Diving at Altitude

By John Adsit
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Diving at altitude demands adjustments to the procedures used at sea level. With moderate increases in altitude and with shallower dives, the differences can be minor, even minor enough to be ignored. As altitude and depth increase, the need for concern grows. There are three primary reasons for this.

1. In cases where the diver has ascended to altitude, the diver begins the first dive with residual nitrogen from change in altitude, so it is similar to having done a dive already.
2. Decompression sickness depends largely upon the difference in the body's tissue pressure upon ascent and (especially) surfacing, and that difference is potentially greater at altitude.
3. Bubbles that are formed in the body can increase in size upon ascent, and that rate of growth needs to be controlled. The growth is greater at higher altitudes.

Most of what we know about diving at high altitude comes from work done at what are really moderately high altitudes—usually up to 8,000 feet/2,500 meters. Little study has been done at greater altitudes than that. Most of the truly high altitude studies have been done in relation to astronauts and other high altitude pilots, and some of the scientists working on that kind of high altitude work have also been involved with decompression with diving. They caution that there is much more going on when you get to those higher altitudes, so that kind of diving should not be considered a mere extension of the norms associated with diving at more moderate altitudes.

Diving with nitrox has become increasingly popular, and many divers will not realize that altitude affects nitrox use as well. The most significant difference is in maximum operating depths (MOD), the maximum depth a specific enriched air blend can be used safely.

This article will come in Five Parts:

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Part Two: Tissue Pressure Gradient Upon Surfacing
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Part One: Starting with Residual Nitrogen

Beginning open water divers learn that before they begin a second dive, they must have a surface interval after the first dive. That is because when they surfaced, they still had more nitrogen in their system than normal. Because the air they breathe on the surface has a lower partial pressure of nitrogen than their body tissues, their body will slowly lose the excess nitrogen they still have in their tissues after surfacing. Unless they wait a long time, though, they will still have more nitrogen in their tissues when they start the second dive than they did for the first. That extra nitrogen, called residual nitrogen, must be accounted for in dive planning. That accounting can be done through dive tables, but today most people use computers, and the computers will factor the residual nitrogen into the following dives.

When a diver travels from low to high altitude, the diver will have residual nitrogen because of the higher partial pressure being breathed at the lower altitude, just like the higher partial pressure breathed during a previous dive. The diver must therefore plan the first dive as if it were a repetitive dive. PADI teaches divers using their tables to treat every 1,000 feet of ascent as two pressure groups, so a diver leaving sea level and traveling to an altitude of 6,000 feet would be in the L pressure group already, so an appropriate surface interval is required. With the PADI tables, a diver in the L pressure group would be back at the A pressure group in 2:10 hours, and that diver could be at a first dive level after 5:10 hours. Because the PADI tables wash out at 6 hours, divers who have been at a site for longer than that need not consider the effects of residual nitrogen. The US Navy tables and other tables that follow them wash out at 12 hours, so they require 12 hours at altitude before residual nitrogen is no longer a factor.

Of course, no one is teleported to a dive site, like crew members being beamed up to the Star Ship Enterprise. A diver driving to that altitude would be off-gassing all the way up to the dive site and would arrive well on the way to first dive status. A diver flying in a commercial aircraft would be at an even higher altitude for that time, because commercial aircraft are pressurized to an altitude greater than 6,000 feet. That means that most divers will have already completed much or all of the full surface interval by the time they have set up their gear for the dive.

For divers using computers, most will adjust to altitude automatically but some will have to be adjusted manually. That computer will then know you are at altitude, but it will not know how long you have been there. In most cases, this will not matter. However, in the rare case of a diver preparing to dive with a significant load of residual nitrogen, it should be considered when deciding how close to dive to decompression limits. For technical divers diving with software generated tables, most decompression software programs will ask divers to input their current altitude, their previous altitude, and their time at the present altitude.

Because most divers will have had enough time at that higher altitude before they begin their dives to have gotten rid of most residual nitrogen even without trying to do so, this is the least important of the factors involved with altitude diving. Pressure difference upon surfacing and bubble growth are far more important factors, because they have the same impact no matter how long the diver has remained at that altitude.

Summary: Divers who arrive at altitude from a lower altitude have residual nitrogen in their tissues, as if they had already done a dive. A first dive must therefore be treated as if it were a second dive. Many and perhaps most divers, however, will be at that altitude long enough before the dive to have had enough of a surface interval to eliminate that that problem.

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Part Two: Tissue Pressure Gradient Upon Surfacing

Before a bottle of carbonated beverage is opened, you will see no bubbles in the liquid. This is because the carbon dioxide in the bottle is held in solution due to the high pressure inside the bottle. Upon opening the bottle, bubbles instantly appear because of the difference in pressure between the bottle and the atmosphere. When you open that bottle at high altitude, as anyone working in the lunch room on a ski slope will tell you, the bubble formation is much more dramatic because the pressure difference is so much greater.

That difference in pressure, or gradient, is one of the key concerns for decompression sickness—a diver must make sure that the nitrogen pressure in the tissues is not too much greater than the surrounding pressure, both at depth and especially when reaching the surface. As a diver ascends, the tissues that are off-gassing must not be allowed to have too high a pressure when compared to ambient pressure. The ascending diver must control the ascent rate and use appropriate stops to allow tissues to off-gas sufficiently before either continuing the ascent to a lesser ambient pressure or surfacing. Because the atmospheric pressure is less at altitude, if the diver were to use the same ascent strategy commonly used at sea level, there is a chance the diver's tissue pressure could exceed the allowable gradient.

Although the ambient pressure the altitude diver experiences upon surfacing can be significantly less than at sea level, the tissue pressure accumulated during the dive will be about the same. Water weighs the same at altitude as it does at sea level, so when a diver is at the deepest point of the dive, the vast majority of the pressure will come from the weight of the water. As the diver ascends, the weight of the atmosphere becomes more and more of a factor--slowly at first but then very rapidly during the last 30 feet and upon surfacing. That means that the diver will off-gas during the first part of the ascent at a rate similar to sea level, but at the end the ambient pressure will drop rapidly and create the danger.

Let’s compare a diver at sea level to a diver at 6,600 feet (2,000 meters) to see how much of a difference this makes. We measure air pressure in atmospheres of pressure, with sea level being 1 atmosphere. Every 33 feet of salt water and every 34 feet of fresh water also weighs 1 atmosphere. That means that a diver at 102 feet of fresh water at sea level is under 4 atmosphere of pressure, which is abbreviated 4 ATA. That pressure causes the diver to inhale 4 times as many air molecules as at the surface, so the diver has much more nitrogen entering the body than leaving it, resulting in significant on-gassing. The diver at altitude is diving with an atmospheric pressure of 0.8, so at 102 feet, the diver is under 3.8 ATA and is breathing in 3.8 times as many nitrogen molecules as at the sea level surface.

That is not a huge difference—only 5%--so the diver is taking on nitrogen about as fast as at sea level. As the diver ascends at the end of the dive, there is still very little difference at first. At 68 feet, the difference is less than 7%. At 34 feet, the difference is 10%, and upon surfacing, the difference is a full 20%. That means the diver is on-gassing almost as much as at sea level, is off-gassing upon early ascent about the same as at sea level, but faces a dramatic difference in pressure gradient in the last feet of the dive.

Depth Feet/meters	S. L. ATA	Alt. ATA	Difference at altitude	Comment	Comment
102/31	4	3.8	5%	On-gassing at nearly the same rate as sea level	Difference in pressure at altitude increases only 5% during 68 feet/21 meters of ascent.
68/21	3	2.8	7%	Off-gassing at slightly higher rate than sea level	
34/10	2	1.8	10%	Ambient pressure lower than sea level	
Surface	1	0.8	20%	Ambient pressure MUCH lower than sea level	Difference in pressure at altitude increases 10% in 34 feet/10 meters of ascent.

Summary: Divers at high altitude have almost the same experience as at sea level during the working portion of the dive because most of the pressure upon than comes from the weight of the water. Water weighs the same at any altitude. The deeper the dive, the truer this is, because the weight of the atmosphere becomes an increasingly smaller percentage of that total weight. This means the diver on-gasses at nearly the same rate as a sea level diver. As the diver ascends, the difference grows, but not significantly at first, so the diver off-gasses during ascent at nearly the same rate as a sea level diver. During the last 34 feet of the ascent, the weight of the atmosphere becomes the most important factor in the diver’s total pressure, and the difference between sea level and altitude changes rapidly. The ambient pressure when the diver surfaces will be less than at sea level, and the diver must make sure tissue pressures have been reduced enough to ensure the gradient between tissue pressure and ambient pressure are not too great.

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Part Three: Bubble Growth at Altitude

Early decompression theory focused on preventing the creation of bubbles by keeping excess nitrogen dissolved in the tissues before being eliminated through the lungs. Later research indicated that some bubbles were usually in existence throughout the dive, with the degree to which they exist depending primarily upon the diver--some people bubble a lot, and some barely bubble at all. As the diver ascends, these bubbles will grow in size because of lesser ambient pressure. At the same time, they are shrinking in size due to gases leaving through the off-gassing process. Decompression planning seeks to find the ascent rate that will allow the diver to reach the surface with bubble size sufficiently controlled.

Boyle's Law

Boyle's Law predicts changes in volume due to changes in pressure. If you multiply the volume by the pressure at one depth, it will equal the volume times the pressure at another depth (the equation is $P_1 \cdot V_1 = P_2 \cdot V_2$). In scuba, we measure the pressure in atmospheres (ATA) as was shown in the last part. To show how this works mathematically, let's look at how a bubble would grow if a diver went directly to the surface from 102 feet of fresh water at sea level (4 ATA). To make the math easy, we will give the volume at depth the value of 1. The starting pressure of 4 ATA equals 3 atmospheres of water weight plus 1 for the weight of the atmosphere itself.

$$4 \cdot 1 = 1 \cdot V_2$$

To solve that equation, we need to multiply the starting pressure and volume (in this case $4 \cdot 1$) and then divide by the new pressure (in this case 1). The result is that $V_2 = 4$, meaning a bubble formed at 102 feet would grow to 4 times its size if the diver went right to the surface. This could be very dangerous, so we ascend at a rate that will allow the bubble to off-gas enough to keep the growth at a safe level.

What is that safe rate of ascent? No one can be sure. Most people believe the ascent rates, safety stops, and decompression stops commonly used in scuba are safe because they have a good record of preventing DCS. Others argue that to control bubble growth on deeper dives, divers should do extra stops at deeper depths to control bubble growth. Whatever is right for sea level, if we compare bubble growth there with bubble growth at altitude, we can see if there is any possible need for an adjustment.

To do this, let's look at the diver ascending from the same depth at an altitude of 6,600 feet/2,000 meters. At that altitude, the atmospheric pressure is 0.8 ATA, so P_1 will be 3 atmospheres of water plus 0.8 for the atmosphere (3.8), and P_2 will be 0.8. Here is the equation for that same ascent at the higher altitude:

$$3.8 \cdot 1 = 0.8 \cdot V_2$$

So at this altitude, the new volume will be 3.8/0.8, or 4.75. A bubble going directly to the surface from that depth at that altitude will be nearly 20% larger than at sea level. This means it is even more important to control the rate of growth when ascending at altitude.

We saw with the changes in ambient pressure that the pressure changes upon ascent are minor during the earliest part of the ascent but become major during the last 34 feet. That is also true for the increase in bubble size. As a diver begins to ascend from 100 feet, the rate of expansion for the bubbles will be nearly the same as at sea level, but as the diver gets nearer to the surface, the difference will become much greater. Divers at high altitude should be especially careful of their ascent rates in the shallowest parts of the ascent, and they may want to consider a longer safety stop or final decompression stop.

Comparison of Bubble Growth from 102 feet/31 meters of Fresh Water			
Depth	**Size on sea level dive**	**Size at altitude**	**Difference**
102/31	1	1	0%
68/21	1.33	1.36	2%
34/10	2	2.11	5.5%
Surface	4	4.75	18.8%

Although this will usually not have a significant impact on a dive, the rate of bubble growth will also pertain to the bubbles in a BCD, wetsuit, or drysuit. This means that controlling buoyancy in shallower water will be increasingly difficult as divers dive at higher altitudes because the bubbles will grow or shrink more quickly with changes in depth than they will at sea level.

Summary: If bubbles form in a diver's tissues during a dive, they will increase in size during ascent, which can be dangerous. Ascent rates and stops are will control bubble growth by allowing bubbles to shrink through off-gassing at a rate that will offset the growth due to pressure changes. When bubbles form at altitude, they will increase more than they will at sea level, with most of that difference coming in the shallowest 34 feet of the dive. Air spaces in BCDs, dry suits, and wetsuits are affected the same way.

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Part Four: Decompression Strategies for Altitude Diving

Divers used tables to plan decompression for decades, but those tables were created for use at sea level. The traditional strategy for altitude has been to use those tables with depth adjustments for altitude. A diver can use altitude adjustment tables to read the altitude and see how to change their depth for planning purposes. For example, a diver planning to dive to 100 feet at 6,600 feet altitude would round off the altitude to 7,000 feet. The table would then tell him or her to treat the dive as if it were a dive to 129 feet. The diver can then use that adjusted depth with the sea level tables for planning. The safety stop would also be adjusted by multiplying that depth by the atmospheric pressure. Altitude adjustment tables will typically cover that as well, telling the diver at 6,600 feet to do a 15-foot safety stop at 12 feet instead.

One challenge with using tables to dive at altitude is the fact that many depth gauges will not give an accurate reading and will need to be adjusted for altitude. If divers are using a computer or a bottom timer that does adjust for altitude, these will give the actual depth and do not need to be adjusted. Divers wishing for more detailed information on using tables for altitude diving can refer to the US Diving Manual, Revision 7, pages 9-46 through 9-50.

Very few people use tables anymore, with computers being almost universally used instead. Some computers have to be adjusted manually for altitude, but many will read the atmospheric pressure and adjust automatically. If a computer is adjusted for altitude, then all readings will be adjusted automatically, and the diver should be safe to follow the computer as if it were at sea level. No further changes should be necessary. *If the computer is not adjusted properly for altitude, then the guidance it provides will not be accurate.* Technical divers planning technical dives using desktop software to generate tables for their dives should be sure the program is adjusted for altitude as well.

Let’s look at an example of how a desktop software program adjust for altitude. From reading the previous section you would expect an altitude-adjusted software program to contain almost all of its differences upon ascent to the shallower depths. That is indeed what happens. Let’s look at a decompression dive to 180 feet for 30 minutes using EANx 50 as a decompression gas to see how a popular software program (*i.e.*, Buhlmann ZHL-16 C) accounts for altitude. We will compare a dive at sea level with a dive at 6,600 feet/2,000 meters.

Depth	Sea Level		Altitude	
	Time at Depth	Total Dive Time	Time at Depth	Total Dive Time
180	30	30	30	30
Ascent	3	33	3	33
80	1	34	1	34
70	1	35	2	36
60	3	38	2	38
50	3	41	4	42
40	4	45	5	47
30	7	52	9	56
20	13	65	15	71
10	22	87	31	102

1. Until the divers pass 60 feet upon ascent, the two dive plans are nearly 100% identical. They will pass that depth at 38 minutes of total dive time.
2. From that point on, the decompression stops for the altitude dive begin to get increasingly longer, but not too much at first. After the 40-foot decompression stop, the altitude diver will have only added 2 extra minutes.
3. By the time the dives are over, the altitude diver will have had to do 15 more minutes of decompression, with 9 of those coming on the last stop at 10 feet.

The software program added 17% more time to the total dive to account for altitude. Calculating for decompression time alone, the program added 35% more decompression time to account for changes due to altitude.

Some divers trained by some agencies do not use traditional tables but instead rely upon systems that were created by those agencies for use at sea level. In some cases, they have no official guidance on how to adjust for altitude. In some cases, they are advised to use their sea level system at altitude without adjustment. Anyone doing that might want to consider the difference in the example above to see how established programs handle altitude before deciding not to make any adjustments.

Higher Altitudes

Not many people will ever have the opportunity to dive at very high altitudes, such as 10,000 feet/3,000 meters and above. If they do, they will be entering territory that is largely unknown. As you get into those kinds of altitudes, factors that are not worthy of consideration at lower altitudes become increasingly important. For example, acclimatization to that altitude and its effect upon breathing rates can be very important. Because diving at those altitudes is so very rare, there has been little opportunity to study it or gather data about it.

Acclimatization is a critical factor at these altitudes. Anyone who has even taking a hike at altitudes above 10,000 feet knows that the altitude puts significant stress on the body. After someone has been at that altitude for a while, the body begins to acclimate, meaning it feels somewhat more normal to be there. The diver is not, however, in the same condition after acclimating as he or she was at a lower altitude. The degree to which this impacts diving has not been well studied. The US Navy Diving Manual contains this warning just about ascending to very high altitude on page 9-50:

Altitudes above 10,000 feet can impose serious stress on the body resulting in significant medical problems while the acclimatization process takes place. Ascents to these altitudes must be slow to allow acclimatization to occur and prophylactic drugs may be required to prevent the occurrence of altitude sickness. These exposures should always be planned in consultation with a Diving Medical Officer.

There has, however, been a lot of work on high altitude decompression in non-diving circumstances. Both astronauts and U2 pilots would suffer severe decompression sickness on their flights if they did not follow careful procedures developed by NASA scientists. Some of these scientists were also involved with the development of diving decompression theory. For example, NASA decompression scientist Dr. Michael Powell was a member of the team that created the PADI Recreational Dive Planner (the PADI tables).

Although the information gathered by NASA over the years would be helpful in planning high altitude decompression, little of that has been done. Because of the lack of firm data on diving at such an altitude, scientists such as those working for NASA are understandably reluctant to make any public recommendations to which their names might be attached. A conversation with a NASA decompression scientist and technical diver about diving at a very high altitude (16,000 feet) drew the estimate that there were only a few scientists in the world with the ability to plan such a dive.

To give a brief example of how significant the difference can be, consider a dive at 16,000 feet/4,900 meters. The atmospheric pressure there is about 0.5. In the bubble growth section, we saw that a bubble rising from 102 feet to the surface will grow to 4 times its size at sea level and 4.75 times its size at 6,600 feet/2,000 meters. At this high altitude, it will grow to 7 times its size. In the gradient section, we saw that the gradient upon surfacing at 6,600 feet/2,000 meters will be 20% greater than at sea level. At this altitude, it will be 50% greater.

Surprisingly, some decompression software programs will allow divers to plan decompression dives at such altitudes using standard algorithms like Buhlmann and VPM, even though there have been few such dives attempted. If you input the dive plan and the altitude, you will get a decompression plan, but how is one to know if it will work? Divers in such a situation are advised to be very wary of very high altitude decompression plans that are not backed by solid science.

Summary: Divers using tables should use altitude adjustment table to plan dives as if they were at a deeper level, as indicated by those tables. Divers using computers should be sure their computers are adjusted to altitude before following their guidance. Divers intending to dive above 10,000 feet/3,000 meters should be aware that there is little research available on safe diving practices at those altitudes, and high altitude decompression scientists caution that additional factors need to be considered at those altitudes, particularly with decompression diving. Software programs that will provide decompression profiles for those altitudes are providing profiles that have never been tested and rarely been used.

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Part Five: Maximum Operating Depths at Altitude

Most recreational and technical divers who use nitrox or trimix are accustomed to referring to a chart to tell them the maximum operating depth (MOD) of the gas they are planning to use. Those MODs, however, are based on dives in salt water at sea level. Divers at altitude rarely consider that the MODs in their diving are different, both because of the altitude and the fact that they are diving in fresh water. If asked to make an adjustment for altitude, many would be tempted to consult the same altitude adjustment tables that are used for decompression planning using tables, but if they did, they would be making a mistake. In fact, they would be making an adjustment that is nearly the precise opposite of the correct one.

Such a table tells divers to plan as if a dive is deeper than it actually is. That would lead a nitrox diver to assume the MOD is shallower at altitude than at sea level. With nitrox, though, it is just the opposite. Because of the decreased weights of both the water and the altitude, the MOD of dives is actually *deeper* than when diving in the ocean at sea level.

Veteran recreational nitrox users are probably so accustomed to writing "110 feet" or "34 meters" on a Nitrox log sheet for the MOD of 32% nitrox that they don't have to look at a chart before doing so. Since most modern introductory nitrox courses do not focus on the mathematical equations behind nitrox diving the way they used to, many divers do not know how MODs are calculated. They are determined by a mathematical equation that links depth to the partial pressure of the oxygen in the mix to be breathed. If you divide the maximum partial pressure you want by the percentage of oxygen in the mix, you will get the ambient pressure (in atmospheres) that will give that maximum partial pressure. To get your MOD, you then convert that partial pressure to feet or meters.

Let's see how we get the familiar MOD for 32% Nitrox. We start with the common maximum partial pressure used by most divers of 1.4. If you divide that by 0.32, you get 4.375, so you with that mix you will get a partial pressure of 1.4 when you are at an ambient pressure of 4.375.

1.4/0.32 = 4.375

To convert that to feet or meters, you subtract the weight of the atmosphere (1) and then multiple by the number of feet or meters in an atmosphere of water (33 or 10). Multiply 3.375 by 33, and you get 111. Multiply 3.375 by 10, and you get 34 (those numbers are typically rounded off on charts).

Imperial: (4.375-1) X 33 = 111 feet
Metric: (4.375-1) X 10 = 33.75 meters

Now let's see what happens if we do the same process for a dive at 6,600 feet/2,000 meters. We again divide 1.4 by 0.32 and get 4.375. This time, however, we are going to subtract 0.8 for the weight of the air at that altitude, giving us a new total of 3.575. Instead of multiplying by 33 feet or 10 meters, we will multiply by 34 feet or 10.4 meters, because fresh water is that much lighter than salt water. This gives us new MODs of 122 and 37—a significant difference.

Imperial: (4.375-0.8) X 34 = 121.6 feet
Metric: (4.375-0.8) X 10.4 = 37.2 meters

For recreational divers, it means that they can plan dives using nitrox deeper than they would be able to at sea level. If they are using computers that are adjusted to altitude, the computers should accept the deeper MOD, and they should adjust their no decompression limits accordingly.

For technical divers using trimix, it means a deeper MOD and a deeper END (equivalent narcotic depth), enabling them to dive deeper with a specific trimix blend or use less of that expensive helium at some depths.

It also makes a big difference for accelerated decompression. Divers using EANx 50 for decompression can switch to that gas at 70 feet/20 meters at sea level, but at 6,600 feet/2000 meters, they can make that switch at 80 feet/24 meters. Divers using pure oxygen for decompression at sea level switch to that gas at 20 feet/6 meters, but at that altitude they can switch at 27 feet/8 meters. Getting onto lower nitrogen mixes earlier will help accelerate decompression schedules.

Other Nitrox-related Information

The general equation that gives you the MOD (Partial Pressure = Pressure at Depth X Fraction of Oxygen) can be used to find other altitude-related facts related to nitrox use. You can find the atmospheric pressure at any altitude online. Once you know that and know how to use it find the pressure at depth, all you need to do is plug in the 2 factors you know and do the math to find the 3rd.

- If you want to know the richest nitrox mix you can use at a certain depth (fraction of oxygen), you divide the desired partial pressure by the pressure at depth.
- If you want to know what partial pressure you will be under if you take a certain mix to a certain depth, you multiply the fraction of oxygen by the pressure at depth.

Summary: Nitrox and Trimix divers who are not familiar with the equation for MOD may mistakenly believe nitrox limits on operating depths will be shallower at altitude, but they are actually deeper. This allows nitrox divers to use nitrox mixes at deeper depths at altitude and thus get more bottom time or stay farther away from NDLs. It allows decompression divers to go deeper with trimix and use enriched air for accelerated decompression at deeper depths and thereby decrease total decompression time. By using the atmospheric pressure at altitude instead of sea level and by using the weight of fresh water instead of salt water, one simple equation will enable you to correct all Nitrox-related issues to altitude.