughout the whole experimental session on a secure digital memory card. Impedance recorded traces were then analysed by employing a digital chart recorder (ADInstruments, PowerLab 8sp, Castle Hill, Australia), and hemodynamic parameters were calculated. To establish the validity of the C.O.Re., comparison with an impedance cardiograph (NCCOM3-R7, BoMed, CA Inc) previously validated in scientific literature was carried out [15, 16]. Stroke volume values were obtained by both instruments on 18 male subjects (mean ± SD of age, height, and mass were 28.8±5.1 years, 175.8±3.9 cm, and 66.8±6.1 kg respectively) during rest and exercise up to 70% of maximum HR calculated as 220-age.

**Study protocol.** Hemodynamic changes were assessed during dynamic apnoea in a 3-m-deep pool with a water temperature of 25°C. In detail, during one session three trials were carried out as follows by each subject. Test A: consisted of a 3-minute head-out immersion during normal breathing. This situation was considered the baseline level (Fig.1, panel C). Test B: involved dynamic apnoea till exhaustion with the body fully immersed at the surface (Fig.1, panel D). Test C: during this test divers underwent dynamic apnoea till exhaustion at 3m depth.
During periods of dynamic apnoea, divers were instructed to follow a light signal placed at the bottom of the pool in order to maintain a constant speed of 0.5 m·sec⁻¹, according to the usual methods of dynamic apnoea training. The goodness of the speed control was tested by a standard chronometer. All divers had a 2 to 4 minute period of respiratory preparation before performing apnoea sessions. They were asked to begin apnoea phases after a maximal inspiration without any manoeuvres of hyperventilation. Ballast applied to the waist was used during tests B and C and the weight of ballast was chosen according to subjects' personal experience and body mass to ensure neutral buoyancy. The portable impedance cardiograph was applied to the subjects' chest by 8 electrodes [12], which were waterproofed using surgical 15x10 cm patches (Plastod, Bologna, Italy). Then, subjects simply wore a diving suit and a diving mask. At the end of each trial electrodes status was inspected to attest that the waterproof condition was maintained.

Statistical analysis. The Bland and Altman statistics [17] was used to assess agreement between the two methods of measurement to compare SV obtained from the C.O.Re. and the NCCOM3. In order to compare subjects with different body masses, data during apnoea phases were transformed into percentage changes from test A values. One-way ANOVA for repeated measurements was applied to determine significance between the various periods of the protocol and Newman-Keuls post-hoc was performed when appropriate. Significance was set at a p value <0.05.

Results

The Bland and Altman statistics show that there was positive agreement between the C.O.Re. and the NCCOM3 both at rest and during exercise as limits of agreement between the two methods were within +7.01 and -8.12 ml at rest and + 6.77 and -9.86 ml during exercise (Fig.2).

![Fig. 2. Bland and Altman plot applied to stroke volume measured by the C.O.Re (SVc) and the BoMed (SVb) at rest (top panel) and during exercise (bottom panel).](image)

The group mean duration of dynamic apnoea periods was 91.6±18.2 and 95±32.1 s for Test B and C respectively. Absolute values of hemodynamic data during test A preceding apnoeas were: HR = 68.8±3.9 beats·min⁻¹; SV =
During test B the same variables showed the following values: HR = 70.2±4.8 beats•min⁻¹; SV = 62.1±6.2 ml; CO = 4.3±0.6 l•min⁻¹. During test C hemodynamic data were: HR = 69.5±4.9 beats•min⁻¹; SV = 62.7±8.2 ml; CO = 4.3±0.9 l•min⁻¹. No statistical significance was shown among hemodynamic variables assessed during A, B and C tests (Fig.3).

Fig 3. Heart rate (HR, top panel), stroke volume (SV, middle panel), and cardiac output (CO, bottom panel) time courses during the experimental setting. (A) Head-out immersion. (B) Dynamic apnoea at the surface. (C) Dynamic apnoea at 3m depth. Values are means ± SD percent changes from test A.

Discussion
An important finding arising from the present investigation is that during both dynamic apnoea sessions, HR and SV were at the same level as at baseline, so that CO was stable. It is important to notice that an oxygen-sparing effect is often attributed to the classical diving response, which during exercise appears to be proportional to the degree of the bradycardia [18]. The new finding in this investigation is that hemodynamic response during static apnoea was virtually abolished when dynamic apnoea was performed. Indeed, in this setting HR and SV were substantially unmodified with respect to baseline, so that CO did not decrease. Our data consent us to speculate that the supposed
O₂-sparing effect was less evident during dynamic apnoea compared to static apnoea. Therefore, it is likely that during tests B and C the energetic demand of the exercising muscles, together with the activation of cardiovascular control areas in the brainstem, played a pivotal role in counteracting the hemodynamic effects of the diving reflex. A similar conflict between exercise and diving cardiovascular responses was hypothesized for diving ducks which usually show an increase in HR above resting values during natural dive [5].

It is well known that during exercise an increase in sympathetic tone takes place in order to guarantee adequate mean blood pressure (MBP), particularly during hypoxic exercise [19]. This increased sympathetic drive derives from the integration of two main neural mechanisms: in one, commonly termed "central command", the activation of regions of the brain responsible for motor unit recruitment also activates the cardiovascular control areas located in the medulla [20]; in the other, known as the "exercise pressor reflex", receptors within the muscles reflexively activate afferent nerves and induce sympathetic-mediated cardiovascular adjustments on the basis of the mechanical and the metabolic condition of the contracting muscle [20]. Both the central command and the exercise pressor reflex are responsible for activation of sympathetic activity, which in turn increases HR and cardiac performance, thereby raising CO [21]. These cardiovascular adjustments aim at counteracting the increase in vascular conductance due to vasodilatation in the contracting muscle, thus avoiding falls in MBP [22]. Our findings suggest that, during periods of dynamic apnoea, activation of both the central command and the exercise pressor reflex could have, at least in part, masked the typical hemodynamic response to apnoea, i.e. bradycardia and SV reduction.

We previously reported a similar cardiovascular response during exercise with face-immersed apnoea, when an increase in myocardial performance and SV occurred and obscured the cardiovascular effects of the diving response [23]. In the quoted study, we hypothesised that during simulated dynamic apnoea the exercise pressor reflex acted in opposition to the diving reflex to maintain cardiovascular homeostasis during exercise. The results of this investigation, in agreement with that hypothesis, extend the concept that exercise may also offset the effects of diving reflex for real dynamic apnoea, when hypoxia probably took place and strengthened the metaboreflex-induced sympathetic response [19].

This study also highlights the innovative role of our portable, impedance cardiography device, i.e. the C.O.Re., in easily assessing cardiodynamic changes in subjects engaged in exercise schedules including underwater, dynamic apnoea. In fact, in the light of the above findings, assessing cardiodynamic variable during underwater apnoea ought give relevant helping in optimizing training schedules of apnoea diving athletes. Moreover, underwater dynamic apnoea, with cardiodynamic assessment by the C.O.Re. device, ought be included in breath-hold exercises that often are part of respiratory rehabilitation in respiratory disease patient, since easily acquisition of cardiodynamic profile may help to prevent some cardiovascular accidents during these manoeuvres.

**Keywords**

Underwater Apnoea, Cardio Dynamics, Impedance Cardiograph, Portable Medical Devices.

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