Cardiovascular aspects of glossopharyngeal insufflation and exsufflation.

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J. NOVALIJA,[1,2] P. LINDHOLM,[3] S.H. LORING[4], E. DIAZ,[1] J.A. FOX,[1] M. FERRIGNO[1]

[1]Department of Anesthesiology, Perioperative and Pain Medicine, Brigham and Women's Hospital, Harvard Medical School, Boston, MA, USA, [2]Dept. of Anesthesiology, Clement J. Zablocki VAMC, Medical College of Wisconsin, Milwaukee, WI, USA, [3]Environmental Physiology Centre, Department of Physiology and Pharmacology, Karolinska Institutet, Stockholm, Sweden, [4]Department of Anesthesia and Critical Care, Beth Israel Deaconess Medical Center and Harvard Medical School, Boston, MA, USA

Novalija J, Lindholm P, Loring SH, Diaz E., Fox JA, Ferrigno, M. Cardiovascular aspects of glossopharyngeal insufflation and exsufflation. Undersea Hyperb Med 2007; 34(6):415-423. Breath-hold divers use glossopharyngeal breathing to inhale above total lung capacity (glossopharyngeal insufflation, GI) or exhale below residual volume (glossopharyngeal exsufflation, GE). In these maneuvers, air is moved using glossopharyngeal rather than respiratory muscle activity. Four competitive divers performed several GI and GE maneuvers in sitting or standing position, while cardiovascular parameters were measured with a photoplethysmographic method; echocardiography was also performed during GE. During GI, the divers showed a 48% drop in mean arterial pressure (MAP) to 50 mmHg, with a 88% decrease in pulse pressure (PP), while heart rate (HR) increased by 36% to 103 beats/min and cardiac output (CO) dropped by 79% to 1.3 l/min. The increase in intrathoracic pressure during GI, measured in separate experiments (7), is probably responsible for these hemodynamic changes, by impeding venous return into the chest. Associated with the drop in MAP during GI were various neurological signs and symptoms, including dizziness, tunnel vision, involuntary twitching of facial muscles and one brief episode of loss of consciousness. During GE, initially MAP and PP increased by 36% and 61%, to 149 and 95 mmHg respectively; later HR decreased by 37% to 45 beats/min and CO dropped by 37% to 4.3 l/min. The early cardiovascular changes of GE may be related to a decrease in intrathoracic pressure, enhancing venous return, as shown by a 6 to 15% increase in end-diastolic diameter; later changes are similar to the responses to apnea at low lung volumes. Because of their hemodynamic effects, these breathing maneuvers should be performed with caution, particularly in the case of GI.

INTRODUCTION

Glossopharyngeal breathing (GPB) can be used to inhale air above total lung capacity (TLC) (glossopharyngeal insufflation, GI; also known as lung packing) or to exhale air below residual volume (RV) (glossopharyngeal exsufflation, GE, also know as reverse lung packing). GI maneuvers are employed by competitive breath-hold divers to increase both diving depth and duration: a larger initial lung volume (achieved with GI before a dive) increases both oxygen stores and the depth at which dangerous compression of the chest occurs. In comparison, GE is used to draw air from compressed lungs into the pharynx, for pressure equalization in the middle ear at depth (1). During training, both of these maneuvers are also practiced by competitive divers at the surface (that is, without the large changes in ambient pressure typical of a deep breath-hold dive). Limited information is available on the cardiovascular response to GI and, to date, there have not been any studies on the hemodynamic response to GE. Therefore, we examined the cardiovascular response to both GI and GE in four competitive breath-hold divers, three of whom were world record holders.

GI was originally described in patients with either weak or absent function of their respiratory muscles due to polio or spinal cord injury. Using the glossopharyngeal muscles, these patients were able to increase the amount of air inhaled into their lungs (2). This technique had beneficial effects on coughing, speech and gas exchange and allowed some patients to stay off of the ventilator for hours (3). In contrast to patients who start with impaired pulmonary function and fill their lungs with air within their vital capacity (VC), divers use GI to overfill their lungs by inhaling first to their TLC and then using the GI technique to inhale an additional 1-3 l (1, 4). Two studies have shown a decrease in arterial blood pressure (BP) during forceful and repeated GI maneuvers: one in a patient (5) and the other in divers (6). It has been suggested that the drop in BP during GI maneuvers on land could cause syncope (1, 6) and, according to divers' accounts, fainting is not uncommon for breath-hold divers who practice GI. However, this phenomenon has never been reported in the literature. GI is associated with relatively high intrathoracic pressures (estimated by esophageal manometry, see 7) which could lead to a drop in BP, due to impaired venous return and consequent reduction in stroke volume (SV). This, in turn, would explain the episodes of fainting when repeated GI maneuvers are performed to achieve very large lung volumes.

To our knowledge, GE is used primarily by breath-hold divers (1), although Collier et al mentioned a patient who could perform a technique described simply as "pumping air out of the lungs with the tongue and pharyngeal muscles" (5). It is likely that this patient performed this maneuver starting from a volume above RV. On the other hand, elite divers using this method at sea frequently reach a lung volume that is below their conventional RV; during actual diving, they employ GE to draw air from their compressed lungs in order to equalize pressure in their middle ears (1). On the other hand, during their training at the surface, they first exhale to RV and then, using GE, extract additional air from their lungs. No information is available in the literature on the hemodynamic effects of GE maneuvers, except that MRI imaging of the chest during GE showing engorgement of pulmonary blood vessels and cardiac dilation (1). GE is probably associated with relatively low intrathoracic pressures, which could increase venous return and, consequently, cardiac output (CO).

In the present study, we measured heart rate (HR), BP and CO non-invasively during both GI and GE maneuvers performed by four competitive breath-hold divers. We also obtained imaging of the heart by echocardiography during GE. This study was part of a wider physiological investigation that also included measurements of respiratory mechanics (7) and radiological studies during these maneuvers.

METHODS

One female and three male elite breath-hold divers gave written consent for the study, which had been approved by the Human Research Committee at Brigham and Women's Hospital. They also agreed to publication of their athletic records at the time of the study (Table 1): the female and two of the male divers were world record-holders in different disciplines of breath-hold diving (for a list and description of these disciplines, see www.aida-international.org and 8,9). The divers in the present study were healthy non-smokers, experienced at performing GI and GE maneuvers in training and competition. All GPB maneuvers were performed with the divers in either sitting or standing position, with the arms resting on a table at the level of the xiphoid process. After

Table 1. Subjects' physical characteristics and personal records.

Diver	Age (yr)	Height (cm)	Weight (kg)	Maximal Breath-hold Time (s)	Maximal Depth* (m)
1 (male)	31	182	70	405	55
2 (female)	32	170	57	376	160
3 (male)	28	178	74	495	136
4 (male)	28	193	79	608	122

* Depths reached using different unassisted or assisted diving techniques. For a list and description of these techniques, see www.aida-international.org

instrumentation, baseline measurements were obtained during spontaneous breathing at rest for 2 minutes; then each subject performed 3 GI and 4 GE maneuvers, respectively, separated by at least 15 minutes of rest. To minimize risks to our subjects, no predetermined duration for GPB maneuvers was imposed; instead, the divers were instructed to perform the maneuvers as they usually do during their training.

Beat to beat systolic and diastolic BP and HR were measured continuously with a photoplethysmographic finger-cuff device (Finometer®, Finapres Medical Systems BV, Amsterdam, The Netherlands), which also calculated CO and stroke volume (SV). All the data, including waveforms, were continuously recorded and stored on the hard drive of the Finometer® for later analysis. Artifacts in the Finometer® signal were excluded based on error messages provided by the device and on visual inspection of the tracings. Finometer® data were analyzed using the Beatscope® software. The GI data from one of the divers had to be excluded, as the BP tracing consistently failed at the time when the breathing maneuver was started, probably because of intense peripheral vasoconstriction. Baseline cardiovascular values were defined as the average of readings over 10 s prior to the beginning of each breathing maneuver. For the GI maneuvers, the lowest value of mean arterial pressure (MAP) was identified and the corresponding values of systolic and diastolic BP, HR, pulse pressure (PP), SV and CO were compared to the baseline values. Timing of lowest values of MAP was different among subjects. For the GE maneuvers, the values at successive ten second intervals were compared to baseline values up to 60 s after the beginning of the breathing maneuver. Data from different GPB maneuvers were averaged first for each subject and then for each breathing-maneuver. Then, the mean and standard deviations were determined for baseline and lowest values for GI or baseline and values every 10 s for GE. Two of the divers terminated the GE maneuver before 60 s and therefore the 60 s values represent the results of only two of the subjects.

Prior to, and during the GE maneuvers, an echocardiograph machine (Siemens ACUSON Sequoia™ Ultrasound system, Siemens Medical Solutions USA Inc Malvern, PA, USA) with a 2-4 MHz transthoracic transducer was used to obtain cardiac images in both 2D and M-Mode, in the parasternal short and long axes. These transthoracic echocardiographic images were recorded on VHS tape and digitized loops (4 heart beats at baseline and during GE) were used to assess left ventricular end-diastolic (EDD) and end-systolic diameters. Loops that did not show parts of the left ventricular wall, or that were obtained in an oblique imaging plane, were excluded. The echocardiographic window had to be adjusted to account for the movement of the heart relative to the echo probe during the GE maneuvers. Therefore, as it took a variable amount of time to obtain reliable images during each breathing maneuver, left ventricular measurements were taken at different intervals in each experiment, which prevented data averaging and statistical analysis. Also, it was not possible to obtain transthoracic echocardiographic images during GI, as the inflated left lung overlay the heart and interfered with ultrasound transmission.

Due to the small number of subjects, no statistical analysis of the results was performed. However, the 4 competitive divers showed a similar pattern of cardiovascular changes, during both GI and GE. As part of a larger investigation on GPB, we measured respiratory mechanics during GI and GE maneuvers in the same four elite breath-hold divers (7). In that study we recorded intrathoracic (esophageal) pressure (P_{es}) during 2 to 5 GI and 2 GE maneuvers in each subject. Here, we report unpublished values of P_{es} sustained during GI and GE maneuvers, and also previously published values of transpulmonary and intrapulmonary pressure measured at the end of GI maneuvers to illustrate the physiological stresses that affected cardiovascular responses in our subjects.

RESULTS

GI

Figure 1 shows a typical Finometer® BP tracing obtained during a GI maneuver. Table 2 shows the corresponding cardiovascular changes: MAP and PP rapidly decreased by 48% and 88%, respectively (MAP ranged from 87 to 109 mmHg before GI and from 46 to 54 mmHg during GI; PP ranged from 41 to 75 mmHg before GI and from 5 to 10 mmHg during GI). However, HR increased by 36% (ranging from 64 to 99 beats/min before GI and from 71 to 125 beats/min during GI). Stroke volume and CO also fell by 87% and 82%, respectively (SV ranged from 66 to 98 ml before GI and from 9 to 20 ml during GI; CO ranged from 5.0 to 8.2 L/min ml before GI and from 0.8 to 1.6 L/min during GI). The following clinical signs and symptoms were observed in two of the subjects performing GI: lightheadedness, tunnel vision, involuntary twitching of facial muscles and a brief episode of loss of consciousness. These events occurred towards the end of the GI maneuvers and resolved quickly afterwards with no residual effects.

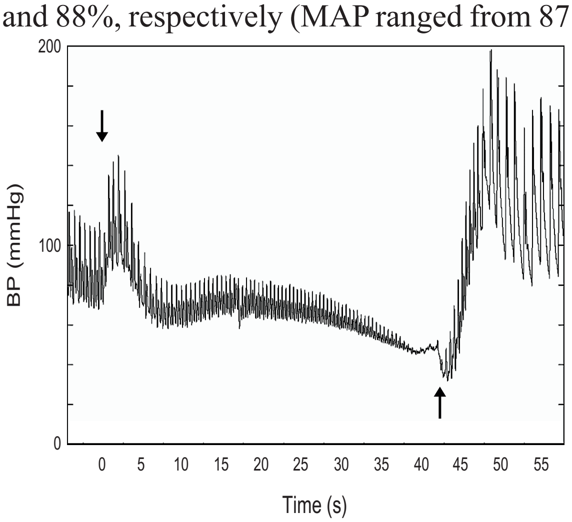


Fig. 1. Finapress® BP tracing during a GI maneuver; ↓ and ↑ indicate start and end of maneuver, respectively.

Table 2. Cardiovascular effects of GI maneuvers

	SAP (mmHg)	DAP (mmHg)	MAP (mmHg)	PP (mmHg)	HR (bpm)	SV (ml)	CO (L/min)
Baseline	126 (4)	77 (5)	96 (3)	49 (7)	76 (11)	82 (10)	6.2 (1.3)
GI	55 (2)	48 (2)	50 (2)	6 (1)	103 (25)	11 (3)	1.1 (0.05)
% change	-56	-38	-48	-88	+36	-87	-82

Mean and (SD) values during baseline and GI maneuvers. SAP: systolic arterial pressure; DAP: diastolic arterial pressure. Per cent change values between the two conditions are also shown.

GE

Figure 2 shows a typical Finometer® BP tracing obtained during a GE maneuver. Figure 3 shows the time course of the average cardiovascular changes. During these maneuvers, we observed a slight increase at 10 sec in both SV and CO, by 18% and 17%, respectively (SV ranged from 62 to 126 ml before GE and from 64 to 132 ml at 10 sec during GE; CO ranged from 4.8 to 9.9 L/min before GE and from 5.3 to 12.5 L/min at 10 sec during GE). Then, in the course of GE, MAP and PP increased by 36 and 61%, respectively (MAP ranged from 98 to 121 mmHg before GE and from 131 to 162 mmHg at 60 sec during GE; PP ranged from 46 to 82 mmHg before GE and from 70 to 136 mmHg at 60 sec during GE). At the same time, HR and CO both decreased by 37% (HR ranged from 58 to 98 bpm before GE and from 48 to 67 bpm at 60 sec during GE; CO ranged from 4.8 to 9.9 L/min ml before GE and from 4.6 to 5.2 L/min at 60 sec during GE). The echocardiographic images showed an increase in left ventricular EDD (from 48, 52, 34 and 44 mm at baseline to 53, 55, 39 and 50 mm, respectively in the 4 divers during GE). This increase in EDD either persisted until the end of the GE maneuver or showed a gradual return towards baseline values.

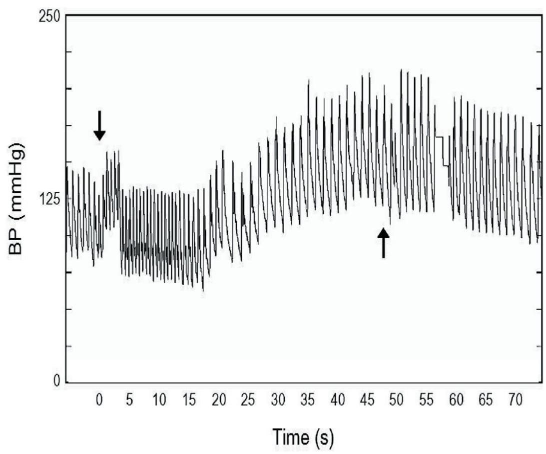


Fig. 2. Finapress® BP tracing during a GE maneuver; ↓ and ↑ indicate start and end of maneuver, respectively.

Fig. 3. Time course of average cardiovascular changes and SD during GE maneuvers: BP (Panel a), PP (Panel b), HR (Panel c), SV (Panel d) and CO (Panel e).

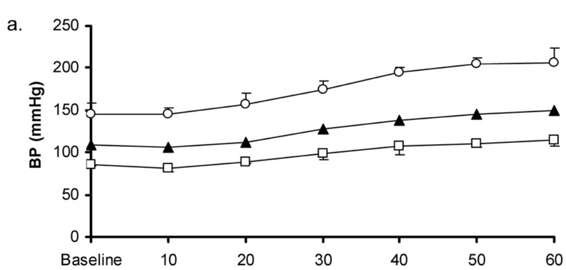
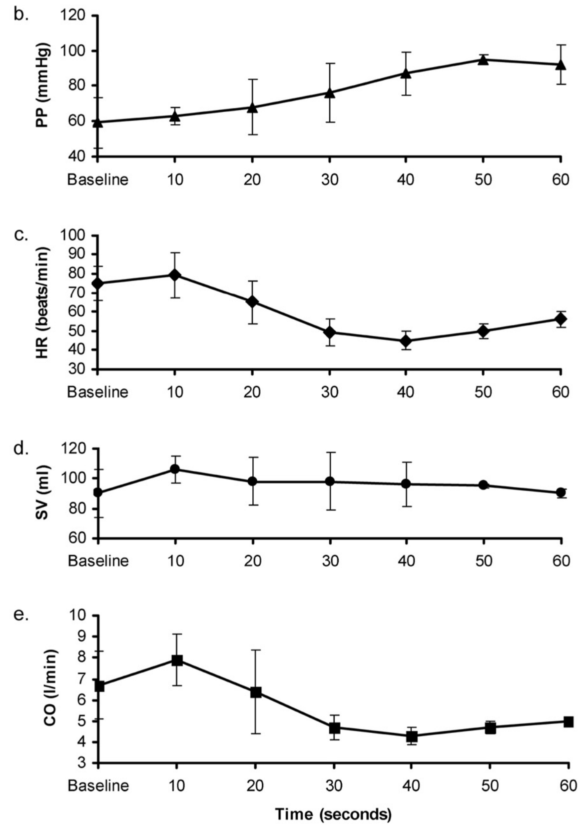


Fig. 3. continued



Intrathoracic pressures

Table 3, below, shows typical sustained P_{es} values for each diver recorded during both GI and GE in our previous study (7). The highest sustained P_{es} during GI in the 4 subjects ranged from 9 to 26 mmHg, while the lowest

Diver	1	2	3	4
P_{es} sustained during GI (mmHg) (Highest/Lowest)	24/10	9/8	20/15	26/18
P_{es} sustained during GE (mmHg) (Lowest/Highest)	-35/-31	-20/-16	-34/-33	-64/-26
Maximal Intrapulmonary pressure during exhalation from GI (mmHg)	38	42	72	81
Maximal Transpulmonary pressure * during exhalation from GI (mmHg)	32	34	54	59

*(= intrapulmonary pressure – Pes)

sustained P_{es} during GE ranged from -20 to -64 mmHg. Also shown are the reported maximum intrapulmonary pressure (an estimate of alveolar pressure compressing alveolar capillaries) and maximum transpulmonary pressure (intrapulmonary pressure - P_{es}) measured after GI (7).

DISCUSSION

This study is the first to examine the cardiovascular responses to both GI and GE maneuvers. The elite breath-hold divers in this study exhibited various neurological signs and symptoms associated with GI maneuvers, including lightheadedness, tunnel vision, involuntary twitching of facial muscles and a brief episode of loss of consciousness. According to divers' accounts, fainting is not uncommon when forceful GI is performed at the surface for training purposes; however, it has not been reported before as an adverse event in competitive breath-hold diving (cf. 10). These neurological signs and symptoms are probably related to a decrease in cerebral perfusion, secondary to a dramatic drop in CO; in fact, in this study we measured an 82% decrease in CO, mostly due to a similar fall in SV, with only a modest increase in HR. The only other cardiovascular study of GI maneuvers was performed by Anderson et al (6) who observed 49 and 36 % reductions in systolic and diastolic BP, respectively, similar to the 38 and 56 % decreases observed here.

In separate experiments with the same divers (7), we recorded sustained P_{es} values as high as 26 mmHg during GI; this high intrathoracic pressure is likely to greatly hinder venous return into the chest, thus causing the decrease in SV and CO we observed (cf 11). High intrathoracic pressures are also seen during Valsalva maneuvers; however, during those maneuvers, intra-abdominal pressure also rises (12), mitigating the deleterious effects on venous return. Still, syncope has been observed with forceful Valsalva maneuvers (13). We also measured maximum intrapulmonary pressures ranging from 38 to 81 mmHg during GI maneuvers. Such high pressures could compress alveolar capillaries, increasing right ventricular afterload which, in combination with reduced venous return, could decrease left ventricular preload and, consequently, SV.

The risk of a symptomatic decrease in cerebral perfusion is probably much less when a breath-hold diver performs a forceful but brief GI maneuver prior to diving. First of all, if the diver is immersed, even partially to his/her waist, venous return into the chest and CO are increased above normal because of the hydrostatic pressure counteracting the dependent blood pooling that occurs on land (14). Second, compression of the diver's chest, particularly rapid in the first part of descent where changes in pressures and volume are more dramatic, will lead to a decrease in intrathoracic pressure (compared to the pressure outside the chest) due to a smaller inward recoil of the chest wall (cf. 15). This may protect the diver from the dramatic drop in CO and cerebral perfusion which tends to occur during prolonged GI at the surface. Anderson et al speculated that the longer a GI maneuver is performed, the more likely neurological symptoms like syncope can be expected (6). However, in one of our divers who performed a particularly long and slow GI maneuver we observed a gradual recovery in BP values, while his PP remained low (see Fig 4**).** This may reflect baroreflex compensation, with increased peripheral vasoconstriction restoring MAP.

With regard to the GE maneuvers, the cardiovascular response included a 36 % increase in MAP with a 37% decrease in HR; CO first increased slightly then fell by 37 %. The initial increase in SV and CO was probably

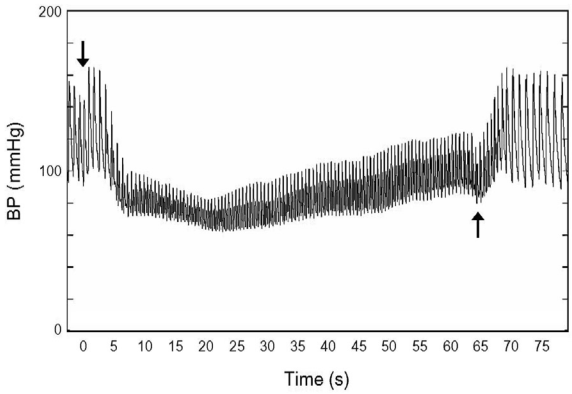


Fig. 4. Finapress® BP tracing during a prolonged GI maneuver; ↓ and ↑ indicate start and end of maneuver, respectively.

related to an increased venous return, as expected from a drop in intrathoracic pressure caused by the GE maneuvers. In fact, the lowest sustained P_{es} values during GE ranged from -20 to -64 mmHg in these 4 subjects (7). An increase in preload during GE was also suggested by our echocardiographic images showing an increase in left ventricular EDD at the beginning of this breathing maneuver in the four divers. Our finding is consistent with the recent observations by Lindholm and Nyren who, using magnetic resonance imaging showed that the size of the heart increased during GE (1). The subsequent cardiovascular response to GE, with hypertension and bradycardia, resembles the diving response to apnea, which includes a vagally mediated reflex bradycardia (16) and peripheral vasoconstriction (17). In particular, breath-holding at low lung volumes appears to potentiate the diving response (cf. 18) and GE, while not strictly apnea as lung volume is continuously reduced, even if by small amounts (1, 7), does lead to lung volumes below RV and decreases intrathoracic pressure (7) during gulping movements produced by oropharyngeal muscles.

The present study has a few limitations. First of all, in order to limit any risk to our subjects, the duration and the volume inhaled or exhaled during GI and GE maneuvers were not predetermined, as the divers were asked to perform these GPB maneuvers the way they are used to. Though all of the divers used the same technique, they performed GI and GE maneuvers at different speed and for different periods of time. This necessarily increased the variability of our data. With regard to the data provided by the Finapres® device we used in our experiments, while BP and HR are measured directly, both SV and CO are calculated from algorithms that are influenced by a change in systemic vascular resistance (SVR); SVR may change during GPB maneuvers, either in response to the hypotension observed with GI or to diminishing amounts of oxygen at the low lung volumes reached with GE. However, the Finometer® device has been found to provide continuous recordings of MAP in close agreement with concomitant invasive recordings (19). Data acquisition by Finapres® has also been shown to be accurate during various stressors affecting both pre- (20) and afterload (21). Finally, the acquisition of echocardiographic images during the GPB maneuvers was technically challenging, as the location where the images could be obtained changed with respiration. We also found variable responses during GE on echocardiographic imaging: we observed an initial increase of EDD compared to baseline measurements. Then, in some cases this increase in EDD would persist until the end of GE, while in other cases the EDD decreased to baseline values before the end of the breathing maneuver. Our echocardiographic observations support the Finapres® results: the late decrease in CO appears to be due to the drop in HR, while the SV did not increase enough to compensate for the bradycardia. This may be due to an increase in SVR expected as part of the diving response.

Our findings suggest that GPB maneuvers should be performed with caution. In the case of GI, forceful maneuvers can cause significant neurological symptoms including muscle spasms and syncope, secondary to decreased cerebral perfusion. On the other hand, forceful GE maneuvers could lead to heart dilation and, possibly, cardiac arrhythmias similar to what has been observed during breath-hold diving (22). In conclusion, GPB maneuvers, and in particular GI, expose the divers to cardiovascular and respiratory risks that require close monitoring and rapid access to medical care.

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