The "Smooth Ride" Profile:
Development, Implementation And Evaluation Of A Hyperbaric Chamber Descent And Ascent Based On A Constant Rate Of Volume Change With Time.

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ABSTRACT

During hyperbaric treatments, the most common form of adverse effect is barotrauma, related directly to the change in pressure that must be applied to the patient environment in order to achieve a hyperbaric effect. Of those, middle ear and sinus "squeeze" are most frequently seen. This paper examines the theory underlying barotrauma and develops a new mechanism for minimizing the chances of its occurrence. In follow-up evaluation of 795 patient dives, the relative risk of barotrauma was only 0.32 for the new profile with $p<3.17X10^{-5}$. Further analysis suggests that this benefit is gained with no additional time required for chamber operations.

Authors Information

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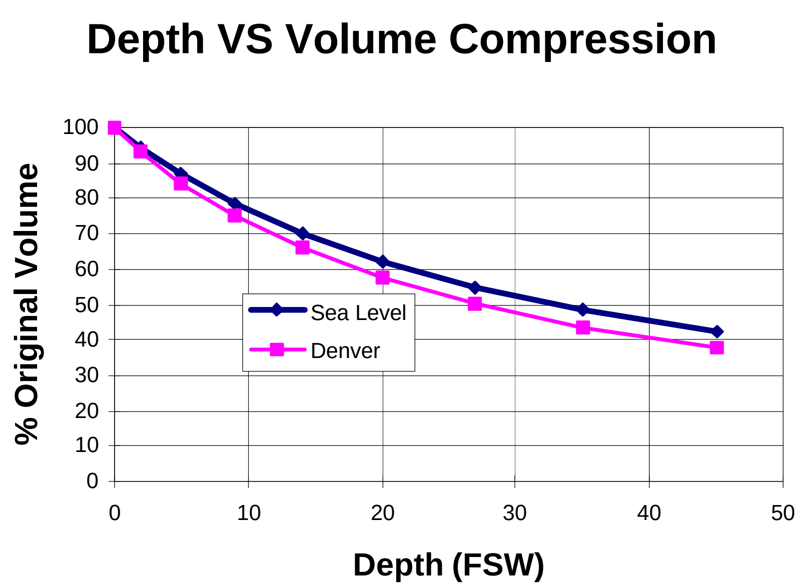
During my hyperbaric fellowship, I learned that pressure was the most important environmental variable. Although this seemed rather ostentatious, upon reflection one realizes that applied to the hyperbaricists realm, the old adage does, in fact, hold true. Consider the most common form of adverse effect upon our patients during their treatment profile in the chamber. Since every dive involves a descent and an ascent, during which we pass from 14.7 PSI to 34.7 PSI, with of course, a return to sea level some two hours later, we put our patients through some significant changes. These changes were admirably predicted by Sir Robert Boyle when he formulated his law relating pressure and volume. We know for a constant temperature if you double the pressure you will halve the volume. In a more mathematical formulation we would say that for a constant temperature T, $P_1V_1=P_2V_2$. Most of our hyperbaric chambers are designed to provide a constant rate of descent towards the target depth in terms of feet per minute. Where the chambers are programmed to go from sea level to 45 Feet of Sea Water (FSW) in five minutes we are in essence instructing the system to perform a constant rate descent at 9 feet per minute. Thus in the first minute we descend from sea level to 9 FSW. In the second minute we descend from 9 to 18 FSW. This scenario continues until during the fifth minute we descend the last 9 feet from 36 to 45 FSW. Let's examine the physics of these steps to gain a better understanding of the physiological processes which are simultaneously occurring.

During the first minute of transition we pass from sea level or pressure of 14.7 pounds per square inch to a pressure equivalent of nine FSW at depth. If we consider our middle ear to have a volume of 100 at sea level by proceeding to nine few sea water depth in one minute that volume using Boyle's law will be compressed from 100 to 78.6. This volume change may be determined by using the equation V = V0*(P0/(P0+.44545D)) where D equals the equivalent depth in FSW and V0 is our original 100%. This equation predicts that by the time we reach our target depth of 45 feet, the volume will have been compressed from 100 to 42.3. It is the relative volume change of 57.7 units which we wish to spread equally over our total descent time in order to enhance patient comfort. The equation in its general form will allow us to draw a curve for the equivalent rate of volume change with time as we descend from the surface to our target of 45 few sea water. As applied to our current example the zero was chosen to be 100 percent and P0 is equal to the atmospheric pressure at sea level or 14.7 pounds per square inch we may easily change this equation if you find yourself performing a dive in say Denver Colorado when the atmospheric pressure at 5200 feet is significantly less than 14.7 PSI. Looking up the estimated value for pressure in Denver at 5200 feet we find that it would nominally be 625.5 Torr or 12.1 PSI. The curves generated by these two equations can be seen in the graph shown below for Denver and sea level.



The graph demonstrates something we all know from having participated in many chamber descents with our patients: the effects related to pressure change occur most rapidly during the first several feet of the descent and then taper off during the latter portion. In an attempt to even this out I reasoned that a more comfortable descent and ascent profile would be one in which the rate of <u>volume</u> change with time was constant. To produce this we would need to adjust the depth rate of descent with time throughout our descent profile. More specifically we need to make our foot-per-minute descent slower at the beginning of the dive and faster toward the end. At Brooks Air Force Base we are fortunate enough to have a computer controlled chamber in which we can have up to 20 segments per dive profile. Previously we had been using two segments to control the descent, taking us from sea level to 15 FSW in the first two minutes and then from 15 feet to 45 feet in the remaining three minutes for a total descent time of five minutes. Not infrequently many of our patients would have ear or sinus blocks during the first two to three minutes of descent time. Using our current descent profile this would be expected since the largest relative volume change occurs during these first several minutes.

In deciding how to configure a standard descent and ascent profile that would minimize the risks on descent for those with mild ear or sinus problems and reduce the risk of air trapping in those having potential obstructive or restrictive lung defects, we decided to use a seven minute total time for every descent and a 10 minute total time for every ascent. In the past we had multiple descent and ascent profiles attempting to optimize our days dive profile in consideration of every mix of patient we could have in the chamber. This led to chamber operator confusion and frequent ear and sinus problems. We attempted to used a five-minute ascent if there were no known lung problems within our patient population on a particular dive; however if we had a patient with a history of asthma, COPD, or emphysema we would use a 15 minute ascent profile. In examining the 15 minute ascent I found we had programmed a single segment linear ascent over 15 minutes from 45 feet to the surface. This meant we were ascending three feet per minute throughout the entire profile. The most rapid rate of volume change would occur during the last minute of ascent during which time we would ascend from three feet to the surface, going through 8.3 units of volume change. I reasoned that if my 10 minute profile did not exceed this final rate of volume change, then it should be just as safe as the old 15 minute ascent. I shall examine the final ascent profile later on in this paper to see if it meets that criteria.

To create our smooth descent and ascent profiles, I broke the descent into seven segments, each of which would take us a part of the way from the surface to 45 feet. Each segment would be completed in one minute. In order to determine how many feet of depth we should pass through in each segment I took the total volume change of 57.7 units and divided it by 7 to get the number of volume change units that should occur during each minute of the descent. This produced a target of 8.24 units of volume change per minute. I built a spreadsheet to make working with the numbers a bit easier. Since our dive controller would only permit the entry of time and depth in integer format and would not accept fractional feet or minutes (aesthetically displeasing, but functional) our boundary values were forced to be a bit more granular then I would have liked. This necessitated some segments volume change being upwards of 9.5 units of volume change while other segments only accumulated 7.4 units. This variation was unavoidable given the constraints of our controller system. One should note that this variation is much less than the variation experienced during our original profile in which the first one minute of descent produced a 7.5 ft. change equivalent to 18.5 units of volume change and the last minute of descent from 35 to 45 feet produced only 6.2 units of volume change. For the 10 minute ascent I had a choice of using 10 segments of one minute each or five segments of two minutes each. In the interests of time and simplicity we chose the latter for our model. The spreadsheets detailing the seven minute descent and the 10 minute ascent (using two minutes per segment) are shown below.

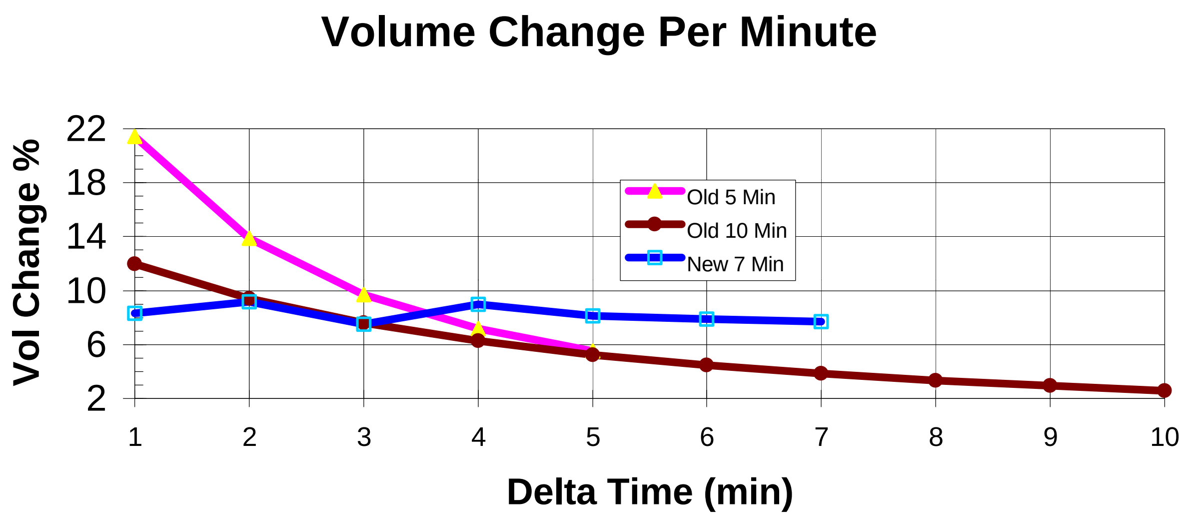
DESCENT PROFILE (7 Minutes)

Period	Start Depth	End Depth	Start Press	End Press	Delta P	Start Vol	End Vol	Delta Vol Calc	Delta Vol Target
1	0	3	1.00	1.09	0.09	100.00	91.67	8.33	8.24
2	3	7	1.09	1.21	0.12	91.67	82.50	9.17	8.24
3	7	11	1.21	1.33	0.12	82.50	75.00	7.50	8.24
4	11	17	1.33	1.52	0.18	75.00	66.00	9.00	8.24
5	17	24	1.52	1.73	0.21	66.00	57.89	8.11	8.24
6	24	33	1.73	2.00	0.27	57.89	50.00	7.89	8.24
7	33	45	2.00	2.36	0.36	50.00	42.31	7.69	8.24

ASCENT PROFILE (10 min - 2 min per period)

Period	Start Depth	End Depth	Start Press	End Press	Delta P	Start Vol	End Vol	Delta Vol Calc	Delta Vol Target
1	45	29	2.36	1.88	-0.48	42.31	53.23	-10.92	-11.54
2	29	18	1.88	1.55	-0.33	53.23	64.71	-11.48	-11.54
3	18	10	1.55	1.30	-0.24	64.71	76.75	-12.04	-11.54
4	10	4	1.30	1.12	-0.18	76.75	89.19	-12.45	-11.54
5	4	0	1.12	1.00	-0.12	89.19	100.01	-10.81	-11.54

To see why this profile enhances patient comfort, one need only examine a chart of the amount of “volume change” that occurs per minute of descent. The more consistent this is, the less variability will be experienced. Also, the smaller the magnitude of the volume change, the more time a patient will have to adjust to the descent and therefore, the less likely to experience an ear or sinus block. Below, I compare two linear descents to 45 FSW with the new “smooth ride” profile. You can see that the new profile is more consistent over the entire descent, and the maximum volume change per minute is the lowest, even when comparing it to a 10 minute “linear” descent.



We have been using this "smooth ride profile" on every treatment dive since May 1998. Subjectively our patients noticed the difference and felt the new profile was more comfortable than the old. Although sufficient time has not yet passed for us to compare objective measures of the frequency of adverse chamber reactions on descent between the old profile and the new profile, my expectation is the number of ear and sinus blocks will be greatly decreased using the new smooth ride profile. In addition, having a single profile for descent and ascent with no reason for profile modification based on patient mix, has made the chamber controllers job less confusing. As promised, the comparison of terminal ascent rates: the old 15 minute rate was 3 feet per minute over the final minute for 8.3 volume units. The smooth ride ascent target was 5.8 volume units per minute (11.54 in 2 min) - 30% less stressful than the old profile.

In September 1998 we reviewed the previous 7 months activity to see if, in fact, our overall impression that barotrauma had been greatly reduced. The data was organized as follows: the unit of study was the Patient-Dive (PD); and the occurrence of interest was the number of PDs in which an ear or sinus block necessitating halting the descent occurred. One PD was defined as a patient entering the chamber and pressurizing to 45 FSW for our standard wound care dive. We did not include staff members, or research divers in the counts. Neither were other treatment tables included in the analysis, as their descents were all manually controlled. Because we operate a multiplace chamber, each chamber descent could produce up to 8 PDs simultaneously. Since we are often able to perform maneuvers to clear an ear or sinus block and continue the descent, a single patient could have more than one block per descent. For the purposes of analysis, multiple blocks by the same patient during a single attempt at descent to 45 FSW was counted as ONE occurrence. Usually if the descent had to be halted a third time for the same patient, that individual was removed from the chamber and asked to return the following day. Two or more removals in the same week usually prompted referral for PE tubes (for middle ear ventilation). If a second patient blocked during a descent in which another patient had blocked earlier, then two occurrences were counted for the one dive.

Our facility has recorded episodes of ear and sinus blocks as a QPI (quality performance indicator) for decades, so extraction of the data from our daily log sheets was relatively straight forward. Since the “Smooth Ride” profile was implemented in May 98, I examined occurrences from February through April 1998 as representative of the standard linear descent profile, and occurrences from June through August 1998 as representative of the Smooth Ride profile. The month of May was discarded as a transition month, since the chamber operators needed some transition time to become familiar with the new mode of descent, and we did not implement the Smooth Ride profile until one or two weeks into the month.

The data revealed that the standard linear descent produced 49 occurrences during 830 PDs, while the Smooth Ride profile produced only 15 occurrences during 795 PDs. Entering this information into a standard 2 X 2 table produced the following:

Barotrauma

	Present	Absent	Marginal Subtotals
Smooth Ride	15	780	795
Linear Descent	49	781	830
Marginal Subtotals	64	1561	1625

The relative risk (a/(a+b)/c/(c+d)) of barotrauma during a Smooth Ride descent compared to a Linear Descent is 0.32. Performing a chi-square analysis on the table produces a test statistic of 17.318 which is significant at the 3.17×10^{-5} level.

So how does this translate into operational efficiency? Previously we had a large number of possible ascent and descent profile combinations, but most commonly: 5 minutes down and 5 minutes up; 5 minutes down and 15 minutes up; and 10 minutes down and 15 minutes up; depending on patient risk factors. On average we had 15 minute ascents on half of the dives, producing, over the long run a weighted average of 16.25 minutes per treatment dive transitioning the chamber - assuming no stops for barotrauma. If we had to stop the chamber descent to work with an ear or sinus block, we could plan on adding an extra 3 minutes. For the Smooth Ride profile, all treatment dives are the same at 7 minutes down and 10 minutes up, for a total of 17 minutes.

Since the occurrence of sinus blocks is a binomial distribution (either a block occurs, or it doesn't), I can calculate the likelihood of having a dive with "n" patients making it to depth with no stops, versus having to stop for one, two, three, etc up to "n" stops to deal with barotrauma. Each stop would add 3 minutes. Since our chamber holds a maximum of 8 patients, I have selected an average patient load of 6 for my illustration. For the Smooth Ride profile, the probability of barotrauma is 0.0189, while for the linear descent is 0.0590. Using these values in the binomial distribution produces the following table:

Probability of exactly "n" occurrences out of 6 patients

n =	0	1	2	3	4
p=.0189	0.892	0.103	0.005	0	0
p=.059	0.694	0.261	0.041	0.003	0

If we now examine 1000 chamber loads of each type, we would expect the following for descent times:

	Smooth Ride			**Linear Descent**			
# barotrauma	0	1	2	0	1	2	3
# profiles	892	103	5	694	261	41	3
Base Descent Time	17	17	17	16.25	16.25	16.25	16.25
Added for Barotrauma	0	3	6	0	3	6	9
Total Descent Time	17	20	23	16.25	19.25	22.25	25.25
Time for 1000 Dives	15164	2060	115	11277.5	5024.25	912.25	75.75

Thus, for 1000 Smooth Ride chamber profiles, each with 6 patients, 17339 minutes are taken, for an average of 17.3 minutes per dive. Examining the linear descent profile, a total of 17289 minutes would be required, for an average of 17.3 minutes per dive - an even wash! Thus for no change in overall crew or facility time, we have decreased our expected number of barotraumas over 6000 patient exposures from 354 to 113, preventing 241 episodes of patient discomfort and anxiety. In all likelihood, this would also obviate the need for many ENT referrals for PE Tube placement, though this hasn't been analyzed. We also avoid the time previously taken to review each patients history for every dive to select the combination of ascent and descent times needed to ensure patient safety. Clinically we have been very satisfied with the overall improvement, patient satisfaction, and operational smoothness provided by our descent and ascent profile modification. I predict that soon, all hyperbaric chambers will control their ascent and descent using a constant volume rate of change instead of the current constant depth rate of change mechanisms. Enhanced patient comfort and overall satisfaction are bound to be the end result.

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