Intrathoracic pressure changes after Valsalva strain and other maneuvers: implications for divers with patent foramen ovale

C. BALESTRA, P. GERMONPRÉ, and A. MARRONI

Laboratory of General Biology, Université Libre de Bruxelles, 28 Avenue P. Héger, CP 168, B-1050 Brussels, Belgium; Divers Alert Network Europe Research Committee, Via Puglie 82, 64026 Roseto degli Abruzzi, Ialy; and Hôpital Militaire Reine Astrid, Rue Bruyn, 1 B-1120 Bruxelles, Belgium

Balestra C, Germonpré P, Marroni A. Intrathoracic pressure changes after Valsalva strain and other maneuvers: implications for divers with patent foramen ovale. Undersea Hyper Med 1998; 25(3):171–174.—Scuba divers with patent foramen ovale (PFO) may be at risk for paradoxical nitrogen gas emboli when performing maneuvers that cause a rebound blood loading to the right atrium. We measured the rise and fall in intrathoracic pressure (ITP) during various maneuvers in 15 divers. The tests were standard isometric exercises (control), forceful coughing, knee bend (with and without respiration blocked), and Valsalva maneuver (maximal, gradually increased to reach control ITP, and as performed by divers to equalize middle ear pressure). All the maneuvers, as well as the downward slope of ITP at the release phase, were related to the control value. ITP levels were significantly higher than the standard isometric effort during a breath-hold knee bend (172%, $P < 0.001$), cough (133%, $P < 0.05$), and maximal Valsalva (136%, $P < 0.05$) whereas "usual" Valsalva maneuvers produced ITPs significantly lower than the standard (28%, $P < 0.001$). The downward slope of the pressure release curve was not significantly different among the different maneuvers ($P < 0.1447$). We conclude that maneuvers other than the usual divers' Valsalva are more likely to cause post-release central blood shift, both by the levels of ITP reached and by the time during which these ITPs are sustained. Divers (especially with PFO) should be advised to refrain from strenuous leg, arm, or abdominal exercise after decompression dives.

diving risk factors, patent foramen ovale, intrathoracic pressure

Scuba divers with a patent foramen ovale (PFO) may be at risk for paradoxical (right-to-left) nitrogen gas embolization when performing maneuvers that cause a rebound blood loading to the right atrium (1). This can cause nitrogen bubbles in the venous blood flow to shift into the left heart and subsequently into the arterial blood flow without transit into the pulmonary circulation where bubble capture could occur. The best-known example of these maneuvers is the Valsalva maneuver (Antonio-Maria Valsalva 1666–1723) that is commonly used to augment the sensitivity of contrast transesophageal echocardiography (TEE).

The Valsalva maneuver consists of a manual blockage of the nostrils, followed by a forced expiration against closed mouth and nose, to provoke an augmentation of the pressure in the nasopharyngeal cavity.

The release of the Valsalva maneuver results in a decrease of the airway and intrathoracic pressure (ITP). This will be followed by a sudden increase in systemic blood return to the right atrium and by an increase of the venous filling of the lungs, with resultant decrease in flow into the left heart (2,3). The blood shift resulting from the release of ITP causes a rise in the right atrial pressure (RAP) that is easily seen during TEE as a leftward bulging of the interatrial septum, and marked opening of a PFO, if present (4,5). By injecting agitated saline during the strain phase of this Valsalva maneuver, and releasing the strain when the first saline microbubbles are seen arriving in the right atrium, these bubbles may be swept through a PFO and thus reveal its presence. Because of intra-atrial blood flow patterns, these bubbles—injected into an antebrachial vein—may not come sufficiently close to the interatrial septum to transgress through an even large PFO (6).

It has been suggested that the maneuvers used by divers during their descent to equalize the pressure in the middle ear (tympanic) cavity with the ambient hydrostatic pressure can likewise cause such an increase in right atrial pressure and lead to permeabilization (opening) of a PFO, if present. Many different maneuvers are available to perform such an equalization of pressure of the ear cavities; the most commonly used is a short and gentle Valsalva maneuver which is performed by pinching the nostrils with one hand and gently blowing through the blocked nose to increase the middle ear pressure by air insufflation through the Eustrachian tube.

The present work was undertaken to investigate if this divers' Valsalva maneuver was somehow similar to the

Valsalva technique that is being used to augment the sensitivity of contrast echocardiography, especially with regard to the intrathoracic pressure rise and fall. We further wanted to compare this divers' Valsalva maneuver to other common events likely to increase the ITP, again with regard to the levels of ITP reached during the event and to the characteristics of ITP during the release phase of the maneuver or event.

METHODS

Sixteen experienced divers (4 female and 12 male) participated in the study. Ages ranged from 22 to 39 yr. All subjects were fully informed regarding the nature of the investigation and the experimental methods, and all gave their informed consent before participation.

We measured the rise and fall in ITP during various maneuvers by means of a 1.5-ml esophageal balloon catheter (filled with saline solution) positioned in the lower third of the esophagus (approximately 45 cm from the nostrils in a non-reflexogenic zone), connected to a Marquette TRAM 500 monitoring system (Marquette Electronics, Jupiter, FL) via an Abbott Invasive Blood Pressure Kit (Abbott Laboratories Ltd., Sligo, Ireland). The system was zero adjusted to the hydrostatic reference level of the xyphoid process. The pressure values obtained were considered to the "relative" pressures, permitting a comparison between values from different maneuvers. The curves were recorded onto thermal paper.

The maneuvers tested were:

1. Control. Maximal isometric arm and chest muscle exercises: while sitting in a standard position (with knees and hips in 90° flexion), arms extended forward in a 90° angle from the chest, the diver had to push down on a scale, placed on the ground, by means of a wooden stick). This test was performed 3 times; the mean push-down force was noted, and the mean ITP reached was used as the control ITP value for the other tested maneuvers in that subject.
2. Gentle Valsalva. Valsalva maneuver (as usually performed by the diver to equalize middle ear pressure).
3. Forced Valsalva. Valsalva maneuver (maximal): a forced equalizing maneuver.
4. Calibrated Valsalva. Valsalva maneuver (gradually increased until the ITP reached the level of the first maximal isometric exercise).
5. Cough. Forceful coughing.
6. Knee Bend with Valsalva. Knee bend (with inspiratory block).
7. Free-breathing Knee Bend. Knee bend (free respiration).
8. Final Isometric Contraction. Final isometric effort: the diver was instructed to repeat the initial maximal isometric exercise. Care was taken to ensure that the same push-down force was reached.

The ITP value of the original isometric muscle exercise was taken as 100%, and the level of ITP reached by the other maneuvers was related to this standard isometric effort. Next, the slope of the ITP fall was analyzed to determine if there were differences for the tested maneuvers and if there was a correlation with the ITP peak reached.

The experimental results were statistically investigated with a standard procedure including mean, standard deviation, median, and the analysis of variance (ANOVA) for repeated measures to test within and between group effects. The regression lines were computed using the least squares procedure and the slopes were compared; regressions were calculated using the peak pressure point reached for each maneuver, expressed as the standard isometric control, and at lest three points of the descending part of the curve for each subject (exempted were gentle Valsalva and the knee-bend maneuvers because the measurement of the releasing part of the curve was inaccurate).

RESULTS

Peak ITP reached: ITP levels significantly higher than the standard maximal isometric effort were reached during maximal Valsalva maneuvers (136 ± 11%, $P < 0.05$), cough (133 ± 7%, $P < 0.05$), and breath-hold knee bend (172 ± 14%. $P < 0.001$). Free knee bend ITP levels were similar to the standard isometric effort (92 ± 14%, $P <$ 0.05) whereas divers' Valsalva maneuver (gentle Valsalva) produced ITPs significantly lower than the standard (25 ± 6%, $P < 0.001$) (Fig. 1).

Slope of ITP curves: After computation of the different regression lines form the experimental data, no significant difference between the various downward slopes ($P = 0.1447$) was found. All regression lines could be pooled in a single one with a representative slope; the pooled slope was −3.17%/s. Thus we found that the release of ITP after different maneuvers was similar, independent of the initial height of ITP reached and the duration of the preceding ITP plateau.

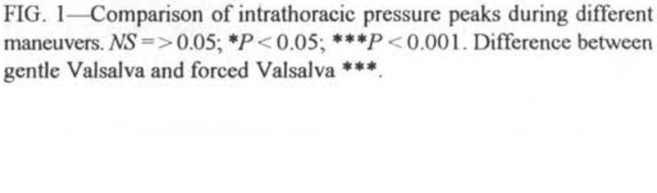

FIG. 1—Comparison of intrathoracic pressure peaks during different maneuvers. *NS* = > 0.05; *$P < 0.05$; ***$P < 0.001$. Difference between gentle Valsalva and forced Valsalva ***.

DISCUSSION

Six major sequences must be considered during the Valsalva maneuver (7): the initial inhaling phase, the exhaling phase, the strain phase, the releasing phase, and finally a second inhaling and exhaling phase (8). Each phase is accompanied by changes in airway and intrathoracic pressure. These pressure changes will interfere with the right and left atrial pressure curves.

During the profound inhalation, initiating the cycle, there is a right atrium pressure predominance due to a decrease in intrathoracic pressure and an increased gradient between the extrathoracic veins and the right atrium. An increased inflow from the superior and inferior caval vein to the right atrium, an increased filling capacity of the expanded lungs, as well as ventricular interdependence cause a successive decrease in left atrial return and pressure. During the exhaling phase against resistance, the airway and intrathoracic pressure increases with a resultant left atrial pressure predominance. The increased intrathoracic pressure diminishes the systemic venous return to the heart. The peripheral venous flow will first fill up the available venous capacity. This occurs at the expense of flow through the central veins, explaining the drop in the right ventricular stroke volume already reported (3). During the first few heartbeats following the release of the Valsalva maneuver, Lee and coworkers (9) observed an increased right atrial pressure above the pulmonary wedge pressure and, therefore, presumably above the left atrial pressure.

Other maneuvers can likewise induce a rise in ITP. From our investigations we showed that the usual maneuvers used by divers to equalize the pressure in their middle ear cavities induces only a very slight rise in ITP. Moreover, it is usually of short duration. Therefore, the release of this kind of maneuver is not likely to induce major blood shifts through a PFO. However, this is drastically different if a "forced" Valsalva maneuver is considered ($P < 0.001$ vs. divers' Valsalva), where the rise of ITP is even greater than that obtained by maximal isometric effort (Fig. 2). Embolization during Valsalva maneuver in patients with PFO has been reported in the literature; our results permit us to more precisely define this observation, in that the Valsalva maneuver performed was certainly a forced one (10). Certain morphologic characteristics of the interatrial septum might not permit a right-to-left shunt in normal circumstances but allow a massive shunt if the diving pressure is sufficiently high (Balestra et al. unpublished data).

Based on this and other PFO studies (1,11), a common advice given to divers with PFO is not to perform any Valsalva maneuvers causing a real rise of intrathoracic pressure immediately after ascent from their dive (e.g., to relieve residual pressure differences in the middle ears), because silent bubbles can be present in the central venous blood for 2 h after a deep dive (12). On the basis of our findings, they should, in our view, also be advised not to perform sustained isometric exercise or abdominal strains (such as defecating, lifting diving tanks, orally inflating a buoyancy control device at the surface).

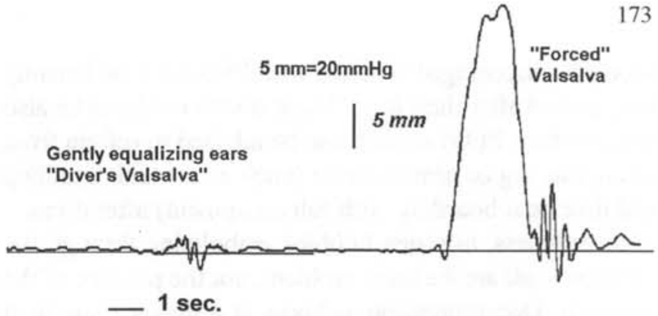

FIG. 2—Sample curves showing the marked differences in ITP reached for different middle ear equalizing maneuvers in the same subject.

Another important implication for diving instruction is that divers should be taught not to perform forceful Valsalva maneuvers to equalize middle ear pressure, i.e., using their abdominal muscles [intra-abdominal pressure can interfere with ITP (13)]. Only jaw and throat muscles should be used and special attention should be placed on this during training (14). The anatomical characteristics of a PFO are well known (2). The repeated rebound blood shift and subsequent rise in right atrial pressure may constitute a mechanical trigger for permeabilization of a previously closed (but only lightly fused) foramen ovale; a minimal PFO may become largely patent in the course of years. This hypothesis, although as yet unproven, is firmly backed up by two findings. First, anatomopathologic studies have shown that in an older age group the incidence of PFO may be a little lower, but the diameter of the interatrial channel is always larger (15). Second, from our own experience, several older and experienced divers have been struck by repeated episodes of unexplained decompression illness (i.e., without having violated currently accepted diving technical rules considered safe) after having sometimes performed more than 1,000 dives without any problem. In all of these divers, on TEE, a large PFO was detected.

We conclude that maneuvers other than the usual divers' Valsalva maneuver are more likely to cause more than post-release central blood shift, both by the higher level of ITP reached and by the time during which these ITPs are sustained, thus causing "pooling" of blood beneath the diaphragm and subsequent release when the ITP falls. Although the mechanisms of rise and fall of ITP may be different in these different maneuvers, the ITP release curves are identical because the slopes of the regression lines are not different. Any maneuver or exercise that is likely to cause such an ITP rise for a prolonged period should be discouraged in divers with PFO for a sufficiently long period after their dive. These divers (and maybe also those without PFO) should also be advised to refrain from strenuous leg or arm exercise (such as air tank handling and dive boat boarding with full equipment) after dives.

Nevertheless, nitrogen bubbles embolizing through the foramen ovale are the basic problem, not the patency of the foramen. Decompression sickness is a bigger topic than just a PFO. To minimize the load of nitrogen bubbles after a dive, several techniques can be used. Diving no deeper than 30 m, making a slow ascent (not faster than 10 m/min), and performing a decompression stop of 5 min between 3 and 6 m even if the dive tables do not impose one (the so-called "safety stop") have all been shown to substantially reduce venous nitrogen bubble load after a dive (12).

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