Cerebral gas embolism absorption during hyperbaric therapy: theory

ANNETTE B. BRANGER,1 CHRISTIAN J. LAMBERTSEN,2 AND DAVID M. ECKMANN3
1Department of Biomedical Engineering, Northwestern University, Evanston, Illinois 60208; 2Institute for Environmental Medicine and 3Department of Anesthesia and Institute for Medicine and Engineering, University of Pennsylvania, Philadelphia, Pennsylvania 19104

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Branger, Annette B., Christian J. Lambertsen, and David M. Eckmann. Cerebral gas embolism absorption during hyperbaric therapy: theory. J Appl Physiol 90: 593–600, 2001.—Cerebral gas embolism is a serious consequence of diving. It is associated with decompression sickness and is assumed to cause severe neurological dysfunction. A mathematical model previously developed to calculate embolism absorption time based on in vivo bubble geometry is used in which various conditions of hyperbaric therapy are considered. Effects of varying external pressure and inert gas concentrations in the breathing mixtures, according to US Navy and Royal Navy diving treatment tables, are predicted. Recompression alone is calculated to reduce absorption times of a 50-nl bubble by up to 98% over the untreated case. Lowering the inhaled inert gas concentration from 67.5% to 50% reduces absorption time by 37% at a given pressure. Bubbles formed after diving and decompression with He are calculated to absorb up to 73% faster than bubbles created after diving and decompression with air, regardless of the recompression gas breathed. This model is a useful alternative to impractical clinical trials in assessing which initial step in hyperbaric therapy is most effective in eliminating cerebral gas embolisms should they occur.

decompression sickness; diffusion; multiple gas model; in vivo geometry

MULTIFOCAL CEREBRAL GAS EMBOLISM (CGE) is a known risk of cardiac operations and a recognized hazard of diving decompression (11). Some of the most serious consequences associated with diving fall in the category of type II decompression sickness (DCS) and involve neurological dysfunction such as motor, sensory, or mental impairment, convulsions, coma, and death (Ref. 14; Association of Diving Contractors, unpublished observations). The cause of the neurological changes is considered, at least in part, to be the result of a diver’s ascent rate to the surface exceeding his ability to maintain inert gas remaining in the tissues in a dissolved state. The gas may come out of solution via nucleation and grow into multiple bubbles that are disseminated throughout the tissue and vasculature. Some of these intravascular bubbles potentially become entrapped in the arterial cerebral circulation and cause the local transient ischemia responsible for the diver’s neurological impairment (11).

Regardless of the cause, the primary treatment modality for CGE is hyperbaric therapy (HT) (11). This treatment consists of initially “recompressing” the patient to an elevated external pressure and usually includes providing a specialized breathing mixture. This breathing mixture can contain one of several gas combinations, air, nitrox (an N2-O2 mixture), or heliox (an He-O2 mixture), as well as a variable percentage of inert gas (79, 67.5, or 50%), with O2 providing the balance. The ambient pressure and breathing mixtures are subsequently changed over time in a stepwise fashion to return the patient to atmospheric pressure and air breathing with minimal trauma.

The HT protocol depends on the symptoms presented, the depth and length of the dive, and available facilities; however, experiments to define the limits of recompression and variable O2 treatment are not carried out in humans suffering from DCS. Protocols have been established based on large numbers of clinical experiences with individual cases in naval and industrial organizations. A mathematical model defining the impact of increased levels of external pressure and inhaled O2 content would, therefore, be very useful in understanding and elucidating potentially beneficial treatment combinations.

Some of the most recognized mathematical models used for calculating bubble growth or decay have assumed a spherical bubble geometry, even when intravascular gas bubbles are simulated (6, 8). On the basis of our earlier published observations (3) and those of other investigators (7, 13), however, it has been shown that gas emboli do not maintain a spherical shape when entrapped in the vessels. The bubbles initially fill the vessel diameter and elongate axially, taking on a “sausage-like” appearance. Using this information, we previously developed a generalized mathematical model calculating the absorption times of single bubbles trapped inside the vasculature that is based on their initial in vivo geometry. This model was validated...
The goal of this study is to apply our earlier model, by use of a realistic intravascular bubble geometry, to the situation of hyperbaria. This work is a natural extension of our earlier methods and provides the opportunity to manipulate parameters such as external pressure and breathing gas to examine their effects on intravascular bubble absorption dynamics. The importance of this work lies in the fact that this is the first attempt to describe how hyperbaria changes the normal absorption process of CBEs as they appear in vivo.

**MATERIALS AND METHODS**

*Model.* The theoretical model we developed to calculate absorption times of a CGE has been described in detail previously (3) but is mentioned very briefly below. We have modeled the in vivo shape of a cerebrovascular bubble as a cylinder of initial length $l_0$, with hemispherical end caps of initial radius $R_0$, (Fig. 1). On the basis of in vivo findings, we stipulate that, as gas absorbs out of the bubble, the cylindrical portion of the embolism decreases in length while the radius of the hemispherical end caps remains fixed. Once the cylindrical portion completely disappears, the remaining hemispherical end caps fuse together to form a sphere. This spherical geometry is maintained for the remainder of the bubble absorption. The absorption of the bubble can, therefore, be solved independently for two separate phases in time, the cylindrical phase and the spherical phase, in each case with the use of Fick’s law for the specific bubble geometry. The time for the bubble to absorb is highly dependent on the initial aspect ratio of the bubble itself, or $L_0/R_0$.

During each phase of bubble absorption, the expression for the pressure inside the bubble is based on several simplifying assumptions. We assume that there is rapid equilibrium of the metabolic gases (O2, CO2, and water vapor) between the pressure inside the bubble and the tissue, with constant tissue partial pressures of O2, CO2, and water vapor in the tissue. The internal bubble pressure, therefore, remains fixed during the cylindrical portion of absorption due to a constant value of $R_0$ and increases during the spherical phase as the bubble volume and, consequently, the radius decrease.

The time for bubble absorption is readily obtained numerically. With this model, we can calculate the absorption time of an intravascular bubble over a range of geometries for any given initial volume, at any recompression pressure, and for any gas content in the breathing mixture. Knowing local tissue characteristics allows further application to specific areas such as the brain.

*Multigas model.* The situation in which a diver is breathing one gas mixture during a dive and decompression and another gas mixture during HT becomes more complicated. A CGE that forms during or after the diver surfaces is composed of the inert gas inhaled during the dive and decompression, inasmuch as this is the gas present in the tissues at the time of bubble nucleation and growth. This gas inside the bubble will follow its concentration gradient, diffusing out of the bubble after the diver surfaces. Introducing a second inert gas in the inhaled breathing mixture during recompression loads the tissues and arterial blood with a new gas species heretofore not present inside the bubble. While the gas inside the bubble diffuses outward, the new gas present in the tissues follows its concentration gradient, diffusing into the bubble. The net effect of gases moving into and out of the bubble can be to slow absorption or even promote bubble growth. To describe this more complex situation, we developed the in vivo multiple gas model based on the same bubble geometry as described above and the basic assumptions defined by Burkard and Van Liew (4).

Our multiple gas model was validated by simulating conditions of only one gas and comparing results with those obtained from the single gas model for a given bubble volume and geometry. In all cases, the absorption times calculated using any of the models never differed by >2.0%.

*Simulations.* We examined three groups of DCS treatments: hyperbaric simulations with air, hyperbaric simulations with variable O2, and multigas simulations. The simulations were applied to the specific case of a cerebrovascular bubble, since arterial emboli in the cerebral circulation are assumed to be responsible for the most serious consequences associated with DCS (11). A single representative bubble was used for simplicity, albeit DCS is usually characterized by multiple gas emboli distributed throughout the vasculature and tissues. A bubble, initially 50 nl in volume at ambient pressure, was simulated, because this embolism size is a reasonable estimate based on physiological bubbles seen by Powell and Weydig (13) in the microcirculation of adipose tissue of rats and rabbits exposed to rapid decompression.

We assumed that all divers maintained a constant body temperature of 37°C during treatment. The appropriate physiological parameters for cerebral tissue were found in the literature (4, 6, 18) or estimated on the basis of available information and are presented in Table 1.

To model the different initial steps of various recompression protocols, we varied the external pressure on the patient and calculated the partial pressure of the gas in the arterial blood on the basis of the percentage in the inspired breathing mixture during recompression. The partial pressure of the inert gas in the arterial blood is relevant to our model, because on the basis of our unpublished observations, a 50-nl arterial gas bubble typically lodges in a 100- to 200-μm-diameter arteriole. The increase in external pressure due to
undersea diving causes changes in the tissue partial pressures of O₂ and CO₂, which were also accounted for in the models (18).

**Hyperbaric simulations with air.** We compared the absorption time of a 50-nl bubble left untreated at an external pressure of 1 atmosphere absolute (ATA) with a bubble of the same volume recompressed to pressures of 2.8, 4, and 6 ATA. We selected these values of hyperbaric pressure for our simulations, because the Association of Diving Contractors recommends recompression to 2.8 ATA or 60 ft of seawater (fsw) (Association of Diving Contractors, unpublished observations) for simple DCS symptoms such as limb pain or skin rash, without any accompanying neurological deficit. If, however, there are any signs of type II DCS, the US Navy recompression protocols require the diver spend 25–30 min at the initial hyperbaric pressure of 6 ATA; therefore, simulating the initial step of recompression: N₂O₂-N₂O₂, HeO₂-HeO₂, N₂O₂-HeO₂, and HeO₂-N₂O₂.

In all the hyperbaric therapies simulated, regardless of the breathing mixture, we predicted that the total time a recompressed 50-nl bubble would take to absorb was ≤30 min. The US Navy and Royal Navy recompression protocols require that the diver spend ≥25–30 min at the initial hyperbaric pressure of 6 ATA; therefore, simulating the initial step of HT is sufficient to model complete embolism absorption into the bloodstream.

**RESULTS**

The time rate of change of bubble volume during absorption for a 50-nl CBE left untreated in a patient breathing air at ambient pressure is depicted in Fig. 2 for two configurations: a spherical bubble ($L_o/R_o = 0$) and a bubble with $L_o/R_o$ of 2.6. These two values for $L_o/R_o$ were found to give the minimum and maximum absorption time, respectively, for a bubble of a given volume (3). The model predicts that a spherical bubble with an initial radius of 228 μm would take 177 min to absorb, whereas a bubble of the same volume with an initial radius of 159 μm and an initial central core length of 414 μm would take 296 min to absorb (Fig. 2). The maximum absorption time for a 50-nl bubble is, therefore, 67% longer than if the bubble were to remain a sphere. The discontinuity in the volume vs. time curve for the embolism with $L_o/R_o$ of 2.6 represents the transition from the cylindrical to the spherical absorption phase, as discussed elsewhere (3).

**Hyperbaric simulations with air.** We used our model to calculate the theoretical absorption times of an air bubble, initially 50 nl at sea level, over a range of
geometries at several different hyperbaric pressures. Because embolism absorption time is clearly dependent on $L_o/R_o$ and, hence, initial bubble geometry (Fig. 2), we plotted the total time for bubble absorption as a function of initial surface area, corresponding to $L_o/R_o$ between 0 (spherical bubbles) and 25 (long slender bubbles). Each recompression pressure, 2.8, 4, and 6 ATA, generates a unique initial bubble volume; therefore, each curve in Fig. 3 represents a different initial bubble volume over the same range of $L_o/R_o$ values.

The far left side of each of the curves in Fig. 3 represents the minimum surface area for a given volume (i.e., a sphere). In the untreated case, 1 ATA, the absorption time on the far left of the curve, corresponds to 180 min, calculated by a slightly different method but approximately equal to the total time for absorption of a spherical bubble shown in Fig. 2. A maximum absorption time also exists for each recompression curve, at $L_o/R_o$ of ~2.6. Again there is agreement between the maximum value on the untreated curve in Fig. 3 and the total time for absorption of a bubble with $L_o/R_o$ of 2.6 (Fig. 2).

Subjecting a patient with a 50-nl CGE at ambient conditions (in which bubble growth due to decompression is no longer occurring) to 6 ATA recompression therapy is calculated to reduce the maximum possible absorption time from 298 min in the untreated case to 7.5 min, a reduction of 98%. The decrease in bubble absorption time, however, is not a linear function of the external pressure (Fig. 3). A step change from 1 to 2.8 ATA corresponds to a decrease in the maximum absorption time from 298 to 30 min or 90%, while a change from 1 to 4 ATA reduces the maximum absorption time to 16 min, a decrease of 95%.

**Hyperbaric simulations with variable $O_2$**. The effects of changing the inert gas content in the inspired breathing mixture are shown in Fig. 4. The range of absorption times theoretically possible for a gas bubble, originally 50 nl at ambient conditions, is presented as a function of hyperbaric pressure for various concentrations of $O_2$ in the breathing mixture during recompression: 21% $O_2$-79% $N_2$, 32.5% $O_2$-67.5% $N_2$, and 50% $O_2$-50% $N_2$. Decreasing the $N_2$ content of the inspired gas from 79% to 67.5% was calculated to reduce the maximum absorption time of a bubble at 2.8 ATA by ~40%, from 30 to 18 min. An even greater reduction in maximum absorption time was achieved when the breathing mixture contained 50% $O_2$ instead of 21% $O_2$, changing the maximum CGE residence time from 30 to 11 min, a decrease of 63%. The relative percent reduction in maximum absorption time between the various breathing gases was consistent at all the recompression pressures, 2.8, 4, and 6 ATA.

The decrease in bubble volume associated with each hyperbaric pressure is shown in Fig. 4B. An increase in the external pressure from 1 to 2.8 ATA reduces a 50-nl bubble to 15.6 nl. If this same bubble is exposed to 6 ATA, the bubble volume is compressed to 6.9 nl, a reduction of 43.1 nl from the untreated size. A slight variation (~1.3 nl) in the recompressed bubble volume exists between the different breathing gases at the same hyperbaric pressure. This occurs because the internal bubble pressure is dependent on the partial pressure of $O_2$ in the tissue, in equilibrium with the
bubble, which is obviously related to the concentration of O2 in the breathing gas.

At specific pressures, the curves representing the maximum and minimum residence times for a cerebrovascular bubble in a patient breathing each of the gas mixtures do not overlap with one another at any point in Fig. 4, regardless of the recompression pressure evaluated. The lack of overlap indicates that even the longest possible absorption time for a CGE with 32.5% O2 in the breathing mixture at a given pressure is still 4% more rapid than the shortest possible absorption time in a patient breathing 21% O2. Likewise, the same-size CGE in a patient breathing 50% O2 absorbs a minimum of 5% faster and a maximum of 37% faster than if the patient were breathing 32.5% O2.

Multigas simulations. The step change in bubble volume, as a result of the initial recompression from sea level to 6 ATA, is from 50 nl at ambient pressure to 6.9 nl. The subsequent changes in bubble volume over time during HT at 6 ATA for four different diving and decompression recompression gas variations are shown in Fig. 5. The shortest absorption time predicted for any of the combinations was 4.4 min, in the case of an individual breathing He continually during the dive, decompression, and recompression therapy (HeO2-HeO2). Changing the recompression breathing mixture to N2 instead of He (the HeO2-N2O2 case) increased bubble absorption time by only ~3%. However, although overall absorption time was slightly longer in the HeO2-N2O2 than in the HeO2-HeO2 case, bubble absorption was actually accelerated for a majority of time, as indicated by a smaller bubble volume at any given time. When the bubble was formed by breathing N2 during diving and decompression, regardless of the gas inhaled during recompression, however, absorption times increased dramatically, by 49% in the N2O2-N2O2 case and by 73% with N2O2-N2O2.

The multigas combination of a bubble initially composed of N2 and absorbing in the presence of He was the only case that showed even a temporary increase in bubble volume, although the absorption time, 6.5 min, was still predicted to be less than in the N2O2-N2O2 case of 7.6 min.

To determine the relationship between the behavior of the individual gases as they relate to the dynamics of the total bubble volume, we tracked the influx and efflux of the two individual gases, along with the resultant bubble volume. The time rate of change of bubble volume for the two cases in Fig. 5 involving multiple gases (HeO2-N2O2 and N2O2-HeO2) is graphed in Fig. 6. The bubble initially composed of He and exposed to N2 during recompression takes a total of 4.5 min to absorb; however, all the He has diffused out of the bubble by 3.5 min. The initial influx of N2, therefore, slows bubble absorption slightly but not to the point of causing bubble growth or proving to be disadvantageous compared with the HeO2-HeO2 case. The theoretical prediction for the opposing case, a patient with a CGE initially containing only the inert...
gas $N_2$ and breathing He-O$_2$ during recompression, takes 2 min longer to absorb. The CGE grows in volume for the first 41 s, demonstrating that the rapid influx of He into the bubble exceeds the rate at which $N_2$ diffuses out. The recompression gas, He, reaches a maximum volume inside the bubble of 5.6 nl, whereas in the HeO$_2$-N$_2$O$_2$ case, $N_2$ peaks at only 2.4 nl in the bubble.

**DISCUSSION**

In the absence of the ability to assess the most effective treatment options available with HT clinically, a mathematical model was used to predict the residence time of a gas embolism as a function of specific bubble geometry (Fig. 1) and various treatment parameters. An entrapped 50-nl embolism left untreated in the cerebral circulation is predicted to have absorption times of $\sim 177$ to 296 $\pm$ 2 min depending on the configuration (Fig. 2) and the model used. As shown in Fig. 3, the residence time of a cerebrovascular bubble is a nonlinear function of initial surface area, demonstrating competing mechanisms for bubble absorption. Increasing the bubble surface area, through bubble elongation and narrowing, creates a larger area for gas diffusion out of the bubble and is advantageous for absorption; however, this alone does not lead to a decrease in absorption time. An increased surface area also indicates a longer bubble length and, therefore, a greater fraction of bubble volume, which must be absorbed before the cylindrical core disappears and the internal pressure rises. This theoretically inhibits bubble absorption, especially in aspect ratios between 0.3 and 13.1, and has heretofore been overlooked in theoretical models in which a spherical bubble geometry is assumed (3).

To illustrate the theoretical basis behind the clinically proven therapeutic effects of recompression and various inhaled gas mixtures on embolism absorption dynamics, we simulated the conditions of hyperbaria with air and hyperbaria with variable $O_2$ and multiple gases used to treat patients with DCS with our theoretical model.

*Hyperbaric simulations with air.* In Fig. 3, a recompression pressure as low as 2.8 ATA is shown to have a dramatic effect on reducing the bubble absorption time, by $\sim 90\%$. This decrease in the residence time is attributed in part to the large reduction in bubble volume. The large increase in external pressure due to hyperbaria does not change the basic behavior of bubble absorption, however, inasmuch as all the curves presented in Fig. 3 have the same fundamental shape.

*Hyperbaric simulations with variable $O_2$.* HT can include a manipulation not only of the external pressure but also of the inhaled breathing mixture. The combination of these therapies demonstrates that lowering the inert gas content in the breathing mixture from 79% to 67.5% or 50% at a given recompression pressure is a viable way to decrease bubble absorption time from 40% to 63% for all pressures (Fig. 4). Reducing the inert gas concentration in the inspired gas mixture is shown to increase the rate of bubble absorption to similar values obtained by increasing the external pressure. The drawbacks associated with this manipulation are not included in the model, however. Theoretically, the optimal breathing mixture at any recompression pressure would be 100% $O_2$, thereby reducing to zero the inert gas percentage in the breathing mixture and the tissues and maximally accelerating diffusion out of the bubble. The most significant problem associated with this approach is $O_2$ toxicity, manifested by sudden seizures (5). $O_2$ toxicity is particularly harmful in previously ischemic tissue, injuring endothelial cells (10, 15). Inhalation of 100% $O_2$ has proven to be beneficial in the continuation of therapy; however, when the patient is initially subjected to large recompression pressures and a high $O_2$ content in the breathing mixture, $O_2$ toxicity becomes an obvious concern. The disadvantage of keeping the $O_2$ content at 21% is the extensive time required to return the patient to ambient pressure (Ref. 16; Association of Diving Contractors, unpublished observations).

A difference of 1–28 min can be achieved in absorption times by adjusting the recompression pressure and inhalation mixture, a time potentially vital to the...
patient's recovery. Any prolongation of bubble absorption is additional time during which cerebral tissue is cut off from blood flow and susceptible to ischemia. The perpetuation of the gas embolism within the vasculature can also cause platelet aggregation, activation of the thromboinflammatory pathways, and damage to the endothelium, all through contact at the gas-blood vessel interface (1, 12, 20). In addition, this model was run only for a representative CGE of 50 nl at ambient pressure. A larger initial bubble volume would also show a larger discrepancy in bubble absorption times.

The model demonstrates the two primary factors, which are manipulated during HT to reduce the residence time of CGE: external pressure and inert gas content of the breathing mixture. Within the limits of these parameters, there is room for considerable adjustment of both. Although a difference of 28 min in CGE absorption time may not appear significant when the total time required to diagnose, transport, and prepare the patient is considered, this difference in time represents a discrepancy between various treatment methods, during which the embolism is made to shrink. During the diagnosis and transport stages, the embolism can be growing in size and numbers, inasmuch as divers can experience an exacerbation of symptoms before treatment (Association of Diving Contractors, unpublished observations). For this reason, prompt initiation of therapy is extremely important, and once treatment has begun, everything possible should be done to reduce the residence time of the embolism. This model can be used in assessing the benefits associated with the possible combinations in recompression therapy and can aid in understanding the relationship between the various aspects involved in the clinical treatment of CGE.

**Multigas simulations.** To investigate other bubble absorption phenomena, which occur in divers exposed to more than one breathing gas, we incorporated the multiple gas concept, accounting for divers breathing one inert gas during the dive and decompression and another during the recompression therapy. One might initially predict that combinations with different inhalation gases for diving and recompression will absorb most quickly, inasmuch as the tissue concentration of the gas species inside the bubble during recompression would be negligible, thus increasing the gradient that drives absorption out of the bubble. Although this is basically true, counterdiffusion of the new inert gas, introduced in the breathing mixture, into the bubble during recompression effectively slows absorption. The model presented accounts for this important effect.

The counterdiffusion of gas into the bubble is responsible for the initial increase of bubble volume predicted in the multiple gas case, in which a diver inhaling N₂ and O₂ during a dive and presenting with CGEs is recompressed while breathing He and O₂. This same bubble growth does not occur in a gas embolism of a patient diving with He and being recompressed with N₂ (Fig. 5). The results of the simulations also predict that the absorption time of a CGE is actually longest in a diver continually breathing air during the dive, de-

To understand the mechanisms behind the bubble absorption dynamics in the multiple gas cases, it becomes necessary to examine total bubble volume as a function of the individual inert gas volumes at any given time (Fig. 6). Of the two initial inert gases in each of the bubbles, He has a much faster rate of absorption into the cerebral tissue than N₂. Similarly, He proves to have the larger rate of diffusion into the bubble from the tissues as well. In combination, these factors dictate that the embolism composed of He and collapsing during a recompression with N₂ will absorb much faster than if the opposing conditions are present. The clinical implications of this prediction are that an embolism appearing in a patient after surfacing from a He dive would reside for a shorter time in a vessel with less likelihood of causing cerebral ischemic injury than if the embolism were created from an air dive. A difference of ~2 min may not be enough to affect clinical treatment, but it may reflect the relation between tissue ischemia and infarction. The model aids in prediction of absorption dynamics when a diver is exposed to multiple gases during decompression-induced gas embolism and therapy and indicates potential for decreasing the bubble residence time.

This model, while helpful in gaining a basic understanding of bubble dynamics in the presence of elevated external pressures and different inhaled gas mixtures, also has limitations. When various aspects of HT are simulated, the manipulations in recompression pressures or breathing gases are modeled as instantaneous step changes to simplify the solution. In reality, it takes ~3–5 min to recompress a patient to 6 ATA, depending on his tolerance, during which time the inert gas in the tissue must also approach equilibrium with the breathing mixture, and this has not been factored into the model. To further simplify the model, we assumed that once a bubble became entrapped in a cerebral vessel at a given initial geometry and hyperbaric pressure, the bubble did not dislodge to a location further downstream with a new aspect ratio, although this has been observed occasionally in vivo (3).

This theoretical model is based on the configuration of a CGE in vivo and demonstrates the various interactions of bubble geometry, recompression pressure, and inhaled gas mixtures taking part in determining the residence time. Manipulating the different parameters individually and in conjunction with one another to simulate events resulting from general practice in
the initial treatment phase of DCS provides a simple and effective method of establishing the relevant factors in determining the absorption time and basic dynamics of CGEs. Once these factors are well understood, the model can be used to predict the limits of current and experimental therapies to reduce the damaging effects of CGE.

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