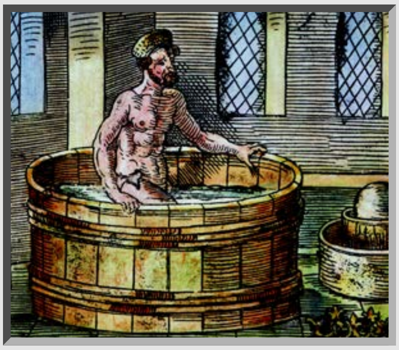
Abstract Theory

The Foundation for Understanding



Physics

Physiology

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SCUBA
Courses & Publications

Abstract Theory – The Foundation for Understanding
Scuba Publications – Daniela Goldstein
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Introduction

Divers at all levels are expected to have knowledge of diving theory. In most cases this is limited to what is needed to understand why you have to do certain things while diving and why things happen. For most divers, there is no need to be able to explain the background of that knowledge.

The required level of knowledge changes when a diver wants to progress toward a professional or Master Scuba Diver level. At that point the "need to know" is no longer limited to what you need to know for personal safety and enjoyment of dives. For these certifications, the level of knowledge must permit giving appropriate answers to any questions other divers may have.

When you are in charge of a dive or a course, it is necessary that the participants respect you in your role. The times when titles came with instant respect are long gone. The respect needed to have people follow your directions now needs to be earned. It is related to your knowledge and skills.

With respect to knowledge, it is not enough to just know what is written in the student textbooks. Your clients have already read those books. What they expect from you is clarification on things they did not yet understand, as well as additional information they feel they need to really understand some aspect of the theory covered. To be able to live up to that expectation, a diving professional must not only "know" diving theory, but really needs to "understand" all the concepts.

This is not the only book that is available about in-depth diving theory, but it is special. Rather than just listing the concepts of physics, or giving a list of signs and symptoms for physiology, this books really gets into the concept of how things develop. It brings you to the point where you can give answers with clarity that motivates divers to ask you more and to recognise you as a reliable source. This book is written to achieve "understanding" of diving theory, not just "knowledge".

It is a complete textbook for diving theory that can be used for leadership level in all diving organizations and federations. It is a book in your own language. The knowledge covered in this book is required when entering an Assistant Scuba Instructor, Master Scuba Diver or Scuba Instructor course.

Physics

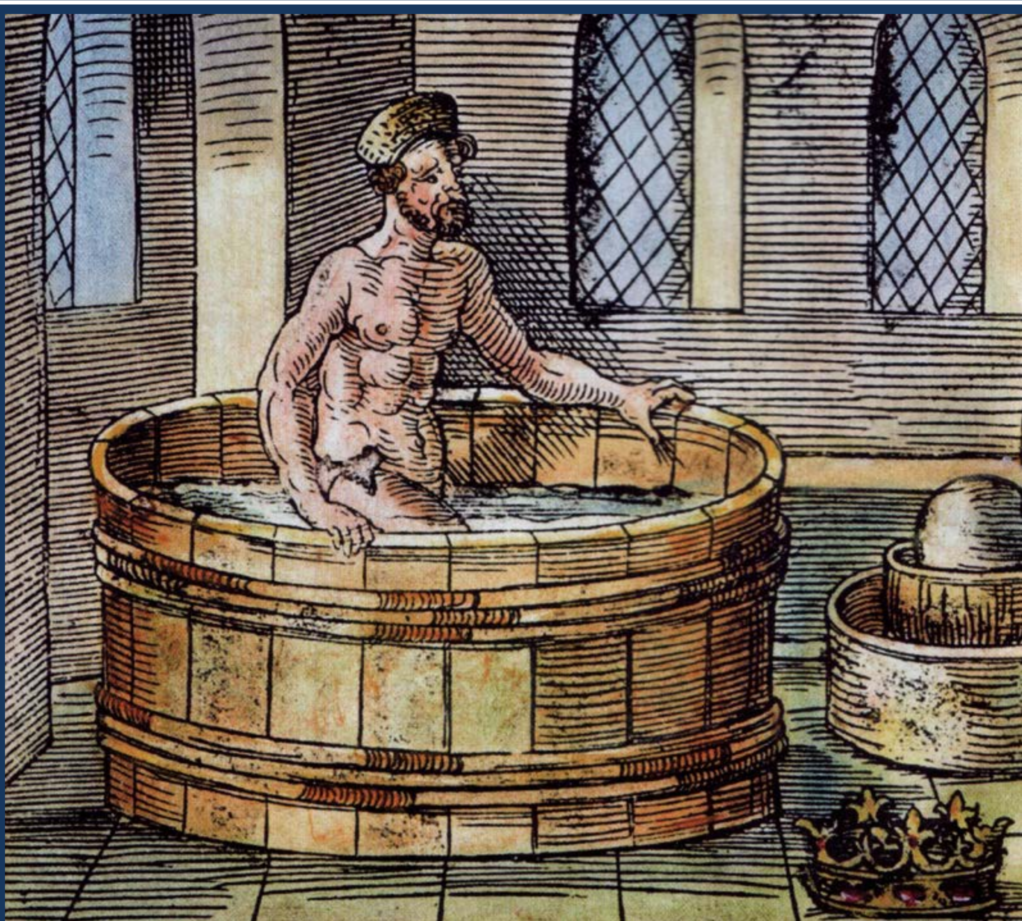
Physics is the foundation of the theory that divers have to understand to be able to dive comfortably and safe. Already in beginner courses we learn the physics of diving, but it is normally not addressed by that name. The concepts are explained and learned and divers apply them in other aspects of diving theory.

When it then gets to leadership level training for recreational diving, physics is called physics. For many this brings back memories from their school time. Addressing the subject with the name “physics” brings thoughts like “this is going to be hard” or “I will never understand that”.

This chapter was written to allow everybody to understand the concepts of physics that are needed for recreational diving without any problems. It is written in a “simple to complex” sequence and gives the information in language everybody can relate to.

The chapter covers the subjects that are considered required knowledge for those who want to take responsibility for the dives of others and is thus meant for leadership level and instructor level training.

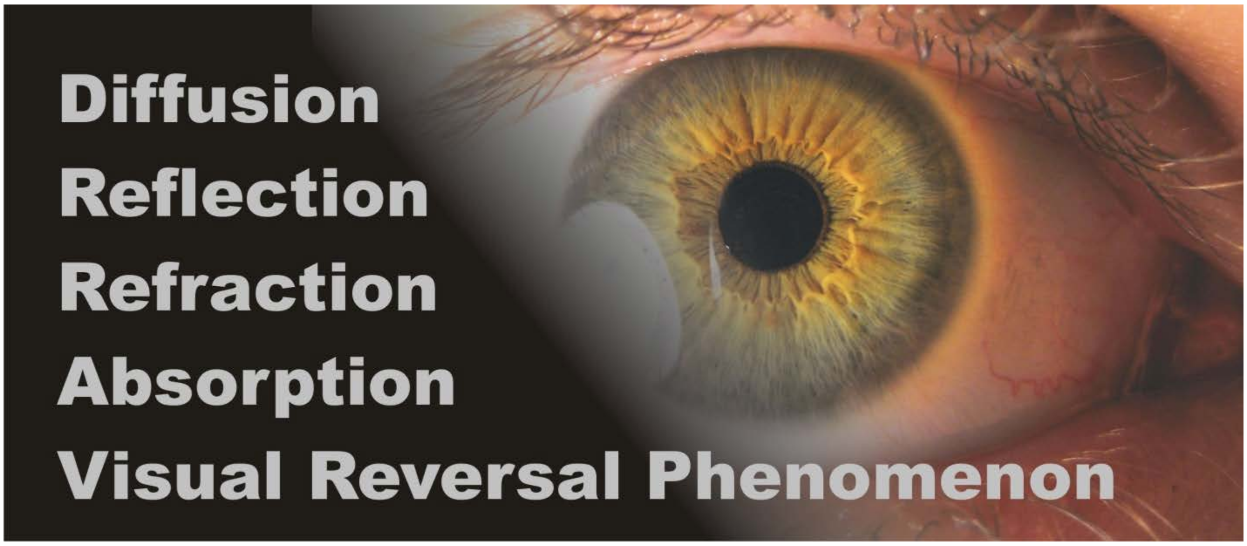
The general concepts of seeing, hearing, heat loss and movement are covered first and then the book moves into the laws of physics and their respective calculations.



Archimedes in the bathtub, discovering the law on buoyancy. HEUREKA!

Underwater Vision

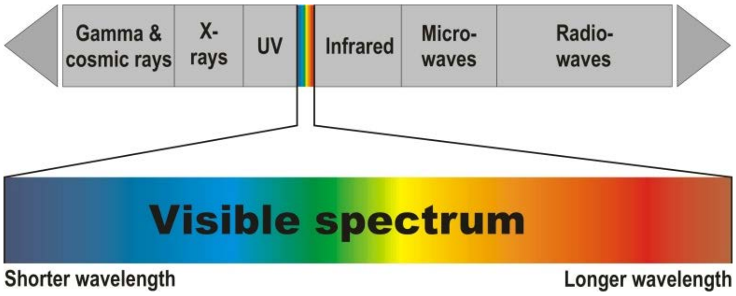
Underwater we see things differently than on land. There are four different phenomena affecting our vision underwater. A fifth phenomenon is related to the way our brain translates the visual information it receives. The phenomena are named reflection, refraction, diffusion and absorption. We describe the way the brain translates visual information with regard to distance under the name “visual reversal phenomenon”.

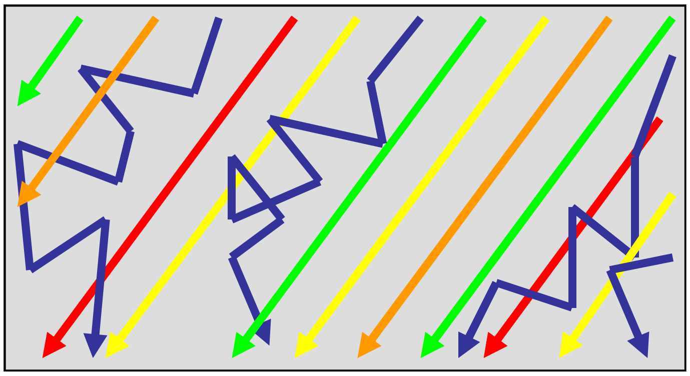


You need to be able to describe what happens to light and what the consequences are. Before going into details, you should get the terminology right. Reflection refers to light reflecting on a surface (and thus not penetrating it), just as would happen with the light of a car at night when shining on a reflector on a bicycle.

Refraction refers to light that is changing its direction when passing from one medium to another. Just like a “fractured” leg can have a different direction below and above the wound. Absorption means that the light gets lost, just like using a sponge for absorbing water from the table. The water is then gone. Diffusion means that light is scattered in different directions. Compare this with the difference between looking through a clear window with normal glass and a bathroom window with “diffuse” glass. Light gets through, but in one case you see a clear picture and in the other case you cannot recognize what it is what you see on the other side. The visual reversal phenomenon describes how your brain comes to wrong conclusions when comparing how you see things underwater with how you see them normally.

Diffusion – Light is scattered in another direction when it hits on something. Light is energy and travels as a wave. It is a wave of vibrating electric and magnetic fields, referred to as electromagnetic fields. There are more electromagnetic fields than just light. All together they are called the electromagnetic spectrum. Electromagnetic waves travel at the speed of light, which is approximately 300,000 kilometres per second in a vacuum. The various electromagnetic waves have different wavelengths or frequencies. The wavelength of the visible electromagnetic wave defines its colour.



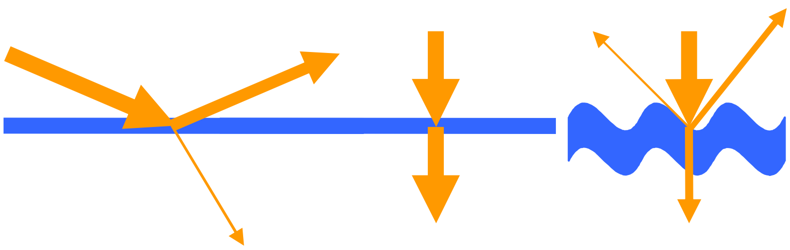


Blue light has a short wavelength (more energy) and red a long one. The wavelength of blue light makes it interact with the nitrogen in the air. Nitrogen first absorbs this freqency and then emits it in another direction. The wavelength is scattered while other colors (green, yellow, orange and red) travel through the atmosphere virtually unobstructed. This gives us the impression that blue "comes from everywhere", what makes you perceive a clear sky as blue.

Obstructions such as water droplets in a cloud are big enough to obstruct all visible frequencies. All light is scattered equally, which makes the clouds appear to be white. When clouds are very thick, much less light makes it all the way through. The clouds now appear to be darker in colour. If you would be standing on the moon, you would see the sun as a white spot against a black background. The moon does not have an atmosphere and thus no nitrogen molecules that scatter blue light.

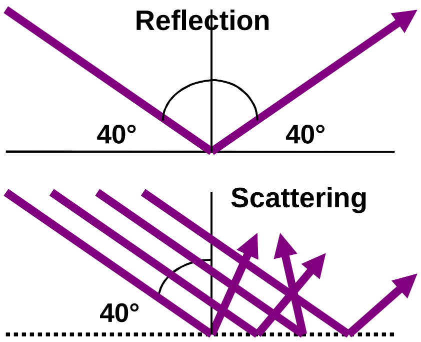
Underwater we are concerned with particles of a size big enough to scatter all light. Depending on the number of particles (visibility) part of the light falling on an object we observe comes to our eyes in a straight line. Another part will change direction several times before reaching us or is bounced off away from us. When most light comes to our eyes in a straight line, we see the object clearly. When a lot of light is scattered, we see a blurred image of the subject. In diving we refer to the scattering of light on particles as diffusion.

Due to diffusion we see less contrast (blur image) underwater than we do on land. With increasing depth diffusion adds to the loss of light making it darker at greater depth. The better the visibility is, the less diffusion there will be. But since water is per definition a diffuse medium, there will always be diffusion to some extent. Visibility is defined at the distance at which you can still see a clear image of an object.

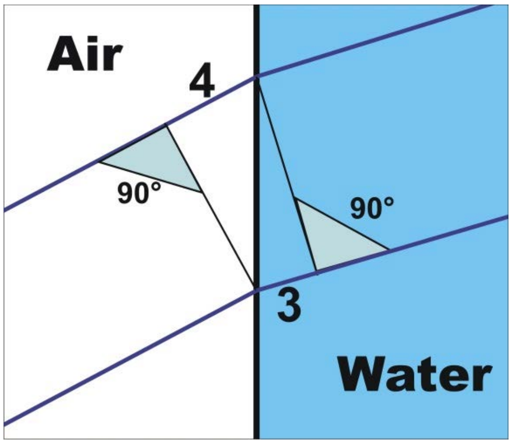


Reflection – Light is reflecting on the surface of the water. Reflected light stays "above the surface". Of the total amount of sunlight hitting the water surface, only the part that is not reflected gets underwater. The consequence is that it is darker underwater than it is at the surface. The angle under which the light hits the surface has an influence on the amount of light being reflected. The lower the sun stands at the horizon, the more light is reflected. Theoretically, all light hitting the water at an angle less than approximately 48 degrees would be reflected. This is only theoretical, because it would assume a water surface as flat as a plate of glass and it would assume that all light comes in a straight line from the sun. This is not the case for blue light.

If the light hits the surface in an angle of 90° (mid-day) you would assume none of the light to be reflected and thus have a situation in which it is just as bright underwater as it is at the surface. Also this is theoretical for the same two reasons. There is always less light underwater than at the surface. How much less depends to a big extend on the angle under which the sunlight is hitting the surface and the surface conditions (waves). The closer the angle gets to 90° and the calmer the surface conditions are, the more light gets underwater. The smaller the angle and the rougher the surface conditions, the less light gets underwater.



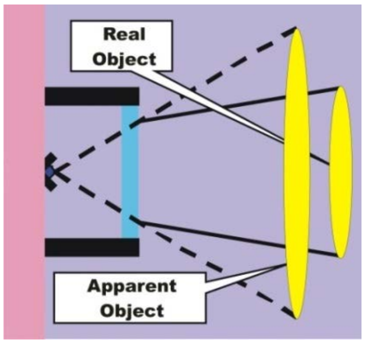
We speak of reflection when the angle of the light falling on the reflecting surface is equal to the angle in which the light bounces of that surface. If different rays of light are bouncing of in different directions, we do not speak of reflection anymore. In that case it is scattering. A mirror is reflecting, while a sheet of paper is scattering. Looking at a mirror, you see a reflection of your own face, looking at a sheet of paper; you see the sheet of paper. Photographers choose the time of their dives with reflection in mind. They also use reflection for creative aspects. Reflection does not only happen when light travels from air to water, but also when traveling from water to air. This means that you can take pictures with the reflection of a diver in the water surface.



Entering water light changes direction because the speed of the light slows down. The angle is not always the same, but it has a consistent 4:3 relationship when comparing two parallel rays of light. That is to say – when the first ray of light hits the water, it slows down, while the parallel ray is still at full speed in air. The ray in the water covers 3 distance units in the same time the ray still in air covers 4 distance units.

Refraction – When light passes from one medium into another, its speed changes. How much the speed changes, depends on the optical density of the “new medium”. When light travels from air into water, the speed is reduced (speed of light divided by 1.33). This causes the light “bend” in another direction. The change of direction causes an “optical illusion”, similar to looking through a magnifying glass. Objects appear larger and closer than they actually are.

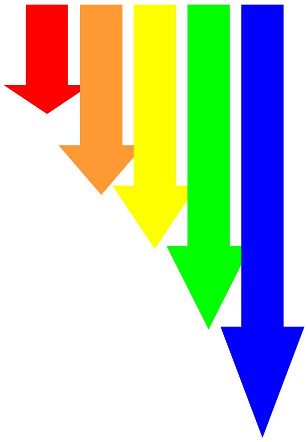
The refractive index of air is almost 1 (as it would be in a vacuum) and the refractive index of water is 1.33. This results in a 4 to 3 ratio (4 divided by 3 equals 1.33). For a diver this results in a visual illusion in distance, size and direction (not in the centre of your field of vision). The 4:3 ratio remains true, regardless of the angle of the light. Depending on the distance between the eye and the glass from the mask and the distance of the subject, the optical error amounts to a maximum magnification of 33%. If the object is close and the distance between the eye and the glass of the mask is short, the magnification will be less. Objects appear to be 25% closer than they actually are. Objects seen in the left part of your field of vision seem farther left (and those to your right seem farther right).



The eye perceives the light as if it is coming from another direction. This will always result in a visual illusion with respect to size, but for distance there are more factors involved. This will become clear in our discussion on the visual reversal phenomenon. That phenomenon is caused by the fact that your estimation of distance is affected by diffusion. Divers adapt well to the optical error and develop accurate eye-hand coordination within a short time.

Just as with reflection, photographers make use of refraction for creative effects in their pictures. When taking a picture in an angle bigger than 48°, the picture will show things above the surface. A photographer could have three different aspects in a single picture: a direct image of a diver, the reflection of that diver in the water surface and a “refracted” image of something at the surface.

Absorption – Light with a short wavelength contains more energy than light with a longer wavelength. Water is 800 times denser than air, which makes it harder for light to travel through it. The less energy the light has, the sooner its energy will be absorbed by the water (the energy is transformed to heat). Of the visible colours of light, red has least energy and will be absorbed first. Even with excellent visibility, red light cannot travel more than about 3 metres in water. In low visibility, diffusion will cause the red light to change its direction so many times that it will not even reach 1 metre of depth. Absorption follows the colours of the rainbow. Red disappears first, then orange, yellow, green and blue last. With absorption, the light actually disappears. Once absorbed, light is not light anymore. This stands in contrast with refraction, reflection and diffusion (scattering). These only describe the behaviour of light with respect to changing its direction, without losing its energy.



Absorption is the reason why many divers carry a torch on dives during mid-day with excellent light and visibility. The fantastic colours of the underwater world can only be observed when a source of white light is brought close to the subject of our observations. Without that additional source of light, we will not be able to see the real colours. Already at a few metres depth, blood will look green. When illuminating the blood with a torch, we will see its normal red colour. For the same reason, underwater photography is done with either a strobe or a torch.

Visual reversal phenomenon – The visual reversal phenomenon is not really physics. It is not related to changing of direction or losing energy of light. We are able to estimate short distances thanks to “stereo vision”. If you want to grab a pen from the table, you can “aim” very precisely when you have both eyes open. You will probably estimate the distance incorrectly when closing one eye. For bigger distances, the “stereo vision” does not work and we rely on other clues. The main clues for estimating distance are knowledge of the size of the observed object and how much contrast we see.

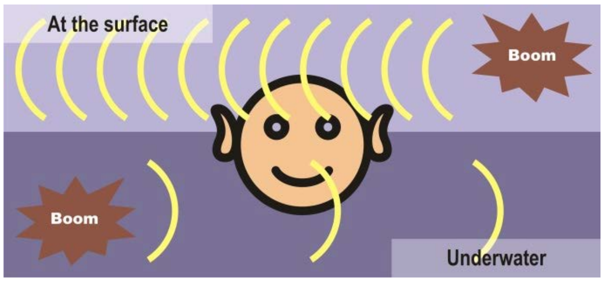
Knowledge of size does not help a lot underwater (as it would on land with for example a car). The only mechanism that plays a role is how clear we see the subject of our observations. Due to diffusion we see objects underwater less clear as we are used to from our experiences above water. This blurred image of the subject of our observations makes us believe it is further away than it actually is.

On distances where “stereo vision” allows us correct distance estimation, only refraction applies and we see things bigger and closer than they actually are. Something beyond our “stereo vision” range of distance estimation will mostly be interpreted to be further away than it actually is because of the limited contrast the image has. On land the same phenomenon plays a role in traffic accidents on a foggy day. The cars do not crash into an obstacle on the road because the driver did not see it, but because the blurred image of the obstacle made them think they were still far enough away to slow down the car.

Underwater Hearing

In saltwater and at relatively low temperatures, sound travels at about 1.5 km/s and in freshwater 1.44 km/s. The speed increases with increasing temperature. Above water the speed of sound is much lower (only 0.344 km/s). This means that sound travels 4.17 to 4.36 faster underwater than it does in air. For practical reasons, we round this to 4 times faster.

There are several factors that influence the speed of sound. This includes density, but it would be wrong to say that speed travels faster in denser materials. In general we can say that solids have a higher speed of sound than liquids and liquids have a higher speed of sound than gasses.



For a diver, this results in the loss of the ability to pinpoint the direction from where a sound is coming. It is the short delay between a sound reaching one ear and then the other that allows us to pinpoint the source. With a higher speed of sound, this delay is much shorter. It does not match our experience. We hear sound as if it came from a head phone set for "mono". Divers cannot adapt to this higher speed of sound. The loss of the ability to pinpoint from where sound is coming stays; regardless of the number of hours spend underwater.

This does not mean that sound is completely useless for navigation. Sound will still increase in volume when you get closer and get less loud when you move away from the source. The volume of sound helps on many dive sites to tell if you move away from shore or toward shore, especially if there are stones in shallow water that move with the waves, or if there is heavy surf. If there is no such source of constant sound, you will have to rely on your compass or other navigation techniques.

Heat and Water

To increase the temperature of 1 kilogram of water (1 litre) by 1 degree, we need about four times as much energy as would be needed to increase the temperature of 1 kilogram (800 litres) of air by 1 degree. If we would want to warm up the same volume of each (for example 1 litre) the energy needed to warm up the water would be 3,200 times the energy needed to warm up the air. This causes a delay in adapting the water temperature to the air temperature. In early summer, the water in a lake may still be significantly colder than the air temperature. After summer the water can still be comfortably warm when the air temperature has already dropped.

In water, an unprotected diver would lose body heat up to twenty-five times faster than in air of the same temperature. This is why even in relatively warm water a dive suit is needed for thermal protection. Heat is lost in 3 different ways: conduction, convection and radiation. In the case of the heat loss of a diver we are most affected by conduction, but on unprotected skin also convection plays a role.

To transmit heat from one substance to the other by **conduction**, there must be direct contact between the two substances. If you would take the metal first stage of your regulator in one hand and the plastic second stage in the other, you would have the impression that the first stage is colder than the second stage. As both were stored in the same location, we would assume both to have the same temperature (which is actually the case), so where does this difference in temperature come from?

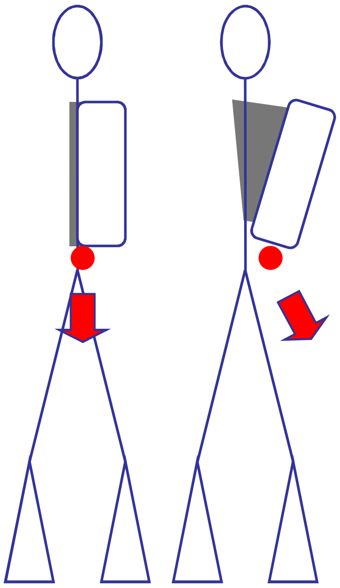
Both the first stage and the second stage are at "room temperature", which is colder than your body temperature. The moment you take the colder object in your warmer hand, the temperatures start adapting to become equal. You are warming up the regulator with your body heat. In the case of the first stage, this goes fast because metal is a good heat conductor. In the case of the second stage this process goes slower, because plastic is not a good heat conductor. The higher speed of transmitting your body heat to the first stage causes it to "feel colder". In the end both the first and the second stage will assume your body temperature, but for the second stage it will take much longer.

Water is a better heat conductor than air. Direct contact with water will cause us to lose body heat fast. Your body is not able to generate the heat that is needed to adapt the temperature of a lake to your body temperature (as in the example with the regulator), so in the end your body will adapt itself to the water temperature in the lake. To prevent heat loss by conduction, we need thermal protection (a dive suit). The neoprene of a wetsuit and the air in a dry suit are “bad conductors”. They do conduct heat, but much slower than with direct contact with water. As a consequence, a dive suit does not keep you warm. A dive suit slows down heat loss.

With **radiation**, there is no contact between the substances. Radiation means that heat is transmitted by electromagnetic waves. Think of the regulator we used as an example for conduction. If you would keep your hand 5 centimetres above the first stage and the other hand 5 centimetres above the second stage, you would not feel a difference in temperature. The regulator would not radiate heat, because it has “room temperature”. For radiation, the source of heat must be warmer than its surroundings. This is the case with a heater, a fire and the sun. You can feel the heat from the source of radiation without touching that source.

Convection occurs after a gas or a fluid is heated up at one location by radiation or conduction. The warmer liquid or gas (convection only applies to liquids and gasses) becomes less dense than the colder liquid or gas that is surrounding it. This will cause the heated liquid or gas to ascend. It is then replaced with colder gas or liquid. An unprotected diver would warm up the water that is in direct contact with the skin. This water would then ascend to be replaced with colder water. Even if you do not move, your skin would be constantly in contact with cold water. A wet suit and especially a semi-dry suit limit convection by trapping the water that is in contact with your skin inside the suit. You warm up the water in the suit with your body temperature and the suit keeps it where it is.

The situation is different when molecules are restricted in their movement. When temperatures increase, molecules start moving faster. In a sealed container (such as a diving cylinder), this would result in an increase in pressure. When the molecules are not restricted in their movement, they move further apart, which results in a lower density. The behaviour of gases when movement is restricted is addressed by Charles' law which describes pressure, volume and temperature relationships. These calculations will be covered later.

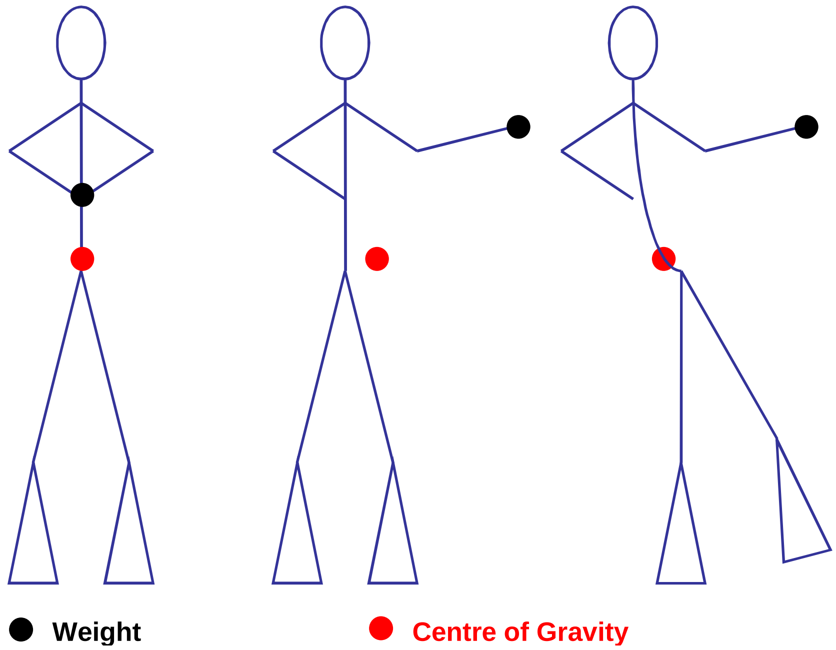


Movement

As mentioned before, water is about 800 times denser than air, which causes drag. Divers must therefore move slowly and deliberately. A streamlined position in the direction of swimming will reduce drag. This involves keeping all equipment close to the body and wearing a BCD of the correct size. In addition to these equipment considerations, divers should pay attention to the distribution of weight.

Your equipment must allow you to hover in both a vertical and horizontal (face down) position. This means that the centre of gravity must be more or less in the centre of your body. If the weight of your cylinder is pulling you in a face-up position, then the equipment must be adjusted to allow for minimal drag while swimming. If a cylinder is pulling you in a face-up position, it can be that the cylinder is too heavy or has too big a diameter (this is often the case with short 12 litre cylinders). A more common reason is that the BCD is too big. This allows the cylinder to lose contact with your back, which brings the weight of the cylinder behind you. A last consideration is the distribution of weights. It might take some time to work out the adjustment of your equipment, but it is worth your while.

The next step with respect to movement is to look if you can assume different positions underwater without creating a need to move with your arms or legs to maintain that position. You will find a dry suit to be ideal for that. The air in the suit will always go to the highest point, which will stabilize you in the position of your choice. That allows you to hover horizontally with the head down, head up, on your left, on your right, etc. If the water is too warm for a dry suit, then you should opt for a BCD that has only limited obstructions for the air passing from one location to the other within the bladder.



Assuming a position of your choice in mid-water does not only depend on your equipment, but also on working with your spinal cord and the positioning of your legs. You can train yourself by taking a 2kg weight in your hands. While hovering stretch your arm with the weight in different directions. The idea is to keep your upper body in the same position while changing the direction in which you stretch out the arm with the weight. You do this by compensating with your bodyweight. By bending your spinal cord in the other direction, you can keep the centre of gravity in the centre of your body. It will take some work to get the feeling for the use of your spinal cord, but those who use this technique during their dives do it as a second nature.

When no movement is needed to maintain your position in the water your air consumption will reduce. Your air consumption will be reduced further when you move slowly when swimming to another location. Swimming at twice the speed will take four times the energy.

Units, Constants and an Introduction to Calculations

In diving we are mostly concerned with pressure, weight, volume, quantity and temperature. Before going into actual calculations, we should take a look at the units and constants that are used for recreational diving.

Litre – the unit we use for volume is the litre. It is best written with either a capital L, or with a handwritten "ℓ". This is done to avoid confusion with the digit 1. Litre is the word used to express a cubic decimetre or dm^3. This means that

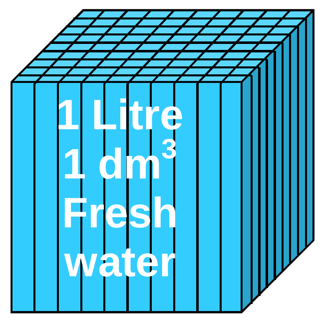
Constants to Remember

0.98	increase in pressure for 10m of fresh water
1	specific weight of fresh water
1	increase in pressure for 10m of seawater
1.01325	average atmospheric pressure in bar
1.03	the average specific weight for seawater
4	speed of sound in water vs. air
Up to 25	rate of heat loss
273	conversion °C to Kelvin
800	approx. density of water compared to air

litre is a unit for size. This is something we can measure with a ruler in width, height and depth. A 10 litre diving cylinder filled at 20 bars would have a volume of 10 litres. The same cylinder at 200 bars would still have a volume of 10 litres. Litre is used to express physical size, rather than a quantity of gas. It can be used to express a quantity of a liquid. Liquids are not compressible and remain the same size, regardless of the pressure.

Barlitre – the unit we use for a quantity of gas. The barlitre comes directly from Boyle's law. P multiplied by V is a constant. Coming back to the above example: 20 bar in a 10 litre cylinder would hold 200 barlitres (20 bars x 10 litres = 200 barlitres). The same cylinder at 200 bars would hold 2,000 barlitres (200 bars x 10 litres = 2000 barlitres). Barlitres are thus the volume a gas would have at atmospheric pressure. It is sometimes called the "surface equivalent".

Kilogram – the unit we use for weight. We express the mass of an object in kilogram. Also the upward force resulting from displaced water is expressed in kilograms. A kilogram equals the weight of 1 litre or dm^3 of fresh water. When combining kilogram with litre, we can express the specific weight of a substance. Since the unit kilogram (kg) is equal to the weight of 1 litre of fresh water, we can say that the "specific weight" of fresh water is 1 kilogram for each litre – $1kg/\ell$. The specific weight can thus also be expressed as $1kg/dm^3$. Later we will see how the unit kilograms can be used to quantify an upward force.

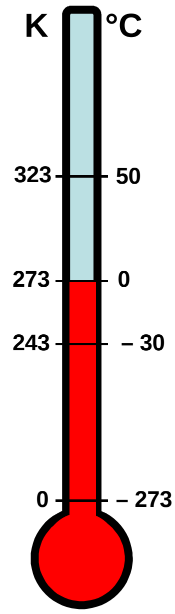


Bar – the unit we use for pressure. Pressure is a force pushing on a given surface area. Using the example of fresh water we could "cut" one dm^3 of fresh water in 100 pieces of 1cmx1cmx10cm. If we would place all these 100 pieces on top of each other, we would have a column of 100dm, or 10 metres, pushing on a surface of $1cm^2$. In this example the pressure at a depth of 10 metres in fresh water would be $1kg/cm^2$. $1kg/cm^2$ is called a "technical atmosphere" or AT (known as ATA for absolute pressure and ATO for hydrostatic pressure which ignores atmospheric pressure). The AT should not be confused with the ATM (physical atmosphere, which is the average atmospheric pressure at sea level). Bar is only indirectly based on kilogram over surface area. Bar is derived from the official unit for pressure, which is Pascal. Pascal expresses a force of 1 Newton ($kg.ms^2$) over a square metre. (1 Pascal = $1N/m^2$). This unit is not practical for diving because it is a unit for very small pressure changes. The average atmospheric pressure in Pascal would be 101,325 Pascal. For this reason, we use the derived unit bar – 1 bar is 100.000 Pascal (1ATM = 101,325 Pascal = 1013.25 hectopascal or millibar = 1.01325 bar ≈ 1bar)

Note that both with bar and with Pascal, we are basing the pressure on Newton and not on kilogram. This means that we have to account for a factor 0.98 which comes from the difference between Newton and kilogram. If we calculate in bar, the pressure in fresh water will increase 0.98 bars for every 10 metres. In some publications we find a pressure increase of 0.97 bar per 10 metres of fresh water, but this is not correct. That would be the conversion rate from kg/cm^2 or AT to ATM.

When calculating the pressure at a depth of 25 metres in fresh water, you would multiply 2.5 (2.5 times 10 metres) with 0.98 to find 2.45 bars. This is the hydrostatic or gauge pressure (most gauges read 0 as a starting point and are thus ignoring the atmospheric pressure). We then add 1 bar for the atmospheric pressure to find an absolute or ambient pressure of 3.45 bars. For the atmospheric pressure we are thus assuming 1 bar to be equal to 1ATM or 1013.25hPa (hectopascal). The atmospheric pressure is not constant and it is likely that the pressure at the dive site is not exactly the "average" atmospheric pressure. It is accepted to be 1.3% off for the average. Always calculate atmospheric pressure at sea level as 1 bar.

Kelvin and Celsius – the units we use for expressing temperature. Celsius is a unit we can relate to. We know which temperatures are comfortable, we know at which temperature water freezes, etc. Celsius is



the unit for temperature we use in day-to-day life. For calculations we cannot use Celsius. Celsius has both positive and negative temperatures in its scale. For calculations we need the "absolute temperature", which is expressed in Kelvin. The temperature scale in Kelvin has only positive temperatures, which means that the scale has to start at the lowest possible temperature. This is approximately minus 273 degrees Celsius. To convert a temperature in Celsius to Kelvin it is thus enough to add 273 (10°C = 283K).

The use of formulas – when using formulas, there are a few things to keep in mind. First of all you should make it a habit to not only enter numbers in a formula, but to always add the unit belonging to that number. If you write a pressure of 10 bars in a formula, you do not write 10, but 10 bars. This helps you to figure out in which unit the answer will come and it prevents mistakes.

A second habit should be to always estimate the outcome of a formula before calculating. If you calculate a pressure/volume relationship and the pressure is reducing, then the answer should be an increased volume. After you finished the calculation you can then check if the calculated new volume actually represents an increase in volume. If it does you can assume your calculation to be correct. If the answer represents a decrease in volume, it is likely that you have mixed up the values in your formula.

To remember which law in physics has which name, you only need to remember the alphabet. ABCD(H). Imagine you throw a sealed and flexible container in the sea. The first calculation you would be confronted with is to find out if the container would sink, float or be neutrally buoyant. This calculation is done with Archimedes (A). If Archimedes shows that the object will sink, the pressure will increase with increasing depth. The increasing pressure will change the volume of the container. This change in volume is calculated with Boyle (B). When the container continues sinking, it will pass the thermo-cline where the temperature is changing. This changing temperature will also affect the volume, which is calculated with Charles (C). Arriving at the bottom the container will stop moving, giving us time to observe details. In physics, detail refers to the percentage and partial pressure of individual gasses, which are calculated with Daltons law (D). With time, the container will deteriorate and the wall will allow water to enter. The gasses in the container will dissolve in the water according to the law of Henry (H).

Rule 1: You can multiply or divide each side of an equation by a same value and the equation will still be true. 4x3=2x6 is true (12=12) if you multiply both sides by 2, it stays true 4x3x2=2x6x2 (24=24). If you divide both sides by 2, it would still work:

$$\frac{4x3}{2} = \frac{2x6}{2}$$

This is the technique you would use when you would want to remove something from the right hand side of the equation sign. This is what you want to do until the "unknown" is isolated at the right. Imagine your equation to be 4x3=2xY. In that case you would want to find out how big Y is. For this purpose you would apply the second rule.

Rule 2: If something is multiplied and then divided by the same value, you can delete that value from the equation. It would not make sense to first multiply by 2 and then divide the result by 2.

$$\frac{4\times3}{2}=\frac{2\times6}{2} \qquad \frac{4\times3}{2}=\frac{2\times Y}{2} \qquad \frac{4\times3}{2}=\frac{\cancel{2}\times Y}{\cancel{2}} \qquad \frac{4\times3}{2}=Y \qquad Y=6$$

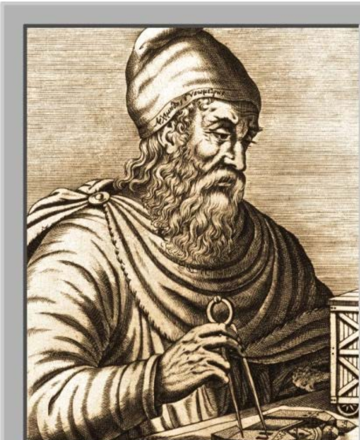
Rule 3: The last rule you might need every now and then (but its need is rather seldom in diving) is that you can "flip-flop" a formula. What's down goes up, what's up goes down.

$$\frac{4\times3}{2}=\frac{\cancel{2}\times Y}{\cancel{2}} \qquad \frac{4\times3}{2}=\frac{Y}{1} \quad\Big|\quad \frac{2}{4\times3}=\frac{\cancel{2}}{\cancel{2}\times Y} \qquad \frac{2}{4\times3}=\frac{1}{Y} \qquad \frac{4\times3}{2}=\frac{Y}{1} \qquad \frac{4\times3}{2}=Y$$

The second situation would be the only case in which you would do this "flip-flop". If you delete the two equal numbers on the right hand side, there is nothing left above or below the line. When there is nothing left, it means that the value is actually 1. If this would happen below the line, then we can ignore it (any number divided by 1 would keep the same value), but when the empty space is above the line, this would mean 1 divided by the value below the line, which is 1 divided by the answer you are looking for. To prevent this from happening, you flip-flop before doing your calculation (this would happen in Charles law when looking for a new temperature with 2 given pressures as we will cover later). We will apply these rules in the discussions of the formulas where there is a need for them and will mention them as being rule number 1, 2 or 3.

Archimedes

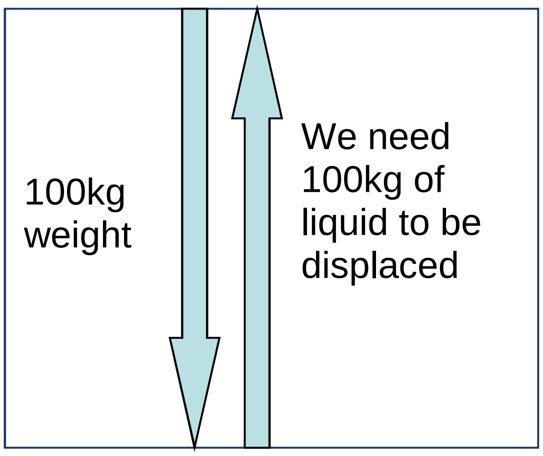
The law of Archimedes is used to calculate buoyancy. We distinguish between positive, negative and neutral buoyancy but all calculations are based on finding neutral buoyancy. Once that calculation is done, we can add or reduce weight, or change the volume as needed to make the object positively or negatively buoyant.

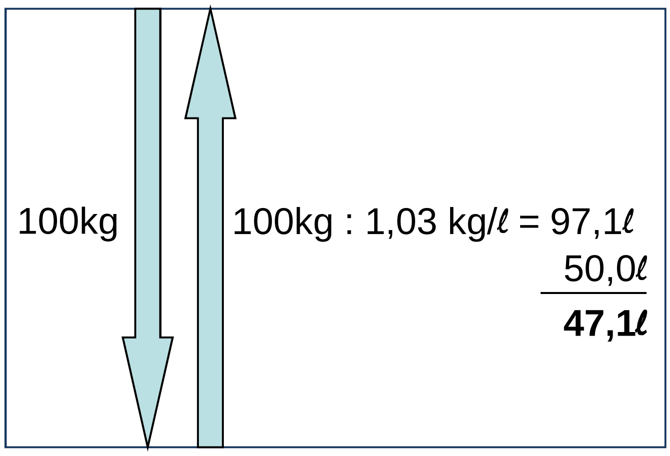


Archimedes
287 - 212 BC

According to Archimedes an object is subject to an upward force equal to the weight of the fluid it displaces. Neutral buoyancy would thus mean that the liquid displaced by an object has the same weight in kilogram as the object itself. If the displaced liquid is fresh water (1kg/l), the amount of water displaced in litres should be equal to the weight of the subject in kilogram. If the liquid displaced has a higher density (specific weight) than fresh water, the object has to displace less litres of the fluid than the number of kilograms it weighs, because each litre of liquid weighs more than 1 kilogram.

The first step in your calculation is to find out how many litres of water need to be displaced for the upward force needed for neutral buoyancy. If the weight of the object is 100kg, we need to displace 100kg of water to achieve neutral buoyancy. For fresh water this would be 100 litres (100kg : 1kg/ℓ = 100ℓ). For seawater with average density (1.03kg/ℓ) this would be 100kg : 1.03kg/ℓ = 97.1ℓ. The second step is to compare the needed volume with the volume of the object itself. If the object would have a volume (size in dm^3) of 50 litres, we would have to add volume to achieve neutral buoyancy. This could be done with a lift bag. In this example we would need a volume of 50ℓ in a lift bag in fresh water and 47.1ℓ in salt water.

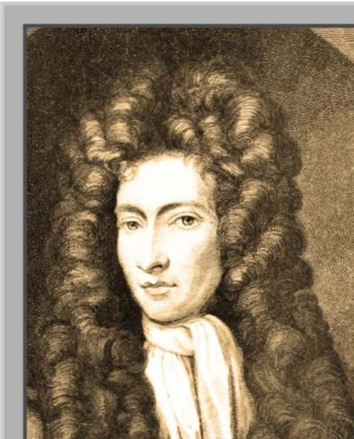




To convert kg to litre you divide by the specific weight and to convert litre to kg you multiply by the specific weight.

Some divers calculate the other way around. For the salt water example: 50ℓ x 1,03kg/ℓ = 51,5kg, to find the upward force the volume of the object itself experiences. Then 100kg minus 51,5kg = 48,5kg to define the missing upward force needed for neutral buoyancy and then 48.5kg: 1,03kg/ℓ = 47,1ℓ, to define the needed volume of the lift bag. This does not make much sense. If you are looking for an answer in litres, you are best off when you first convert all kilograms to litres and not the litres to kilograms. Later in your calculations you would have to convert to litres again (which you could forget and come up with the wrong answer).

Boyle


Boyle
1627 - 1691

Boyle's law is used for the relationship between pressure and volume (found by Boyle in 1662 and later independently by Marriott in 1676). The way we apply the law as divers is $p_1xV_1 = p_2xV_2$. In the formula p is pressure in bar and V is volume in litres. Situation 1 (p_1xV_1) is where we know both the volume and the pressure and situation 2 (p_2xV_2) is where we have one of the values (pressure or volume) but are looking for the other. Sometimes the pressure is not directly given in bar, but rather as a depth. In that case you first need to calculate the pressure at the given depth. Although it would be correct to do it, when applying Boyles law, we normally don't make a difference between salt and fresh water (it would only make a very slight difference). Just calculate 1 bar for every 10 metres of depth.

To adapt Boyle's law to our needs (only the unknown – p_2 or V_2 – should stay at the right hand side of the equation sign) we need to apply rule 1 and 2.

The air volume in an inverted jar at a depth of 5 metres is 4 litres. What would the volume be if the jar were to be taken to a depth of 30 metres?

As a first step we would need to find out what we are missing. 5 metres would be 1.5 bars and would be p_1. 4 litres would be V_1 and 30 metres would be 4 bars and p_2. We are missing V_2.

$p_1 x V_1 = p_2 x V_2$ becomes $p_1 x V_1 = p_2$xmissing. We now apply rule number 1. By dividing both sides by p_2 (the position we want to get away from the right hand side), we create the condition for applying rule 2.

$$\frac{p_1 \text{ x } V_1}{p_2} = \frac{p_2 \text{ x missing}}{p_2}$$

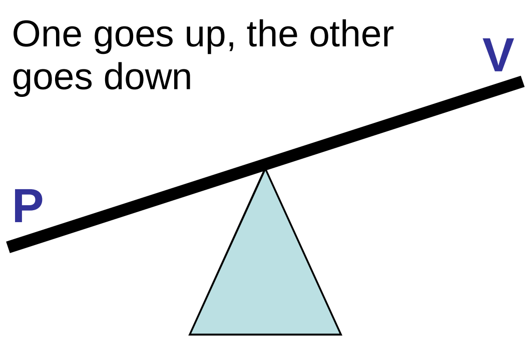
We can now delete the two p_2 at the right to get the formula we need by applying rule 2. As the missing factor is above the line, there is no need to apply rule 3.

$$\frac{p_1 \text{ x } V_1}{p_2} = \frac{\cancel{p_2} \text{ x missing}}{\cancel{p_2}} \Rightarrow \frac{p_1 \text{ x } V_1}{p_2} = \text{missing}$$

Now that we have the correct formula, we can enter the data, figure out the unit of the answer and use a calculator to find the answer. The answer should match our estimation that the volume should reduce with increasing pressure.

$$\frac{1.5 \text{ b}\cancel{\text{a}}\text{rs x 4 litres}}{4 \text{ b}\cancel{\text{a}}\text{rs}} = 1.5 \text{ litres}$$

If it would be P_2 missing, we would do the same procedure, but now we would be dividing both sides by V_2 (rule 1) and then delete the both V_2 at the right hand side (rule 2).



Boyle's law assumes that the temperature does not change. Underwater this would often be true, but on land this is rare. Boyle's law is thus typically a "diver's law". On land there is also a problem with pressure that applies less underwater. In a car tire, you can increase the pressure substantially without seeing the corresponding increase in volume. On land we are always dealing with the flexibility of the container (such as a balloon or car tire) and with gravity (the container walls being "pulled" toward the earth). This makes Boyle's law more theoretical than practical. Underwater there are many situations (a BCD, a lift bag, etc.) where Boyle's law applies exactly as it is written with respect to temperature, flexibility of the container, and gravity.

Pressure, Volume and Density

Next to Boyle's law (pressure and volume) we also need to take density into account in some situations. This is especially the case for air consumption and the use of a lift bag. Density increases at the same rate as pressure. If the pressure doubles, the density of a gas doubles as well. This means that there are twice as many gas-molecules present in the same volume. This explains Boyle's law. The volume reduces to half at double pressure because there are twice as many molecules in a given volume. The same number of molecules only needs half the space.

When we make use of a lift bag, we always need different data to lift an object in a responsible manner. We need to know the weight of the object underwater and above water, for which we apply Archimedes. The underwater weight is needed to decide on the size of the lift bag and the weight above water is needed to know if the winch to be used to remove the object from the water is rated for the weight the object has the moment it comes above water (this can be considerably more than the weight the object has underwater). As a last aspect we need to know how much air (not the volume but the quantity) is needed to fill the lift bag to the desired volume. We need to know this to decide if our personal air supply is big enough for both ourselves and for the lift bag.

To calculate this, we multiply the desired volume in the lift bag with the pressure at the depth of the object we want to lift. To fill a lift bag at 30 metres depth to get a volume of 80 litres this would be: 4 bars x 80 litres = 320 barlitres. A 10 litre cylinder at 200 bars would contain 200 bars x 10 litres = 2,000 barlitres. This would leave 2,000 barlitres minus 320 barlitres = 1,680 barlitres for personal consumption and reserve. The 1,680 barlitres represent 168 bars in your cylinder (1,680 barlitres divided by 10 litres = 168 bars). The pressure in the cylinder will drop 32 bars when filling the lift bag (320 barlitres divided by 10 litres = 32 bars).

For air consumption, we know that we use our air 2 times faster at 10 metres depth (2 bars) than at the surface (1 bar). We use it 4 times as fast at 30 metres depth (4 bars). Boyle's law does not apply because the volume of our lungs stays the same (it is not a pressure/volume relationship). It is the higher density of the air that increases the rate of air consumption.

To do the calculation, we need to know the volume in litres moving in and out of the lungs during a certain period of time. Once we have that, we can calculate the consumption at any given depth (assuming all other factors are staying the same, such as the intensity of movement of the diver). This is done by multiplying the volume moving in and out of the lungs in a minute with the pressure or density at the new depth. Because we are multiplying a pressure with a volume, the result of our calculations will come in barlitres.

A diver consumes 3 bars per minute from a 10 litre cylinder at 12 metres depth. What would be his consumption at 30 metres depth? By logic we can estimate the consumption to be almost double at 30 metres. The pressure at 30 metres is little under double the pressure at 12 metres depth (estimation). 3 bars per minute from a 10 litre cylinder are 30 barlitres at 12 metres depth. 30 barlitres divided by 2.2 bars indicate a lung movement of 13.6 litres per minute (which is equal to the consumption at 1 bar, also called the surface consumption). At 30 metres depth the consumption is 4 bars times 13.6 litres = 54.4 barlitres.

Charles

Charles law (from 1787) describes the relationship between pressure, volume and temperature (as did Gay-Lussac 15 years later in 1802). In diving the temperature relationship is not often used. As mentioned before, underwater we are in a situation in which Boyle's law can be used without being too much concerned with the temperature factor. For this reason Charles' law is mostly used for situations above water. Often these are calculations in relation to filling cylinders.

Charles
1764 - 1823

$$\frac{p_1 \times V_1}{T_1} = \frac{p_2 \times V_2}{T_2}$$

Pressure (p) is indicated in bar, volume (V) in litre and temperature (T) is indicated in Kelvin (°C + 273). It would be correct to use the pressure as an absolute pressure, which the SPG used to measure cylinder pressure would not provide (the SPG reads 0 for an empty cylinder which would actually hold atmospheric pressure of approximately 1 bar). Considering that the scale on a SPG does not allow a reading at 1 bar accuracy and that 273 is only an approximate value (273.16), it is not necessary to calculate with absolute precision. Just use the SPG reading (hydrostatic pressure) directly in the formula and you will be accurate enough. This way we prevent the common mistake at the end of the calculations to reduce the pressure found in the formula by 1 bar to convert it from absolute pressure to a hydrostatic pressure reading on the SPG.

To simplify our calculations, a first step in the use of Charles law would be to reduce the factors calculated by either deleting the volumes, the pressures or the temperatures. When deleting temperature, we are back at Boyle's law (pressure/volume relationships). If we delete the volumes, we can calculate the change in pressure in a cylinder when temperatures change (pressure/temperature relationships) and when deleting the pressures, we can calculate changes in volume for gases when temperature changes (volume/temperature relationships). This last option is very rare. Unrestricted changes in volume of a container do not exist on land due to the elasticity of the container and gravity. Underwater we are rarely confronted with temperature changes that would require a calculation.

The most common use in diving is thus the relationship between pressure and temperature in a diving cylinder. This would mean that we delete the factor volume (the cylinder would not change its volume within a scale that we can measure when temperature changes and is thus a factor we can delete).

$$\frac{p_1 \times \cancel{V_1}}{T_1} = \frac{p_2 \times \cancel{V_2}}{T_2} \Longrightarrow \frac{p_1}{T_1} = \frac{p_2}{T_2}$$

As with Boyle's law we now need to look for a missing factor. The situation in which we have both a pressure and a temperature is situation 1 (p_1 and T_1). The situation in which either the temperature or the pressure is missing is situation 2.

A 10 litre cylinder is filled at a pressure of 210 bars. At that point the cylinder has a temperature of 56°Celcius. The cylinder is then taken for a dive in 15°Celcius water. What would the new pressure in the cylinder be if no air is vented from it?

First of all, we are not interested in the volume. The cylinder is a 10 litre cylinder during filling and will still be a 10 litre cylinder during the dive. We have T_1 (56°Celcius), p_1 (210 bars) and T_2 (15°Celcius). We are missing p_2.

We now have to isolate the missing factor (p_2) at the right hand side of the equation. This means that we have to remove T_2 from that side and bring it to the left. This can be done by applying rule 1 (multiplying both sides by T_2) and then deleting the two T_2, as we have an equal entry above and below the line (rule 2). In this case we are not concerned with rule 3.

Formula	Rule 1	Rule 2	New Formula
$\frac{p_1}{T_1} = \frac{\text{missing}}{T_2}$	$\frac{p_1 \times T_2}{T_1} = \frac{\text{missing} \times T_2}{T_2}$	$\frac{p_1 \times T_2}{T_1} = \frac{\text{missing} \times \cancel{T_2}}{\cancel{T_2}}$	$\frac{p_1 \times T_2}{T_1} = \text{missing}$

Now that we have the formula in the required form, we need to convert the temperatures to Kelvin. This is done by adding 273 to the temperature in °Celsius. T_1 is 56°Celsius + 273 = 329K, T_2 is 15°Celsius + 273 = 288K and P_1 is 210 bars. We are now ready to enter the data in the formula.

$$\frac{p_1 \times T_2}{T_1} = \text{missing} \qquad \frac{210 \text{ bars} \times 288 \text{ K}}{329 \text{ K}} = \text{missing} \qquad \frac{210 \text{ bars} \times 288 \cancel{\text{K}}}{329 \cancel{\text{K}}} = 183.8 \text{ bars}$$

We should have estimated that the pressure reduces with the reduced temperature. When dealing with pressures around 200 bar, we can even do a rather accurate estimation by calculating a loss in pressure of 0.6 bars for every degree in temperature lost. In this case the temperature reduces from 56° to 15°Celsius. The loss in temperature is 41°Celsius. Multiply this with the factor 0.6. This indicates an approximate loss in pressure of 24.6 bars. In our calculation we find a loss in pressure of 26.2 bars which is close enough to assume that our calculation has been correct.

This rule of thumb (assuming a pressure change of 0.6 bars for every degree) should only be used if P_1 is 200 bars or very close to that value. For other pressures this rule of thumb does not work. Let's assume a cylinder with 10 bars (p_1) and the same loss in temperature as in the above example. When calculating with the above formula, this would give us a new pressure of:

$$\frac{10 \text{ bars} \times 288 \cancel{\text{K}}}{329 \cancel{\text{K}}} = 8.75 \text{ bars}$$

When using the rule of thumb, the loss of pressure would be 24.6 bars. This indicates a negative pressure of minus 14.6 bars. First of all this is extremely far off the calculated response and secondly negative pressures are impossible (do not exist).

When looking for T_2 rather than p_2, it is not enough to apply rule 1 and 2 to the formula. In this case we also need to apply rule 3.

A cylinder is filled at a temperature of 60°Celsius to a pressure of 210 bars. In the water (after a while) the diver observes that the SPG connected to the cylinder (from which no air is vented) reads 190 bars. What is the water-temperature?

We have T_1 (60°Celcius), p_1 (210 bars) and p_2 (190 bars). We are missing T_2. We now have to isolate the missing factor (p_2) at the right hand side of the equation. This means that we have to remove p_2 from that side and bring it to the left. This can be done by applying rule 1 (multiplying both sides by p_2) and then deleting the two p_2, as we have an equal above and below the line (rule 2). The problem is that the empty space (1) is located above the line. This brings a need to apply rule 3 (flip-flop the formula).

Formula	Rule 1	Rule 2	Rule 3
$\frac{p_1}{T_1} = \frac{p_2}{\text{missing}}$	$\frac{p_1}{T_1 \times p_2} = \frac{p_2}{\text{missing} \times p_2}$	$\frac{p_1}{T_1 \times p_2} = \frac{\cancel{p_2}}{\text{missing} \times \cancel{p_2}}$	$\frac{T_1 \times p_2}{p_1} = \text{missing}$

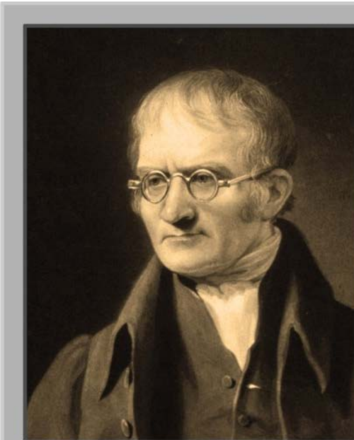
Again we have to convert the temperatures in °Celsius to Kelvin. For this question, T_1 is 60°Celsius + 273 = 333K. P_1 is listed as 210 bars and P_2 as 190 bars.

$$\frac{T_1 \times p_2}{p_1} = \text{missing} \qquad \frac{333\text{ K} \times 190\text{ bars}}{210\text{ bars}} = \text{missing} \qquad \frac{333\text{ K} \times 190\text{ b}\cancel{\text{a}}\text{rs}}{210\text{ b}\cancel{\text{a}}\text{rs}} = 301.3\text{ K}$$

We now have to convert the temperature found in Kelvin to °Celsius by deducting 273. The temperature of 301.3 in Kelvin gives us a temperature of 28.3°Celcius. The temperature dropped as we should have estimated with a decrease in pressure. We can assume that the calculation has been done correctly.

These calculations with Charles assume that we are dealing with an “ideal gas”. This is a simplification assuming that the molecules in the gas do not occupy space and do not interact. With air and Nitrox this assumption is close enough because the characteristics of nitrogen and oxygen do not differ a lot. When doing calculations with a mix containing significantly different gasses (such as helium), then we need to address the difference in the characteristics of the molecules. This is not a concern in recreational diving, but the problem must be addressed when filling cylinders with Trimix (a mix including helium) for technical divers.

Dalton



Dalton
1766 - 1844

Dalton’s law deals with partial pressures. The law states that the sum the individual pressures of the gasses in a mix makes up the total pressure of that mix – or – $p_1 + p_2 + p_3 \ldots\ldots = P_{tot}$

All gasses in a mix behave as if the other gasses would not be present. They all individually exert their pressure and the sum of all these pressures is the total pressure. Air consists of 21% oxygen, 78% nitrogen and 1% other gasses. The total pressure on land is 1 bar. This would result in a partial pressure for oxygen of 0.21bars, a partial pressure for nitrogen of 0.78 bars and a combined pressure of the other gasses in air of 0.01bars. When adding up these individual partial pressures we find the total atmospheric pressure of 1 bar.

When filling a cylinder at 200 bars with air, the air does not change. The fractions of oxygen, nitrogen and other gasses stay the same. This means that each has a consistent percentage of the total pressure. 21% of the gasses in the cylinder will be oxygen. This results in an oxygen partial pressure in the cylinder of 21% of 200 bars, which is 42 bars. For the purpose of calculations, we write percentages as a decimal (21% = 0.21). The calculation is thus 0.21 x 200bars = 42bars.

Calculations with Dalton’s law are rather basic. The percentage always stays the same and the partial pressure is just the percentage (as a decimal) multiplied with the total pressure. What we need to be aware of are the exceptions. Sometimes you are not asked a percentage or pressure, but are asked about the effect a gas is having in some situation. In that case you are not asked what happens to a percentage (which stays the same), but are asked for an “equivalent gas”.

An “equivalent gas” is in most cases a gas at atmospheric pressure. We know at which percentage carbon monoxide becomes a problem on land (carbon monoxide is a poison). When we want to know what percentage should be considered a problem at depth, we have to compare it with the known problem on land. To do this you would for example say: a mixture with 0.01% of this gas at 30 metres depth has the same effect as a mixture with 0.04% of this gas at the surface.

To find an equivalent gas, you can do a calculation similar to Boyle’s law - $\%_1 \times p_1 = \%_2 \times p_2$. It is nothing really official, but it works. It does not even matter if you put the percentage in as a decimal or as the full number. The pressure must be put in bar and as absolute pressure.

Another exception relates to the notion that percentages are always the same. This would be true under the condition that we are dealing with either an inert gas, or that the non-inert gas is not used. If a non-inert gas is used, we do have changes in percentage. For example: the percentage of oxygen in a cylinder does not stay the same when there is corrosion (a form of oxidation) inside the cylinder. With corrosion oxygen from the air is used in the process of creating rust and the oxygen percentage in the cylinder will drop. This is the reason why you should not dive with a cylinder that has been filled several months ago. The air may not have enough oxygen to cover your demand.

Changes in percentage also apply to our breathing. When diving with air, we inhale 21 per cent oxygen. When using open system scuba (a regulator), at the surface we exhale 17 per cent of the oxygen unused. The same would apply to Enriched Air. When diving with Nitrox36, at the surface we exhale 32 per cent of the oxygen unused. The higher presence of oxygen does not lead to a higher consumption. Only an increase in activity would do that. When depth increases, the percentage of the oxygen that is used decreases when the effort of the diver stays the same. A diver breathing air (21 per cent oxygen) at a depth of 30 metres (4 bars) will exhale 20 per cent of the oxygen unused. With the same effort, the diver will use the same quantity of oxygen molecules. At 30 metres depth the density of the gas in the lungs is four times higher. This means that the same percentage (21 per cent) represents four times as many oxygen molecules. Increasing the number of oxygen molecules, does not increase the amount of oxygen used in the metabolism. The quantity of unused oxygen increases with depth and with an increased percentage inhaled. Note that the sum of the CO_2 and O_2 percentage stays the same (for air 21%), but that the individual percentages change when the density of the gas in the lungs is changing. So, in general we can say that percentages do not change, but we must be aware of the exceptions.

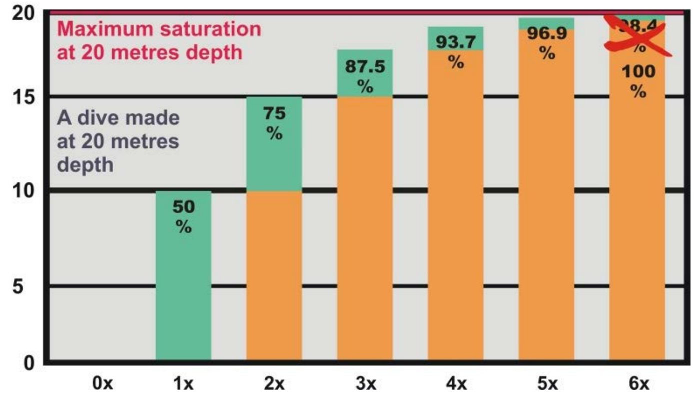
Depth	O_2 inhaled	O_2 exhaled	CO_2 exhaled	O_2 inhaled	O_2 exhaled	CO_2 exhaled
Surface	**21%**	**17%**	**4%**	**36%**	**32%**	**4%**
10 metres	**21%**	**19%**	**2%**	**36%**	**34%**	**2%**
30 metres	**21%**	**20%**	**1%**	**36%**	**35%**	**1%**

Henry

Henry
1774 - 1836

Henry's law describes the process of saturation of gasses in other matter. It is mainly used for decompression theory and is covered in detail in that chapter. According to Henry, gasses dissolve in other matter to achieve a gas tension that is equal to the gas in contact with that matter. The process of saturation is slow. Its speed is different depending on the matter being saturated. In general we state that a difference in pressure is reduced to half of its previous value in one period of time. The new difference in pressure (half of what it was before) will again reduce to half of its previous value in a same period of time. If we repeat this procedure 6 times, we are so close to an equilibrium (the tension of a gas in the tissue is equivalent to the pressure of the gas in contact with the matter) that we consider it total saturation. The duration of one period depends on the matter to be saturated.

Because the chapter on decompression theory explains this process in detail, there is no need for a complete explanation in this chapter. We should already now realize that Henry's law applies to all gasses and not only to nitrogen with respect to decompression sickness. In the physiology chapter we will see that you also have more free oxygen in your blood at depth and that this does have consequences as well.



Physiology

When diving, things change. The pressure changes, temperature, the fact that you are breathing from a container rather than the free air, the reduced effect of gravity and others have an influence on your body. Physiology is the diving related theory that explains what happens in your body while diving. It helps you to understand what you should do and should not do while underwater.

Mistakes made in a test on physiology tend to come from two different sources. Some people make mistakes because they don't get the terminology right, others because they lack understanding of what is actually happening in the body. To master physiology to the required extent, you must concentrate on both aspects you must develop an understanding of the processes taking place and use the right terminology to describe them.

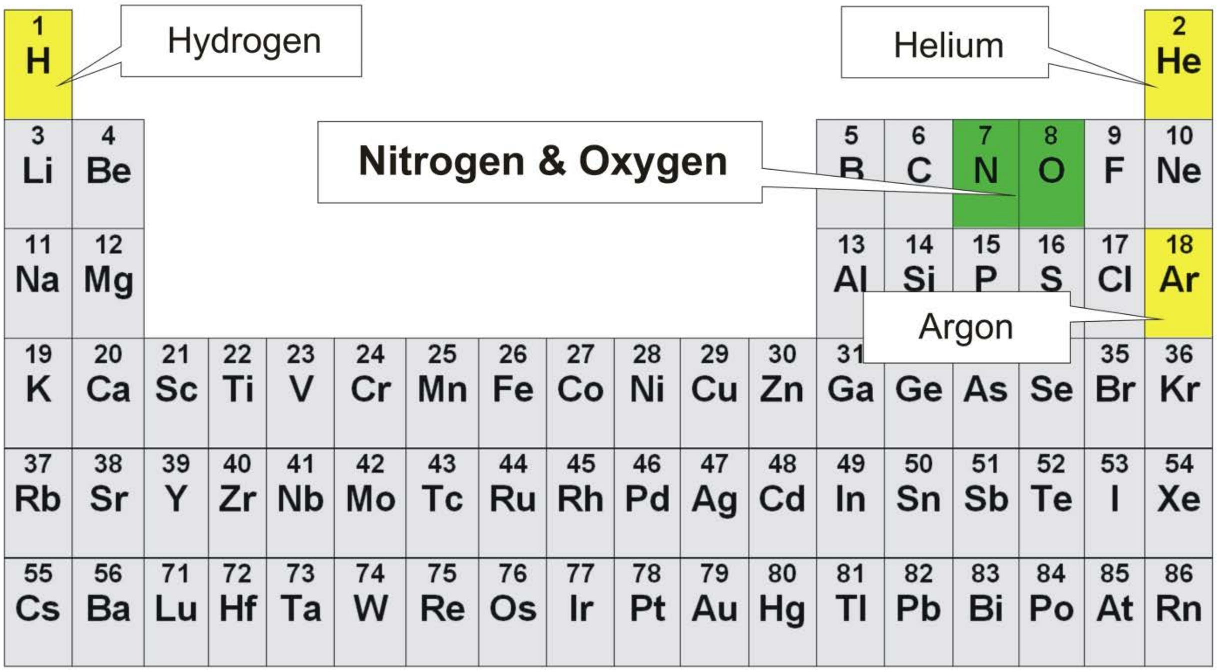
This chapter was written to give attention to both of these aspects. This is not the start of your training in the physiological aspects of diving. This training already starts in a beginner course. After that most continuing education courses address physiological aspects of diving in general or in relation to special activities.

This chapter limits itself to the general physiology of diving and does not go back very much to the basics learned in previous courses. For preparing yourself for an adequate knowledge it is a good idea to read course books from previous courses again. This chapter is also limited to recreational diving. We will sometimes refer to other breathing gasses than air or Nitrox, but there is no intent to give complete information on mixed-gas diving.

As painted by Rembrandt, physiology has a foundation in many years of research.

Nitrogen (N_2) & Oxygen (O_2)

When exposed to pressure changes and/or when changing percentages of gasses in our breathing mix, then we can come into a situation where we are getting too much or too little of a certain gas. When a gas can cause problems both when we have “too much” and when we have “too little, we tend to use Latin names for these conditions. In that case the word for too much would start with “hyper”, and the word for too little would start with “hypo”. In some cases there could also be a need to express the complete absence of that gas. Then the word would start with “ano”. For oxygen this would be hyperoxia (too much oxygen), hypoxia (too little oxygen) and anoxia (no oxygen at all). If a gas only causes problems in one direction, like for example nitrogen which only causes problems when you get too much, we do not distinguish like this. We simply refer to nitrogen-related problems.



From the elements, the gasses we are mainly interested in are nitrogen and oxygen. Technical divers are also interested in helium and commercial divers in rare cases even in hydrogen. For cold water diving argon has a use as a gas that performs better as protection against cold. In that case it is only used to fill a dry suit and not for breathing. Helium and hydrogen are found in the top row of the periodic system and are thus very light gasses. Nitrogen and oxygen are found in the second row and are close together, meaning that their molecular weight is almost the same.

Oxygen is our primary concern. We need oxygen to live. We can tolerate variations in the partial pressure of oxygen without getting problems, but there are limits. If you are living at sea level, you are likely to tolerate oxygen partial pressures from 0.16 bars (which would be the oxygen partial pressure at 2,400 metres altitude) up to 1.6 bars. Outside of this range, oxygen can start to cause problems. Below 0.16 bars your condition would be hypoxia and above 1.6 bars it would be hyperoxia. Both of these conditions could be fatal. That is one of the reasons why dives with other gases than air require special training. Divers are recommended to allow some margin for error. It is common to avoid oxygen partial pressures lower than 0.18 bars or higher than 1.4 bars.

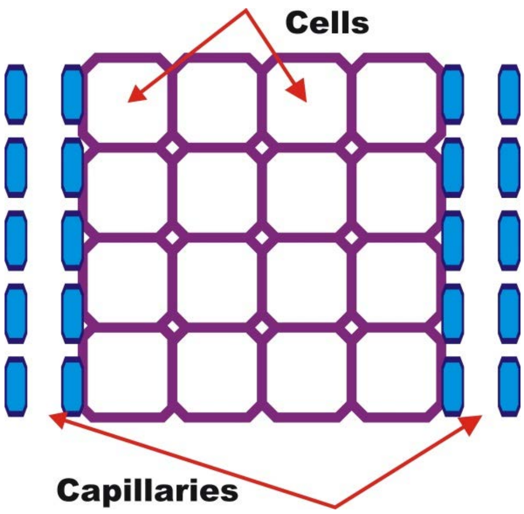
Hyperoxia is mainly related to Nitrox diving. The risk of a too high partial pressure of oxygen increases when the percentage of oxygen in a breathing mix is increased. Theoretically you could also get hyperoxia when diving with air. That would require a depth of 66 metres (1.6 bars divided by 0.21 = 7.6

bars), which is beyond the limit for recreational diving. Due to pressure and the chemical condition in your body, free radicals can develop when reaching an oxygen partial pressure of 1.6 bars. These free radicals confuse the communication via your nervous system and cause violent muscle contractions comparable to an epileptic attack. These are called convulsions.

Convulsions make a diver unable to control movement. This most likely causes losing the regulator as well as the inability to manipulate the inflator or weight belt buckle. A diver with an oxygen-fit underwater will likely drown if not rescued by another diver. A rescue would involve bringing the diver to shallower depth, where there were no problems with oxygen. In Nitrox courses, the subject of too high oxygen concentrations is logically given attention. Another problem with oxygen is the duration of exposure to higher oxygen concentrations. When breathing oxygen at elevated partial pressures, the opposite of acclimatization (like athletes and mountain climbers do) for altitude will happen. Rather than preparing your body for an environment with less oxygen by improving your transport efficiency, your body will see no need to maintain the current transport capacity because of the high availability of oxygen in the breathing gas. With time (several hours) your transport capacity will sink below normal. This causes problems when returning to normal oxygen concentrations at atmospheric pressure. For this reason, divers using other gasses than air must follow tables to keep their exposure to oxygen within limits.

Hypoxia is a lack of oxygen. The cells in the human body need oxygen to function and to stay alive. Nerve cells are very sensitive to a lack of oxygen. Damage could result after as little as 4 to 6 minutes without oxygen. Almost any diving related medical problem involves hypoxia to some extent. The extent to which the body is lacking oxygen is depending on the type problem and can be either local or involve the entire body. If there is a lack of oxygen for the entire body, the skin is also affected. This will result in signs which are easily recognized, such as a grey/blue skin colour. Somebody with hypoxia affecting the entire body looks as if he is not doing well and needs first aid. Such a situation could be caused by near drowning or cardiac arrest.

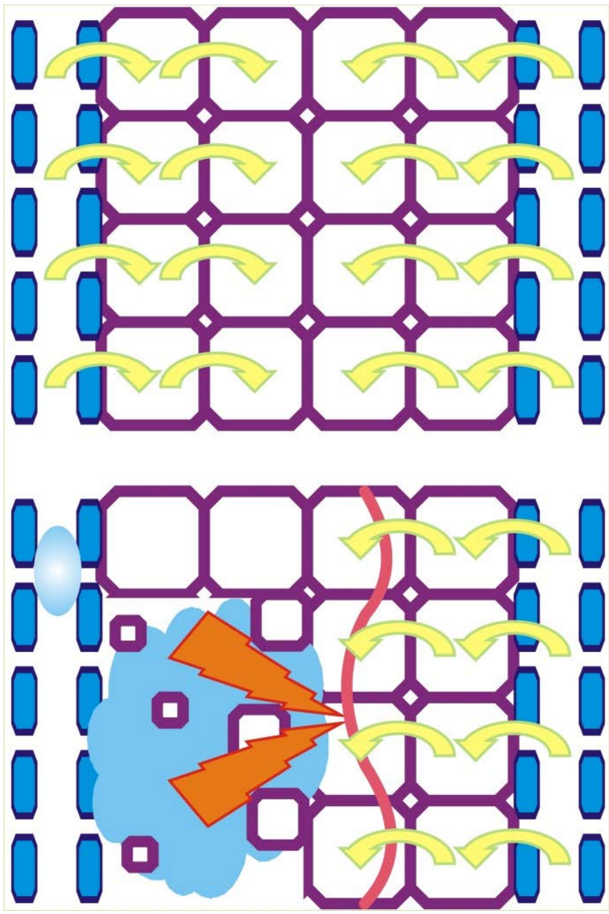
Recognition of a local hypoxia is harder. The affected person might look perfectly healthy on first sight. The skin is not affected, so the person does not immediately appear to have a medical problem. A closer examination might reveal things such as limping, local pain, problems focusing and others. Many of these are not signs, but symptoms. This means that to a large extent you have to rely on the information the patient is giving you. If you know what to look for, you might notice mild signs of hypoxia in a person and can then react by interviewing the diver to confirm what you have seen. To do this, it is necessary to understand what hypoxia is doing and what you achieve when you give oxygen. We'll explore these issues in detail.



This drawing is a simplified illustration of some tissue with two capillaries. Normally you find more cells between two capillaries, but to illustrate what happens in hypoxia, 4 cell rows serve all purposes.

You have an enormous amount of capillaries. How big would you estimate the chance to stick a needle through the skin and have no blood coming out of the wound? Probably you estimate this chance very low. There are more than 4 rows of cells between two capillaries, but the distance is small. There are 3 things you need to know about capillaries.

- You have just enough of them. If you would go in an environment with less oxygen (mountains) the number of active capillaries would increase. If you move to an area with more oxygen you would lose active capillaries. If you gain weight, you not only get fatter, but also get the additional capillaries that are needed to supply the fat with blood.
- Capillaries are semi-permeable, meaning that they let through oxygen, nitrogen, salt, sugar, liquid, etc. They are meant to exchange what is needed between the blood and the tissues.
- The wall of capillaries is made out of living cells. Also the capillary itself needs oxygen to stay alive.



When breathing air, you inhale 21% of oxygen. You live in an air environment, so your body (and thus the amount of capillaries) is adapted to that. In the drawing at the top, each capillary supplies the two rows of cells next to it with oxygen.

If the capacity of a capillary would be adequate to provide three rows of cells, the next capillary would be further away. There is no membrane between the rows of cells, but if one capillary would stop functioning, the next capillary would not have enough oxygen available to supply all the cells. A local hypoxia could develop.

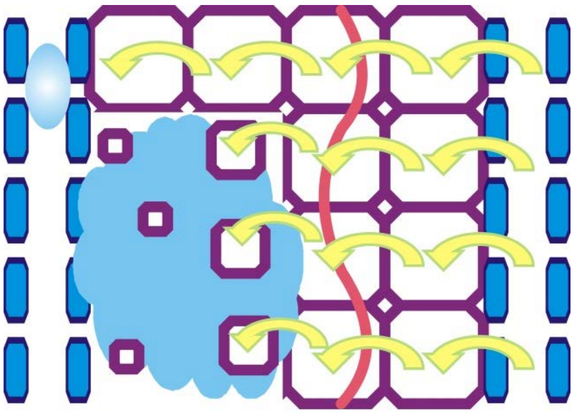
Most of the mass of the human body is water (liquid). Most of this liquid is located in the cells. Cells maintain their stability by assuring they are completely filled with liquid under tension. This tension is achieved by having a higher salinity within the cell than in the surrounding liquid. Liquid is in a continuous attempt to enter the cell to achieve an equilibrium in salinity. Because of the limits in flexibility of the wall of the cell, this equilibrium will never be achieved. The on-going attempt to enter liquid keeps the cell under sufficient tension and thus stability.

Cells release fluid when they are dying of unnatural causes (such as hypoxia). The released fluid has a higher salinity than the salinity of the free liquid in the body, but there is no more cell-wall available to limit the liquid in its attempt to reach equilibrium in salinity. An unnatural amount of liquid will accumulate in the affected area. An oedema (or swelling) is the result. This swelling can irritate nerves, which can develop symptoms: pain, fatigue, etc. If the capillary was supplying a nerve with oxygen, the nerve can die – neurological damage – leading to symptoms such as paralysis, losing the ability to walk, remember, speak, or see, numbness, etc.

The swelling will exert pressure on the next capillary. As a result that capillary is also going to be blocked (capillaries have a diameter that is just large enough to allow red blood cells to pass through. If they are flattened by the oedema, red blood cells will block the capillary). This then creates a snowball-effect. The oedema expands. Four medical conditions provoke the same symptoms. The cause is different, but the further development of the oedema is the same.

- Nitrogen bubbles from decompression sickness (DCS) Type II block the bloodstream.
- Air bubbles from an Arterial Gas Embolism (AGE) block the bloodstream.

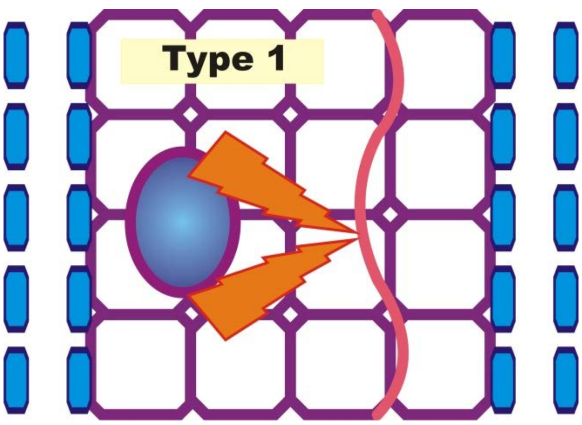
- Solid material blocks the bloodstream in thrombosis.
- A stroke starts with a ruptured blood vessel (or thrombosis in an arterial vessel supplying the brain).



Breathing 100% Oxygen

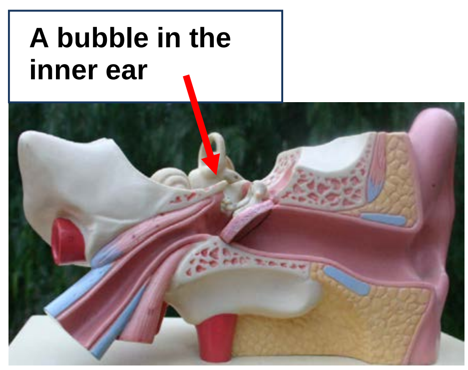
The distance between capillaries is based on a supply with 21% oxygen. When we now give the patient 100% oxygen, each capillary is transporting more (not 5 times as much, because of hemoglobin limitations) oxygen and can supply more tissue. A neighboring capillary can take over the role of a blocked capillary. This will bring oxygen to the isolated cells and, if they didn't die yet, this oxygen can help them to survive.

Oedema results from dead cells. Oxygen cannot bring these cells back to life, but cells that are still alive can stay alive because of the oxygen that is now available. The oedema will not develop any further. The snow-ball-effect is halted. This explains the first two benefits of the administration of oxygen. Hypoxia is cured and oedema is stopped at the level to which it has developed.



There is also another type of decompression sick-ness, where bubbles develop in the tissue itself – not in the bloodstream – and cause mechanical damage. In this case the bloodstream is not blocked, so there is oxygen flowing to the tissue. The cells will not die due to lack of oxygen. This is called Type I decom-pression sickness.

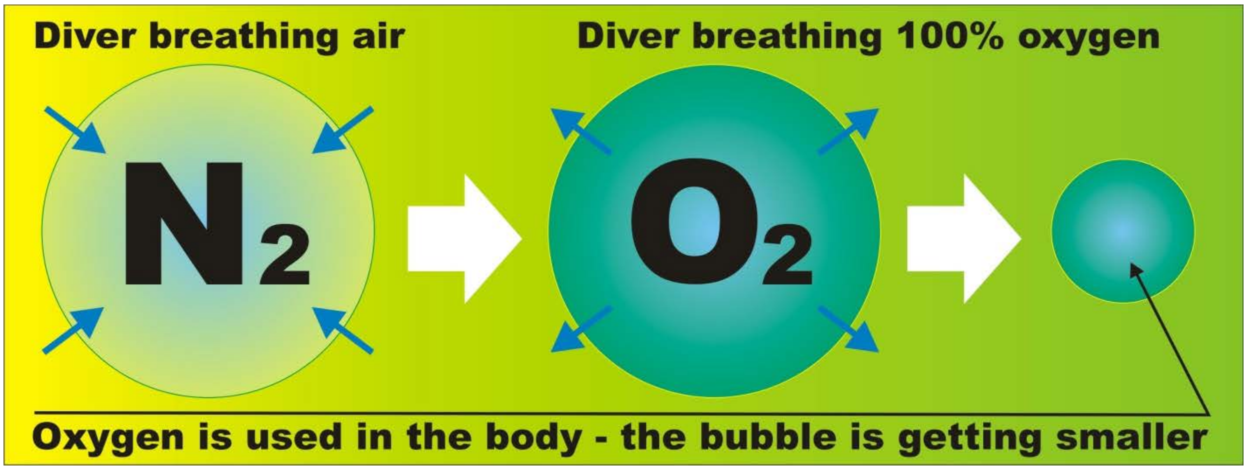
The symptoms are caused by irritation of nerves, which results from the pressure exerted by the bubble. Once the bubble is gone, the symptoms are gone. There is no neurological damage, so chances of healing are rather good.



The symptoms can include pain in the limbs, irritation, itching and others, but there is normally no neurological damage and thus no neurological symptoms such as paralysis, problems with seeing, talking, walking, etc. Normally, the patient does not lose consciousness and is alert. However, there are exceptions. If a bubble forms in the liquid of the inner ear, the sense of balance is irritated. This leads to vertigo and the patient may vomit following each movement of the head. In this case there is no neurological damage, but the symptoms appear to be neurological and might be misinterpreted. A bubble in the inner ear occurs frequently. Because the sense of balance is affected, the diver will sufer extreme vertigo, leading to frequent vomiting.

Another exception is a bubble in the spinal cord. If a bubble forms in the spinal cord, but not in the bloodstream, it can still block the flow of blood. In the spinal cord the capillaries and nerves are sur-rounded by bone. There is no room for a bubble. If a bubble forms, it will push away the capillaries and nerves, but they cannot move out of the way. The pressure from the bubble will flatten them, restricting the blood flow. In this case we do risk neurological damage. Symptoms are initially comparable to a hernia, but can develop into paralysis from the affected area down. The diver may limp or completely lose control over the legs. The diver may have problems with urination, or may feel tingling in a leg. For this type of decompression sickness recompression can be urgent. During recompression the size of the bubble is reduced immediately, which will allow blood flow in the affected area and can prevent neurological damage.

The bubbles caused by decompression sickness are nitrogen bubbles and the bubbles caused by an embolism are air bubbles. In both cases, most of the gas in the bubble is nitrogen. Nitrogen is an inert gas. When breathing air, the bubble is surrounded by approximately 80% of nitrogen. Nitrogen is not used in the body and the bubble will not reduce in size.



When breathing 100% oxygen, the bubble will, after a while, be surrounded by pure oxygen. Due to Henry‘s law, the bubble will give off nitrogen and take up oxygen in an attempt to achieve an equilibrium with its new environment. The nitrogen bubble will become an oxygen bubble. Oxygen is a consumable gas. Living cells surrounding the bubble consume oxygen. As a result there is always a lack of oxygen in the tissue surrounding the bubble.

The bubble will supply this missing oxygen to the surrounding tissue and will reduce in size. Eventually the bubble will disappear completely. How long this takes depends on the size of the bubble and the speed of the metabolism in the surrounding cells. If there is no neurological damage, the symptoms can disappear with the bubble.

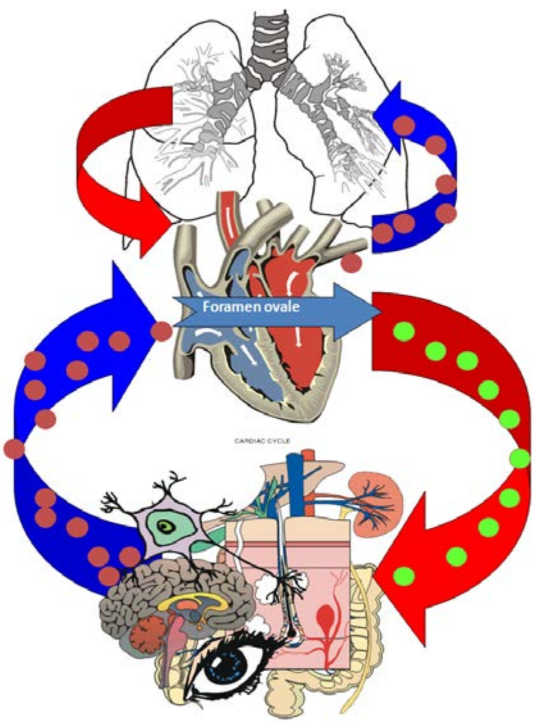
The absence of nitrogen in the breathing gas is thus important for treating a diver, but is not so important for people with “normal” medical problems. We require first-aid equipment that gives the highest possible oxygen percentage. “Normal” oxygen equipment design does not necessarily take divers into consideration. It will give the advantages of an increased oxygen percentage, but will not do the maximum with respect to the absence of nitrogen because it may not bring 100% oxygen to the lungs. Courses on First Aid with oxygen provide the technical details to look for in equipment used for this purpose.

With the explanation on Hypoxia, we already went a long way into the problems related to nitrogen. Bubble formation can cause Hypoxia, but in the case of decompression sickness finds its cause in nitrogen. It is not always easy to tell if you are dealing with an overexpansion injury to the lung or decompression sickness. This is the reason why we often (for the purpose of first aid) address both under one name – **decompression illness** or **decompression incident**.

There are three main types of decompression sickness. For first aid this does not really matter, because we provide the same care in all decompression incidents and some patients are affected by more than one type at a time. Type I DCS normally results out of long exposures to pressure. It is also referred to as “mechanical decompression sickness”. In this case the bubbles have formed in the tissue itself and exert pressure on nerves. The bubbles do not block the oxygen supply to the tissue. There is no hypoxia and thus no neurological damage. Symptoms involve pain, itching and similar.

In DCS type II, we are dealing with nitrogen bubbles in the bloodstream. This is a more serious problem. Just as with a stroke, AGE and thrombosis, hypoxia can develop with neurological damage as a result. Nerves can die due to lack of oxygen. Neurological symptoms can include a local numb feeling, problems seeing, hearing or speaking, paralysis, etc. Where patients with DCS I have good chances of a full recovery after treatment, victims of type II in many cases have irreversible damage and will have to deal with a reduction in quality of life after treatment is completed.

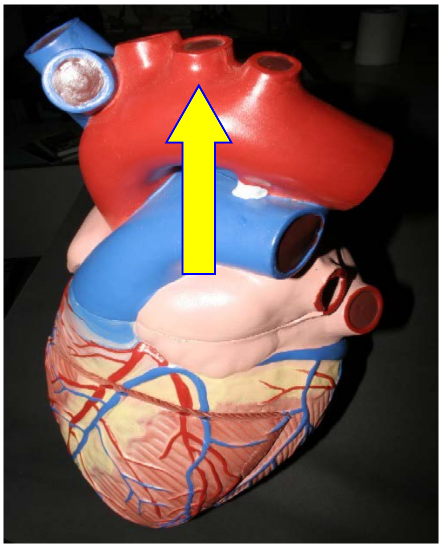
Damage resulting from decompression sickness which does not cause immediate symptoms is sometimes referred to as DCS III. In this case there are bubbles in the body, but they do not block the supply of blood and do not irritate nerves. There is no immediate indication that there is a problem. Type III can have a negative effect on long term. A typical example is necrosis. The spinal cord and joints degrade over time. If bubbles do not cause symptoms, we speak of silent bubbles.



Theoretically seen type II could not happen. The nitrogen comes from the tissues, so it enters the veins and is transported to the lungs. The veins have small diameter where the nitrogen enters, but the diameter increases on the way to the heart. Bubbles could pass without problems and would not block the bloodstream. It is believed that the main cause for bubbles entering the arteries (the arteries decrease in diameter on the way from the heart to the tissues) is the foramen oval. This opening between the two sides of the heart can allow bubbles to pass from the veins to the arteries, rather than following their normal path to the lungs, where they are filtered out of the blood.

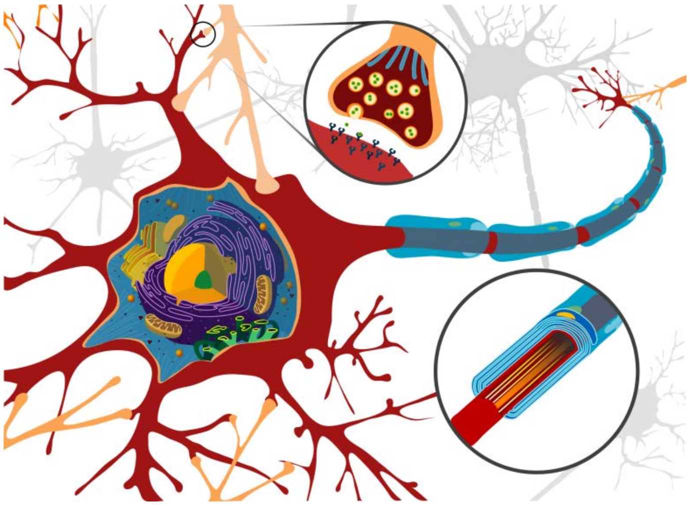
Before you are born, your foramen oval is open to allow an even distribution of blood throughout the body. The foramen oval is kept open by the difference in blood pressure (higher pressure in the small circulation than in the big circulation). Shortly after birth, the relation in blood pressure changes. The expansion of the lungs reduces the blood pressure in the small circulation, while the big circulation increases blood pressure to fight gravity. The higher blood pressure in the big circulation closes the foramen oval. The distribution of blood is now adapted to the new situation. This is a situation in which the lungs are used for the oxygen supply. If the blood pressure in the small circulation gets higher than the pressure in the big circulation, the foramen oval could be forced open again.

This can happen when many of the blood vessels in the lungs are blocked with bubbles, when coughing, when holding breath with maximum inhalation, when lifting heavy loads while holding breath, etc. In some people the foramen oval is never completely closed.



When blood with bubbles from the veins passes into the arteries, the consequences are the same as with an arterial gas embolism (AGE). A part of the body will not be supplied with oxygen and nerve tissue can die, leading to neurological damage. The chance that the brain is affected is rather high, because the main artery leaving the heart immediately splits in several arteries supplying different parts of the body. Bubbles are likely to flow into the artery going up.

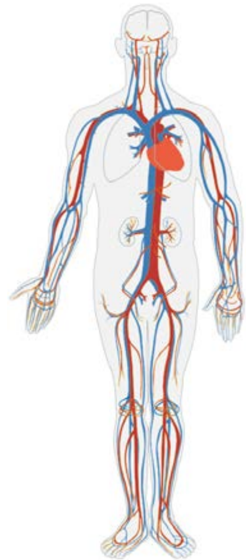
Another problem related to nitrogen is **nitrogen narcosis**. The increased nitrogen presence in the body disturbs the nervous system. When breathing air, we normally teach that nitrogen narcosis can become a problem starting from a depth of 30 metres. There are specialists who advocate a shallower depth. Symptoms of narcosis include absent behaviour, difficulty to concentrate, impaired coordination, an inability to perform simple tasks and emotional changes such as euphoria or a high level of stress. The symptoms subside when ascending to a shallower depth where nitrogen narcosis was not a problem.



The problems related to nitrogen narcosis can be reduced by replacing some of the nitrogen in the breathing mix with another gas. Oxygen (as is done in Nitrox) is not suitable for this. The narcotic properties of both gasses are almost the same. Diving with Nitrox is thus not a solution to reduce narcosis. The only option to reduce narcosis is the use of lighter gasses. That comes with its own problems. When using helium to replace part of the nitrogen, we increase problems with temperature. A diver breathing a mix including helium gets cold faster than a diver breathing air. At greater depth the diver starts to tremble due to HPNS (high pressure nervous syndrome). When replacing some of the nitrogen with hydrogen, the problems are even bigger. In that case we are dealing with an “explosive” gas. The procedures needed to prevent the gas from igniting during the dive are enormous. Because of that only few experimental dives have been made with mixes including hydrogen.

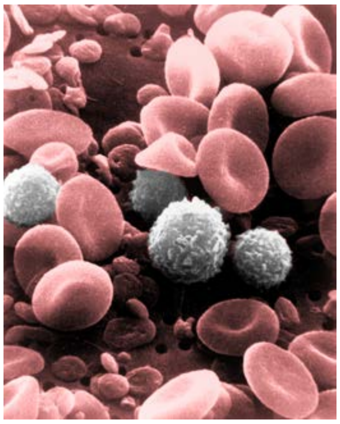
Carbon monoxide (CO) & Carbon dioxide (CO_2)

We need oxygen to live. Oxygen is used in our body to create energy. The main waste product from that process is carbon dioxide. The process of using oxygen is called metabolism. The oxygen inhaled in your lungs is transported to the heart via the pulmonary veins, then to the body tissues via the arteries and from there distributed by the capillaries. The waste product carbon dioxide is then taken up by the capillaries, from where it will be transported back to the heart via the veins and via the pulmonary



arteries to the lungs where it is transferred to the air space in the lungs via the lung capillaries. In medical drawings, arteries are coloured red and veins are coloured blue.

The quantity of oxygen needed for the tissues is too big to be transported in solution in the blood plasma. Based on Henri's law, only 21 per cent of the gasses dissolved in the plasma will be oxygen (when breathing air). There is not enough plasma to cover the need for oxygen transport (it would only cover 2% of the demand). Red blood cells provide the solution. Red blood cells are made out of haemoglobin and temporarily connect oxygen by "corroding" in a reversible form. The oxygen is transported as a solid (oxy-haemoglobin) rather than a gas. This means that during transport the gas laws do not apply. The moment the blood reaches an area with a lack of oxygen, the "corrosion" is reversed and the oxygen becomes available to the tissues. "Corroded" haemoglobin is bright red and haemoglobin that is not "corroded" is dark red. This explains why arterial blood is bright red and venous blood dark red.



The white balls in the picture are white blood cells; the red ones are red blood cells.

If the plasma cannot hold enough oxygen to meet the demand, logic tells us that the plasma can also not transport carbon dioxide in an adequate way. If CO_2 is the waste product of the metabolism, it must be a combination of one carbon and one oxygen. There is one CO_2 created for each O_2 used in metabolism). To assure adequate transport, carbon dioxide is connected in several different ways. A part is transported by haemoglobin, another part binds with a water molecule (H_2O) and becomes a carbonic acid – H_2CO_3. The same acid is found in "bubbling" soft drinks. Saturation with carbon dioxide gives you the impulse to breath. The urge to breath does not come from a lack of oxygen, but from too much CO_2 in the blood.

The waste product CO_2 thus has an important function to keep you breathing. Too much carbon dioxide would be a problem, because breathing impulses would come in short intervals and too little would cause a problem because you would not breathe often enough to assure an adequate oxygen supply. Too much is called hypercapnia and too little is called (you guessed it) hypocapnia.

Mild hypercapnia will give you an impulse to breathe more often than needed to assure an adequate oxygen intake. In extreme cases of hypercapnia, you can lose consciousness and thus drown. Symptoms progress from disorientation, panic, hyperventilation, convulsions, unconsciousness to death. Extreme cases do not happen when diving with an open scuba system, but are possible in rebreather diving. This could be when the one-way valves in the breathing loop are malfunctioning, when the soda lime does not work (anymore) or when the canister for soda lime is only partly filled and the exhaled gas is passing through without actually being cleaned of CO_2 (channelling).

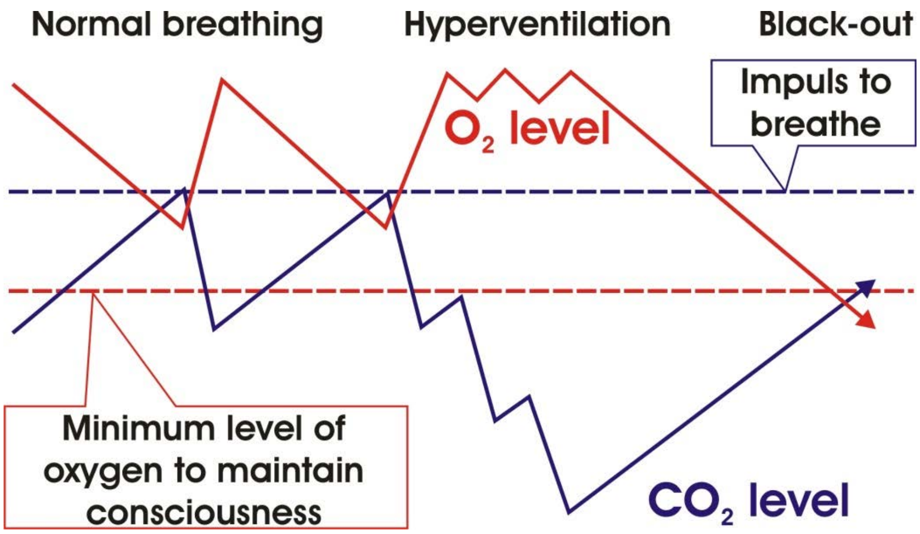
Mild hypercapnia is not immediately dangerous, but it should be prevented anyway. It reduces comfort (pulse, blood pressure and breathing pattern go up and make you feel "out of breath") and it makes you use your gas supply faster than necessary. Mild hypercapnia can result from a variety of causes, but they fall into one of three categories. You inhale too much CO_2, you retain too much CO_2 or you produce too much CO_2.

The passage from the supply of fresh breathing gas to the active part of your lungs (alveoli) is called "dead air space". When exhaling a part of the exhaled gas (with CO_2) stays back in the death air space and when inhaling again, your lung first takes this already used gas in. Only then fresh gas from the source of fresh breathing gas enters. If the dead air space makes up a big percentage of the total breathing volume, you re-inhale too much CO_2. As a consequence slow deep breathing is more efficient than shallow breathing. Compared to breathing on land, a diver has a bigger dead air space. A snorkel, the cup of a second stage (and in more extreme cases a full face mask or helmet for commercial diving) can increase the dead air space considerably. This calls for limiting the size of a snorkel and adding technical features to regulators, full face masks and helmets to limit the increase in dead air space. No matter what we do, there will be an increase. For divers it becomes even more important than for those who breathe on land to achieve a favourable ratio of fresh gas reaching the lungs by breathing deeply and slowly.

When increasing effort, metabolism goes faster and so is the amount of CO_2 the body is producing. Things as basic as the depth of a dive play a role. The breathing gas gets denser when we go deeper and requires extra effort to inhale and exhale. Other factors may include drag from a big BCD, not being neutrally buoyant, swimming too fast, current, etc.

Skip breathing was a technique used by early divers to reduce their air consumption. It was counterproductive. Skip breathing means that you resist the impulse to breath for a while before actually taking a breath (hypoventilation). The result is that the diver forces himself into hypercapnia. Pulse, blood pressure and breathing rate go up after a while making the diver consume much more breathing gas than was economised with a few minutes of skip breathing.

Hypocapnia can be the result of a psychological condition, or can be self-induced. Where hypercapnia can only in some cases be related to hypoventilation, hypocapnia is virtually always related to hyperventilation. Hypocapnia in itself is not immediately dangerous. The low acid levels in the blood can lead to pins and needles and muscle contractions especially in the hand and feet. The main problem is the absence of an urge to breath. If the hypocapnia is caused by psychologically induced hyperventilation, then this lack of an urge to breathe is caused by a feeling of suffocation. This in its turn urges the patient to breathe even more. As a consequence more CO_2 is exhaled. The patient finds himself in a vicious circle. The only way out is to increase the CO_2 in the blood, which can be done by “guiding breathing”. When you are sure that you are dealing with hyperventilation you can help by making the patient inhale his own exhaled air for a few breaths (inhale and exhale in a plastic bag).

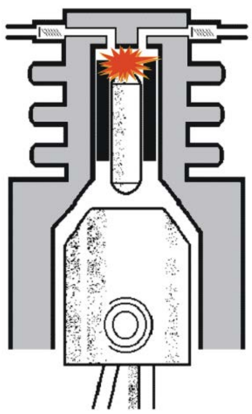


In breath hold diving we are dealing with self induced hypocapnia, called voluntary hyperventilation. Although the principle is the same, it is more dangerous. Voluntary hyperventilation is done to extend breath hold time. The longer the urge to breath is delayed, the more we like it. We do not get a feeling of suffocation, but a feeling of success. This can make us push the limits and stay underwater without breathing too long. Too long meaning that we do not have enough oxygen in our body to keep us conscious. This condition is called a shallow water black-out. A shallow water black-out is dangerous because it comes unnoticed for the breath-hold diver and mostly also for bystanders.

When hyperventilating, you take deep breaths in quick succession. You do not wait for the urge to breath and the lungs remove more CO_2 than is produced. This lowers the CO_2 in your body, but it does not increase the amount of oxygen in a significant manner. A normal breathing rate already fills the blood with oxygen to capacity. While your body needs more time to produce enough CO_2 to trigger the urge to breath, the available oxygen is used. When the oxygen level drops below its threshold to maintain consciousness before the CO_2 is at the level to urge breathing, a shallow water black-out develops. This is why hyperventilation should be limited to two or three breaths only.

A deep water black-out is related, but not the same. A shallow water black-out is directly related to hyperventilation and normally occurs during breath-hold record attempts in a pool. A deep water black-out is the result of a rapid drop in oxygen partial pressure when returning to the surface after a breath-hold dive to a depth of 10 metres or more (in most cases in the last 3 metres before arriving at the surface). The risk of a deep water black-out is increased after hyperventilation, but this condition can also occur without hyperventilation being practiced, while the shallow water black-out cannot.

Too little carbon monoxide (CO) does not exist, only too much. Carbon monoxide results from incomplete burning in fire and explosions. An ideal fire should produce only carbon dioxide (as your metabolism), but in reality a part of the burning process will be incomplete, resulting in CO rather than CO_2. To have a risk of problems with CO, it must get into your diving cylinder in some way.



CO comes from fire. One cause could be that a car is running next to the intake of a compressor. It could also be the engine (not electric) of the compressor itself if it is wrongly positioned and exhaust ends up in the intake of the compressor. A more common reason is that the compressor (which is oil lubricated) is running hot and oil in the cylinders of the compressor ignites, producing both CO and CO_2. To prevent problems with carbon monoxide, some compressors filters are not only filled with active carbon (to remove grease, oil and odours) and molecular sieve (to dry the air), but also with Hopcalite. This material chemically transforms CO into CO_2.

The affinity of carbon monoxide to haemoglobin is 200 times stronger than that of oxygen. When CO is inhaled, it will occupy space on the red blood cells and reduce the transport capacity for oxygen. When too much of the haemoglobin is blocked with CO the transport capacity for oxygen is too low to cover the demand of the body. The diver will develop hypoxia. A person with hypoxia will normally have a grey/blue skin colour, but with carbon monoxide poisoning this is less than with hypoxia caused by other problems. The reason for that is the haemoglobin. We already learned that haemoglobin is responsible for the difference in colour of the blood in the arteries and the veins. Haemoglobin that has oxygen attached to it turns bright red and so does haemoglobin that has carbon monoxide attached to it. Oxygen would leave the haemoglobin in the capillaries to let it return via the veins in a dark red colour. CO does not. A patient with CO poisoning has bright red blood in both the arteries and the veins. This blood in the veins changes the colour of the skin, especially in tissue with many blood vessels, such as the lips and under the nails. A reddish colour on these locations indicates a problem with carbon monoxide.

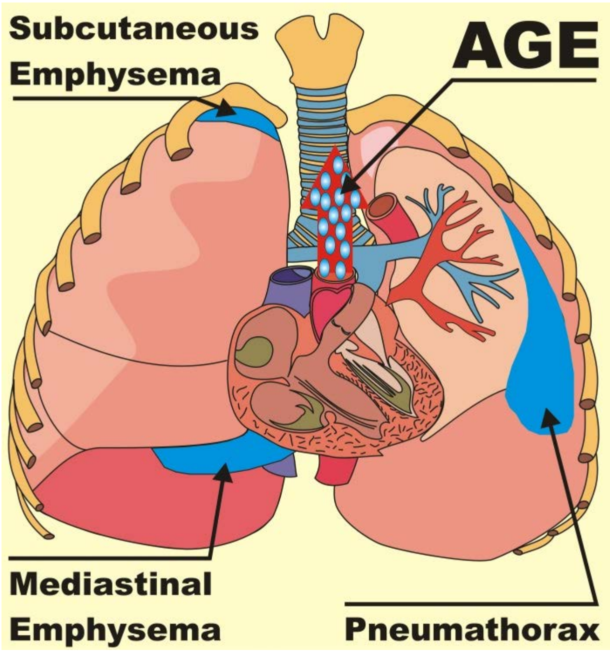
At depth carbon monoxide poisoning could go unnoticed for a longer time than on land. At the surface the plasma can only cover 2 per cent of the oxygen transport that is needed to meet demand. At depth the transport capacity of the plasma increases. As the partial pressure of oxygen in the lungs increases with increasing depth, the amount of oxygen taken up in the plasma does as well. At 30 metres depth the lung holds 4 times more oxygen. The plasma will take up 4 times more oxygen than it would at the surface. The plasma can now thus meet 8 per cent of the demand. The need for available haemoglobin is less and the diver will develop hypoxia later than he would at the surface. When the diver returns to the surface at the end of the dive, the plasma will drop its transport capacity to normal. The diver now depends on the full transport capacity of haemoglobin again, which is not available. Underwater it is thus hard to recognize problems with carbon monoxide. Hypoxia is delayed or less pronounced. On the other hand it can go unnoticed because a buddy would not recognize a red colour at depth.

Mechanical Injuries

Pressure changes result in a change in volume. The body air spaces are affected by this principle. Most air spaces have a certain flexibility to accommodate changes in volume, but the moment we exceed this flexibility, medical problems will occur. The most serious consequences of pressure changes are lung overexpansion injuries. There are four types. In three types, the air leaves the airspace of the lung and gets trapped between tissues. The name of the injury indicates where the escaped air is accumulated. In any case the diver will experience problems immediately, where in decompression sickness the symptoms can be delayed for a considerable amount of time.

The lung is a passive organ. It cannot move by itself. The lung is “packed” in a vacuum. Movement of tissue around the lung is transferred into lung (breathing) movement. Between breaths the lung falls back to its natural volume (exhaled). When we inhale, the lung is expanded. The lung also expands when we ascend without exhaling. If the lung is expanded too much, a lung overexpansion injury can result. If both the lung and the “packing” rupture, emphysema will develop. If only the lung or only the “packing” is affected, this will cause a pneumothorax.

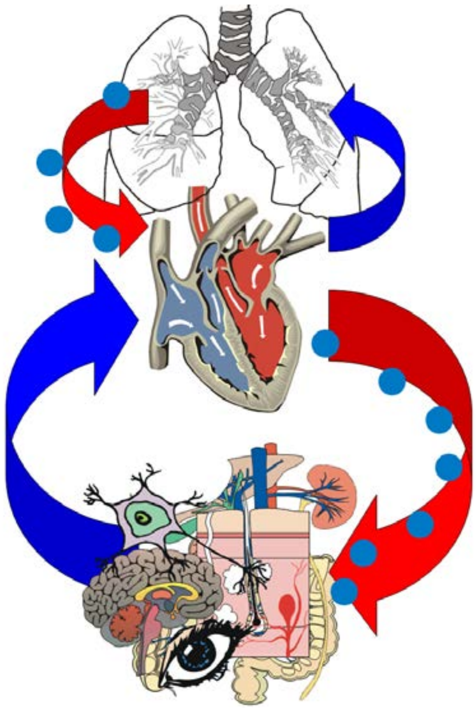
Subcutaneous emphysema – the air leaves the lung and accumulates near the collar bone at the base of the neck. There is a hole from the air space of the lung up to the outer layer around the lung that packs it in a vacuum. Air leaves the lung and travels to the highest point. This is the top of the lung. An emphysema is a pocket of air. This particular emphysema is found under the skin (subcutaneous) which adds up to the name subcutaneous emphysema. This is the least serious type of lung overexpansion injury. The lung will heal rather quickly and it is not too hard to remove the pocket of air.



Mediastinal emphysema – the air leaves the lung and accumulates between the lungs and around the heart. This problem results from injury to the lung tissue and its lining as in the subcutaneous emphysema. Now the injury is found in the lower portion of a lung. Again the air moves up to the highest point it can reach. This is the location where the bronchi enter the lung. The pocket of air (emphysema) now exerts pressure on the heart. This can cause problems with the functioning of the heart. The injury to the lung will heal rather quickly, but the pocket of air that is left behind is harder to remove and more likely to cause complications.

Pneumothorax – the air accumulates between the tissue of the lung and the membrane around the lung. In this condition the trapped air pushes the lung to the side, leading to a loss of space available for lung movement. This condition occurs when either the lung tissue or its lining are punctured and have an opening from where air can be pulled in. On land it is likely to be the lining that is damaged, for example because of an injury caused by a knife. In a pressure related injury it is the lung tissue that will be damaged, while the lining that is supposed to keep the lung in a vacuum stays intact.

When the diver inhales, the lung expands. The lung has its natural volume when the diver has exhaled. When inhaling, the lung will resist to this expansion. If the resistance for air flowing through the hole is lower than the resistance the lung tissue offers to the expansion, a new air space between the lung and its lining will be caused. Since exhalation does not create pressure (the lung just “falls” back to its normal volume) the air is not pressed out of the hole. It stays where it is. With the next breath more air will be pulled through the opening. The pneumothorax will get bigger and bigger with each breath, leaving less and less space available for lung movement. This condition is sometimes referred to as a collapsed lung, but in reality the lung is pushed aside rather than collapsing.



A pneumothorax is more serious than an emphysema. The lung tissue is exerting pressure to the heart, causing the same potential risk of heart problems as the mediastinal emphysema. At the same time the diver is missing half of his capacity to take up oxygen from the environment, leading to hypoxia. A history of a pneumothorax can exclude a person from ever diving again. Some people also experience a spontaneous pneumothorax (an opening in the lung tissue) without being exposed to changes in pressure. Also this can be a contraindication for diving.

In the fourth type of lung overexpansion injury, the air does not accumulate between organs or tissues. In this case, the air is entering the bloodstream. This can happen because of the pressure differences between the bloodstream and the environment. The arteries have a high pressure (this is why they are far inside the body with enough tissue surrounding them). In the veins (many very close to the skin) the pressure drops to just above ambient pressure. The key to the development of an embolism is that the heart sucks blood from the lung, after having pumped blood at high pressure into the arteries. This means that the blood pressure in the veins leading from the lung to the heart is at times lower than ambient pressure.

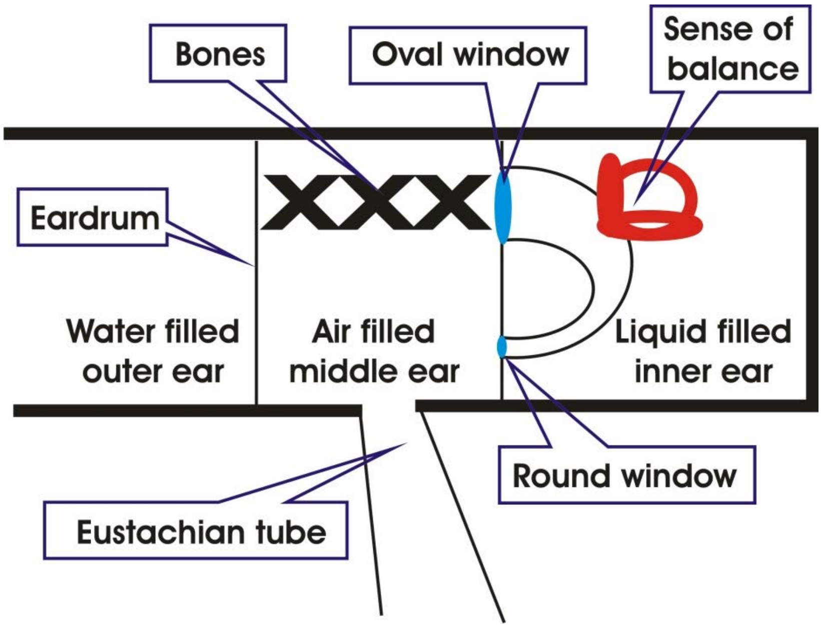
If the blood pressure is higher than the ambient pressure, blood will flow out of a wound. If the blood pressure is lower than the ambient pressure, air will enter the blood vessel via the wound. The moment the heart sucks, the blood pressure between the lung and the heart falls below ambient pressure. If a blood vessel surrounding an alveoli would be damaged due to an overexpansion injury, air is sucked into the bloodstream (in all other locations blood would flow out) and via the heart introduced into the arteries.

As air is lighter than blood, it tends to travel to the highest possible point which is the artery leading to the brain. This is the worst place you can imagine for an **AGE (Arterial Gas Embolism)**. Of all the lung overexpansion injuries, this is the worst scenario. It causes symptoms just as type II decompression sickness, a stroke and a thrombosis. If the patient does not die, a decrease in quality of life is likely.

The most common cause of lung overexpansion injuries is running out of air. Divers who have air to breathe are inhaling every few seconds and thus also exhaling. This goes a long way to prevent lung overexpansion injuries. When a diver is running out of air, he cannot inhale anymore. The stress that results from that situation may cause the diver to stop exhaling as well. Statistics suggest that the best way to prevent lung overexpansion injury is to never run out of air.

Another concern with lung overexpansion injury is air trapping. Air trapping means that only a part of the lung is obstructed. This is one of the main reasons why people with asthma are well advised not to dive. Also smokers have an increased risk of air trapping. If air passages in the lungs close due to swelling, the air cannot escape from the section of the lung behind that swelling. The lung overexpansion injury develops in that part of the lung only. The consequences are the same as for an overexpansion injury caused by breath holding.

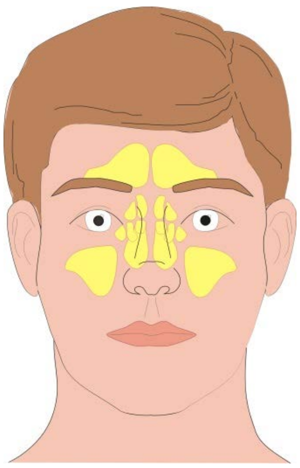
Also the ear is sensitive to changes in pressure. The middle ear is connected to the mouth/nose airspace via the Eustachian tube. This tube is not a "rigid" opening as the air passages to the lungs, but is soft. In most cases it does not allow air to flow into the ears (the other way around normally works without action from the part of the diver). This is the reason why divers must take an action called equalizing when descending. Already in beginner courses divers learn different techniques to equalize the ears.



If a diver descends without equalizing, the body itself will take actions to do so. The middle ear will fill with body fluid to reduce the volume of the air space in the middle ear. After the dive this fluid will stay in the middle ear (possibly for a day or even longer). The diver will feel fluid in the ear and hear sounds different from normal. When the descent speed exceeds the speed with which the body can fill the middle ear with body fluid, then the diver risks a ruptured eardrum.

The main role of the middle ear is thermal isolation of the inner ear. The sense of balance is located in the inner ear and is very sensitive to temperature changes. The airspace in the middle ear protects against changes in temperature, just as the airspace between the double walls of a house helps to keep the temperature inside a house constant. When the eardrum ruptures, water flows into the middle ear and comes in direct contact with the oval and the round window separating the middle ear from the inner ear. This causes drastic temperature changes in the inner ear (especially if the eardrum ruptures in cold water) and causes vertigo. If this happens you must follow your exhaled bubbles as indication of which way is up. Due to vertigo you will have lost your feeling for direction.

Another sensitive part of the ear is the round window (both **R**ound and **R**upture start with an **R**). If you would equalize with too much force at the surface, the eardrum would bent outward. Underwater the water in the outer ear restricts that movement. As a result the oval window (which is much bigger than the round window) flexes inward. The oval window is connected to the eardrum with small bones to transfer the movement of sound waves. The oval window is the connection to a liquid filled tube with small hairs in which the liquid can move forward and backward to move the hairs. This makes you hear. To allow this movement, the round window is located at the other end of the tube. It flexes with the oval window allowing this forward and backward movement of the liquid. The round window is much smaller than the oval window and cannot handle the liquid that is moved when the oval window flexes too much. It is thus the round window that ruptures as a result of too much strain on the oval window.



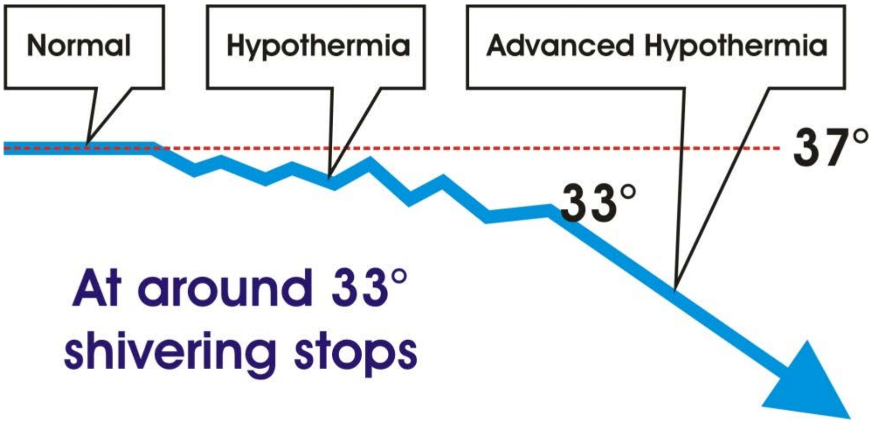
Problems with the sinuses are rare in diving. When sinuses are blocked, you could not even descend half a metre without being forced to resurface due to intense pain. When your sinuses cannot equalize there is nothing you can do. The only problem that requires some attention is a reversed block. A reversed block results when air can get into an airspace while descending, but cannot escape while you ascend. With sinuses this could happen when you have a cold or allergic reaction. This could happen spontaneously during a dive, but that is very rare. In most cases such a reversed block results from using nose spray before a dive. Nose spray does not work forever. When it wears off before the end of the dive, a reversed block can be the result.

A reversed block could also be located in the stomach or teeth. Again this is very rare. The stomach is rather flexible and a reversed block would probably only cause discomfort. Teeth are another story. If there is airspace left under a filling in a tooth, an air passage could develop along that filling, allowing air to flow in the airspace during your dive. If the ascent is too fast for the air to flow back through the small opening, a problem can occur. Often it involves a tooth from which the nerves have already been removed. In that case the tooth would simply break without you feeling any pain. If there is still a nerve, and if it is irritated by the increase in pressure inside the tooth, then a reverse block in your teeth can cause intense pain.

Artificial airspaces also require some attention. To equalize the mask, a diver needs to exhale by the nose from time to time. When diving in a dry suit, you must add air to the suit when descending. Otherwise you can get bruises on locations where the suit squeezes against the skin.

Thermal Problems

In order to function correctly, the human body needs a rather constant temperature. Outside sources of heat or cold can interfere with the attempts of the body to keep the temperature constant and require the body to act. There are several mechanisms that allow compensating for an influence from outside sources. As long as they work, the temperature will be more or less stable. If the outside influence is too intense, the body will need to give up at some point in time. Thermal problems are not rare in diving. While preparing for a dive we sometimes wear thick exposure protection on land on a warm day. On the other hand we sometimes go diving in water with a temperature near the freezing point.

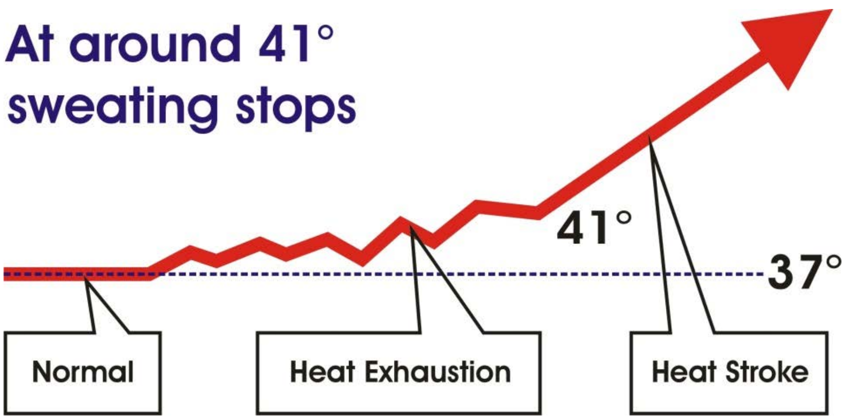


During a dive in cold water your suit will slow down the loss of body temperature. If your choice of suit was appropriate for the water temperature you are diving in, there will be no need for your body to react to the cold. If the insulation of the suit is not adequate, your body will start to take action to keep the body temperature constant. One of these actions is that the body will try to prevent more heat loss by “pulling” the circulation more inward. Capillaries close to the skin allow the blood to take a path close to the outer layer of skin, or a path more inward where the bloodstream is protected by a thin layer of fat (this also explains skin bends – in the beginning of the dive nitrogen is brought to the upper layer of the skin, but at the end of the dive the blood needed to take the nitrogen away is following another path).

Your body will also try to generate heat to warm up. You start to tremble. As long as the combination of avoiding more heat loss and generating heat works, you are fine, but the fact that your body is starting to take action should be considered a warning sign. You might have some distance to cover to get out of the water and once you are out you can maybe not warm yourself up. It is common that divers react to shivering by aborting the dive. The condition in which your bloodstream is “pulled” inward and start shivering is called hypothermia. The next step would be advanced hypothermia.

Advanced hypothermia means that the body has given up on its attempts to increase body temperature. The body accepts that it has lost the fight and allows the temperature to drop without any attempt to fight back. The shivering stops and you become disoriented. After some time you will stop feeling cold.

This is a life threatening condition. It is very hard to warm somebody up who has advanced hypothermia. Warming up the extremities will cause the blood vessels to dilate. That can cause circulatory problems and shock (not enough circulating fluid for the given volume). Warming up should be done gradually and as close to the body’s core as possible. An option could be breathing warm air. First aid should initially be limited to preventing further heat loss, until a method is found that fulfils the above criteria or until professional help arrives. A diver who is still shivering can be warmed up with less caution, but also there the first priority is to prevent further heat loss.



With heat, the situation is similar. Initially the body will fight against a rising temperature. This is done by bringing the circulation to the outside (which is sometimes a counter-effective reaction) and by starting to sweat to get rid of access heat. This condition is called heat exhaustion (the body is exhausting its resources – fluid and salt – to fight the rising temperature). As long as the body feels up to the job, the sweating will continue, but you will start noticing symptoms indicating a lack of salt and fluid such as tiredness and headache. Also here at some point the body will give up the fight and allow the temperature to rise. This condition is called a heat stroke.

A person with a heat stroke will stop sweating (there may still be sweat on the skin from before). The skin will feel warm to the touch and eventually dry. If the temperature rises too much, the blood will get thick and circulation will fail. The patient will die. A person with a heatstroke is in the process of dying and help is as urgent as for a patient who had a heart attack. The patient must be cooled down immediately with any means available, even if this means you must immerse the patient in water. Just as for any life threatening injury, you need to contact the emergency services immediately.

Mammalian Dive Reflex & Carotid Sinus Reflex

The mammalian dive reflex is a leftover from evolution (just as for example the appendix). Whales have a long breath-hold time because their heart rate goes down the moment they go underwater. Under certain conditions, the same happens to humans. Some are more sensitive than others. To find out if you are sensitive, you can have cold water flowing over your fingers for a while and then push the cold and wet fingers against your closed eyes while measuring your pulse. If your pulse slows down, you are sensitive to the **mammalian dive reflex** (or **bradicardia**).

The mammalian dive reflex mostly occurs during a dive in cold water when you take off your mask. The drop in heart rate causes an uncomfortable feeling and divers might drop their regulator as a result. In order to prevent problems with bradicardia, some instructors teaching in cold water ask their students to submerse their face in the water for a moment before putting their mask on. That way the nerves in the face are already used to the temperature and the risk of a strong reaction is reduced.

Another risk divers are facing is a carotid sinus reflex. The carotid artery is the main artery supplying the head with oxygen. The sense that measures blood pressure and helps regulate the force with which the heart is pumping is located at that artery. When the carotid sinus detects a pressure higher than normal, it “orders” the heart to pump with less force. Unfortunately the carotid sinus cannot distinguish between blood pressure and a pressure exerted from outside. If something pushes from outside, the carotid sinus will interpret that as too high a blood pressure.

Such a pressure from outside can be caused by a hood that is too tight or by the seal of a dry suit that is too small. When the blood pressure is too high, a signal from the carotid sinus solves the problem, but when it is caused by an outside source the pressure will remain. This prompts the carotid sinus to signal to the heart over and over again that the pressure is too high. Eventually the blood pressure will be too low to fight gravity and to bring enough blood to the brain. When that happens, the diver will lose consciousness.

Near Drowning

In near drowning, the exchange of gases between the lung and the bloodstream is impaired. Even a diver who inhaled water, but was able to cough and solve the problem himself, should be considered a near drowning case. Water entering the lungs will prevent a diver from breathing. When the water stays in too long and the diver cannot breathe until the oxygen supply in the body is completely depleted, we speak of drowning (fatality). If the person was resuscitated in time and respiration functions again, we speak of a near drowning.

Problems related to a near drowning are not solved when the person starts breathing again. With water coming out of the lungs (which is only a part of the water entering the lungs), surfactant (which stand for: **Surf**ace Re**act**ive **A**ge**nt**) will be washed out. This is why the exiting water is foamy. The surfactant is a protective layer in the alveoli that prevents the walls of the alveoli of sticking together. When the surfactant is gone, the alveoli will one after the other will stay closed. The number of alveoli that are available for gas exchange will at some point be too low to assure enough oxygen gets in the bloodstream. The patient will fall into hypoxia. This, along with the risk of infection of the lungs, is the reason why everybody who has experienced a near drowning must get medical attention.

Deco Theory

The number of articles and discussions in the internet on decompression theory is endless. You can find articles on compartments, M-values, ascent procedures and so on. Unfortunately most of these publications come from the field of technical and commercial diving and are more aimed at pushing the limits than on conservative diving procedures. Information on decompression theory for recreational dive profiles is harder to find.

Dive computers base their recommendations for remaining dive time at a given depth on a limited number of factors – depth, dive time, altitude, previous dives, gas mix and in some cases diver behaviour, water temperature and workload during the dive. Dive computers do not or hardly take secondary factors into consideration. Workload before and after a dive, illness or injury, drug or alcohol abuse, age, sex, dehydration and all the other factors known to be of concern for decompression sickness.

It is up to the diver to take decisions based on the data of the computer and on common sense (computer assisted diving). Just following the data on the computer without adding common sense (computer controlled diving) could increase your risk of decompression sickness dramatically. Common sense requires informed decisions, meaning that you should know what a computer is doing (and especially what a dive computer is not doing) before taking a decision on a need to be more conservative and, if yes, in what way. This chapter is intended to give you the information needed to enable you to take informed decisions.

Decompression sickness was not yet a concern for the dives made by Alexander the Great. This has changed!

Rationale

Decompression theory is an attempt to predict the behaviour of nitrogen in the body of a diver during and after the ascent at the end of a dive. It can be considered a successful attempt. It is not possible to produce accurate statistics because it is not known how many dives are actually made and because an unknown number of cases of decompression sickness go unreported. The number of incidents is relatively low. A widely accepted estimate for recreational diving is less than one case for every 25,000 dives.

Although we can argue that this estimate indicates that diving is a safe activity (compared to other sports) we should also keep in mind that every single one of these incidents has the potential of reducing quality of life. In some cases damage is so extensive that the success of treatment is limited. If you knowingly push the limits of dive tables and computers, decompression sickness should not come as a surprise. Unfortunately statistics show that approximately 60 per cent of all cases of decompression sickness do come as a complete surprise. The affected divers were under the impression that they have done everything consistent with the procedures they have learned to avoid decompression sickness.

With so many cases coming as a surprise (people who have exposed themselves to additional risk without being aware of it) a first thought would be that the currently used mathematical models for decompression theory are wrong. It would suggest that more research is needed to come up with a more accurate mathematical model that could warn a diver of any increase in risk. That would allow the diver to take steps to avoid becoming a victim of decompression sickness.

It is very well possible that future research shows a path to a mathematical model that limits the number of decompression incidents. It is just as possible that such research shows that the current models are the best we can do. There is not enough information available to either confirm or deny the current mathematical models. It is arguable to what extent future research can change the situation. The current models take the experience of decades of trial and error into account. Maybe we can do better, maybe not. The main problem to be solved is the reasons why some people are more affected by decompression sickness than others.

Dive tables and dive computers base their recommendations for ascent procedures on depth, dive time, altitude, breathing gas and previous dives. To some extend, factors such as water temperature and diver behavior are taken into account by some computers. Factors such as age and body fat can sometimes be set by the diver. Factors such as fatigue, injury, illness, drug or alcohol abuse, dehydration, effort before or after the dive and others are hardly ever taken into account. It would not be realistic to think that future mathematical models will be able to do that.

The approach to take the dive profile of every decompression incident into account and to exclude these profiles from the computer and table options would not work. Many accidents occur far within the accepted limits. Excluding these incident profiles from the table and computer limits would leave us with a restrictive model that does not allow realistic dives.

Fact is that the current limits from dive tables and dive computers are widely considered to be acceptable. Fact is that incidents do occur within these limits. There are enough equivalents of “acceptable risk” in day-to-day life. An accepted procedure for crossing the street is to look to the left, then to the right and then left again. The estimation of the distance and speed of the traffic are then the basis for your decision to cross the street. It is an accepted procedure, it works well in most cases, but incidents do occur. Some people accept a higher level of risk than others when crossing the street, but if you don't want any risk; your only option is not to cross (which would be unacceptable).

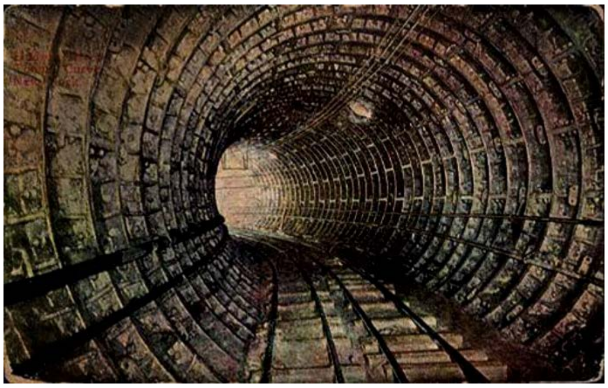
So, if you do want to exclude the risk of decompression sickness, do not dive, do not go in airplanes and do not expose your body to change in pressure in any other way (or dive, but never come up – you don't get decompression sickness if you stay at depth). If it is unacceptable for you not to dive, you will have to take the potential risk of decompression sickness into account.

In the example of crossing the street, we indicated that some people take more risk than others. Also in diving we see people who accept more risk than others. If you want to limit your risk, you have to know how to do that. To limit your risk with respect to decompression sickness, you must be able to take an informed decision. In day-to-day life, you can do that on basis of your education and experiences. In diving you do not have that luxury. The theory covered in "standard" diving courses does not offer the basis for such decisions and let's hope you do not have enough experiences with decompression sickness as basis for your decisions. This chapter's intent is to develop your understanding of the issue of decompression theory to an extent that allows you to take informed decisions.

The practice of computer assisted diving (versus computer controlled diving) can go far in improving your safety. The idea is to take the data the computer or dive table provides into account, but to recognize situations in which a more conservative dive is prudent. To recognize such situations, you must first of all understand what the mathematical model is doing (and what it is not doing). This understanding will be developed in this chapter. We are not going to be looking for "the best computer", but for "the best way to dive with a computer".

History

The first documented case of decompression sickness dates from 1841. In this case the victim was not a diver, but a worker in a caisson (an inverted container allowing people to work on the bottom without diving equipment). As there was no explanation for the symptoms of the worker, it was referred to as caisson sickness.



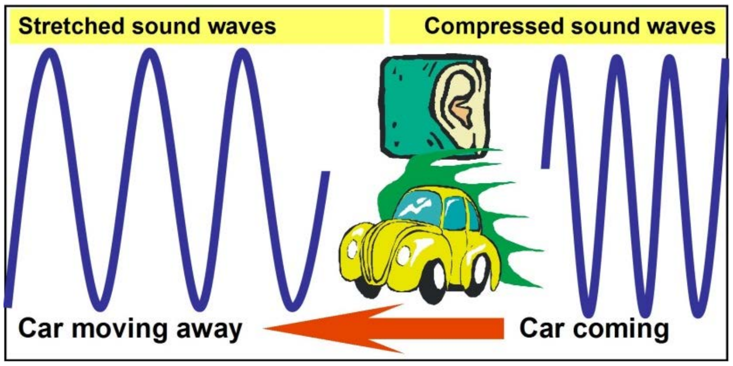
In 1878 Paul Bert discovered that this caisson sickness was related to nitrogen and that a slow decompression was needed to avoid symptoms. nitrogen was thus the cause of the "Grecian bend," a term invented by workers during the construction of the piers of the Brooklyn Bridge. The bent body position of affected workers was similar to the "Grecian bend" (a fashionable posture assumed by women during that period). Decompression sickness later became known as "bends". Ernest Moir then performed the first successful treatment of decompression sickness in 1889 on affected workers during the construction of the Hudson River tunnel (it is said that up to the moment of the first successful treatment, about a quarter of the affected workers died of decompression sickness).

The success of Ernest Moir inspired many. The general idea was that it should be possible to come up with a method to avoid “bends” (what can be healed can be avoided). Research started and in 1908 John Scott Haldane, Arthur Boycott and Guybon Damant came up with the first workable method to “prevent compressed-air sickness”. This is what they named decompression sickness in their paper. Their research is now referred to as the “Haldanian model”. This procedure, which is basically the first dive table in the world, was not easy accessible and was only used by certain groups.


"Grecian bend"

The first widely used dive table in the world was the US Navy dive table. The first version from 1937 did not allow repetitive diving. That option which was included in 1956 with the second version. For both versions together, only about 60 test dives were made to confirm the mathematical model. The 1956 version of the US Navy dive tables has been in use by recreational divers all over the world. There was hardly an alternative, it was available and as it had already been paid for by the taxpayer. Its use is free and there is no enforcement of copyrights.

Until 1974 there was hardly any discussion with respect to dive tables and decompression theory. Divers were confident that the US Navy tables were safe and since everybody was using the same dive tables (those who did not have dive tables frequently used the number 50 as the maximum sum of depth in metres and bottom time for a single dive), divers did not compare between different models. They did thus not wonder about the rationale behind different times for a same depth in different tables. In the seventies this all changed when Spencer showed with Doppler measurements that divers could have substantial amounts of bubbles in their bloodstream when diving within the limits of the US Navy tables. The discussions started and divers started looking at other dive tables. No-decompression limits became a subject of conversation between divers.



Johann Christian Doppler (Austria) published in 1842 that the frequency of sound (and light) is perceived different when the source is stationary or in movement. We all know the effect on the sound of the siren of an ambulance coming toward you, passing you and then driving away from you. The sound is higher when the ambulance approaches and lowers when it is driving away. The sound changes the moment the ambulance is passing. Doppler ultrasound measurements use this Doppler principle. Ultrasound is used on the body of a diver, but only frequency changes are registered. This changing frequency is made audible on speakers or a headphone. A frequency change indicates a bubble passing by in the bloodstream. As the measurement is made at the skin, the Doppler indicates the amount of bubbles passing in the veins. Doppler can thus only register bubbles that are in movement and not bubbles that are stationary in the tissue. The presence of bubbles in the veins indicate an increase in the risk of decompression sickness Type II (neurological decompression sickness).

In 1983 the first working dive computers came on the market. The EDGE in the USA and the “Hans Hass DecoBrain” in Europe. Compared to the dive computers we know today, they were rather big. Smaller dive computers are around since 1987. From that moment on the development went fast. Computers started “beeping”, diver behaviour was in some way integrated in the calculations, additions to models such as RGBM were integrated, etc.

Saturation

According to the law of Dalton, every gas exerts a pressure equal to its percentage of the total pressure in a gas mix. If a gas mix contains 50% of nitrogen and the total pressure is 1 bar, the partial pressure of the nitrogen will be 0.5 bars. If the total pressure would be 2 bars (which is the pressure at 10 metres depth), the partial pressure of the nitrogen would be 1 bar – 50% of 2 bars. According to Dalton, each gas behaves as if the other gasses in the mix were not present. To us this means that the behaviour of nitrogen is not influenced by the other gasses in our breathing mix. Oxygen, helium or other gasses in our diving cylinder do not affect the behaviour of nitrogen. In the context of decompression theory for recreational diving, we are only concerned with the partial pressure of nitrogen, regardless if we dive air or Nitrox.

For the purpose of explaining decompression theory, we will simplify the definition of air to be a mix of 20% oxygen and 80% nitrogen. If you prefer, you can address it as Nitrox20. This will simplify the calculations. With this gas mix the partial pressure of nitrogen at the surface will be 0.8 bars, rather than 0.78 bars as it would be in air.

For the remainder of the discussion of decompression theory, we will apply the law of Henry and for bubble dynamics during the ascent the law of Boyle will play a role.

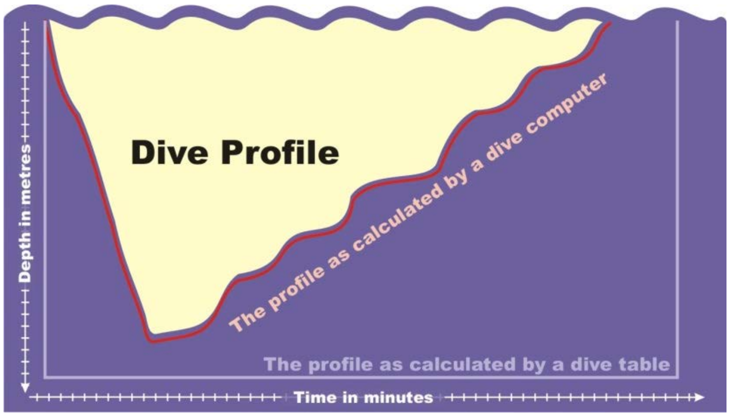
To remember which law in physics has which name, you only need to remember the alphabet. ABCD(H). Imagine you throw a sealed and flexible container in the sea. The first calculation you would be confronted with is to find out if the container would sink, float or be neutrally buoyant. This calculation is done with Archimedes (A). If Archimedes shows that the object will sink, the pressure will increase with increasing depth. The increasing pressure will change the volume of the container. This change in volume is calculated with Boyle (B). When the container continues sinking, it will pass the thermo-cline where the temperature is changing. This changing temperature will also affect the volume, which is calculated with Charles (C). Arriving at the bottom the container will stop moving, giving us time to observe details. In physics, detail refers to the percentage and partial pressure of individual gasses, which are calculated with Daltons law (D). With time, the container will deteriorate and the wall will allow water to enter. The gasses in the container will dissolve in the water according to the law of Henry (H).

According to the law of Dalton our 80/20 mix of nitrogen and oxygen exerts a nitrogen partial pressure of 0.8 bars at the surface. If you have not been diving or flying recently, have not exposed your body to a change in pressure in another way and have not been breathing a different gas mix recently, the nitrogen tension in all the tissues in your body will also be 0.8 bars. According to Henry's law this applies to everything around you. This book, your cat and your cup of coffee all have the same saturation level. The nitrogen partial pressure in everything around you is in equilibrium with the partial pressure of nitrogen in the surrounding gas. Nitrogen is an inert gas. Heavy breathing, exercise and breath holding can change the partial pressure of oxygen and/or carbon-dioxide in your body. It will not affect the partial pressure of nitrogen. The only way to change the partial pressure of nitrogen in your body is to change the gas surrounding you. By changing the pressure or by changing the percentage of nitrogen.

Your body will adapt itself to the nitrogen partial pressure in the gas surrounding you. The gas you are breathing. If the partial pressure of nitrogen in your body is higher than in the gas surrounding you (which can only happen when you just came from an environment with a higher nitrogen partial pressure) you are supersaturated and will thus de-saturate until the equilibrium is reached. Until the nitrogen partial pressure in your body is equal to the partial pressure in the surrounding gas. If the nitrogen partial pressure in your body is lower than the nitrogen partial pressure in the surrounding gas, you will saturate until equilibrium is reached. If you stay in that environment longer than needed to reach equilibrium, you will not take up more nitrogen. You will reach equilibrium and then saturation will stop. You are saturated.

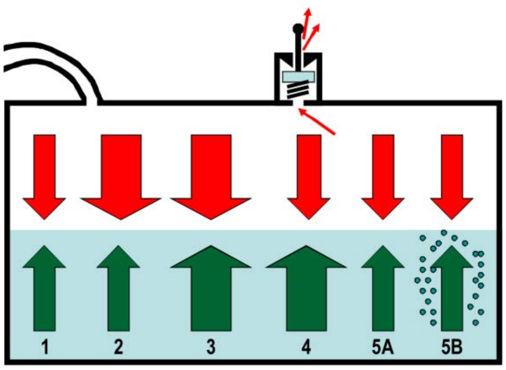
Commercial diving companies sometimes make use of the concept of "saturation dives". Divers live in a pressurized chamber to which the diving bell can be connected. The pressurized chamber and the diving bell are both at the pressure of the depth where the work is taking place. Team after team goes down to work and comes back to the chamber to eat, rest and sleep. The diving crew lives under pressure for several days. That is enough time to be completely saturated. At the end of the working period the divers are decompressed. Because of the long duration under pressure, decompression is a long process.

A recreational scuba dive is too short to reach complete saturation. A recreational diver typically ends the dive when still in the process to be saturated. As the level of saturation depends on the dive profile, each recreational scuba dive is unique with respect to decompression theory. It needs a unique calculation. There are two tools available to do this calculation: dive tables and dive computers.



Of the two tools available to calculate a dive, the dive computer is most accurate. All work with equivalent mathematical models, but the precision differs. A dive table can be compared to a stack of envelopes. When you prepared a file to be sent, you will search in the pile for a matching envelope. The envelope you chose is often too big for the file you want to send. The choice of envelopes is limited, just as the number of dive time/depth combinations on a dive table. A table requires you to round up to the next greater number and does not take into account that you did not spend all the time at the greatest depth. A dive computer is a "real-time" envelope cutter, creating an envelope while you are diving. This is an envelope that fits your dive profile exactly. It uses the same calculation as the table, but it works with the exact time and depth and gives credit when you spend part of the time at shallower depth.

No matter which tool we choose to calculate our dive, the same decompression theory applies. We just use the same mathematical model with different levels of precision in relation to the actual profile of the dive. The first aspect in this calculation is the process of saturation and de-saturation of nitrogen. This process can be illustrated in a small chamber for testing diving instruments. The chamber is half filled with water and half with air. When we close the chamber the water is saturated with nitrogen at ambient pressure. The nitrogen tension in the water is 0.8

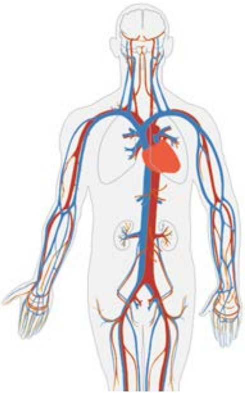


bar. This is the same as the partial pressure of nitrogen in the gas in contact with the surface of the water.

When we increase the pressure in the chamber (2), initially the partial pressure of nitrogen in the air in the chamber only is increased. This creates an imbalance between the partial pressure of the nitrogen in the air and in the water. Nitrogen starts to enter the water and will continue to do so until the partial pressure of nitrogen in the air and in the water are in equilibrium (3). With water this process will go rather fast, but it is still a delayed process. The time needed to saturate a certain matter or tissue depends on several factors which we will discuss later. For the time being it is enough to understand that saturation does take time.

If you pressurized the chamber at 2 bar, the partial pressure of nitrogen in the air will be 1,6 bar and after a while the nitrogen partial pressure in the water will be the same. If you now vent air from the chamber (4) to allow the pressure of the air to return to ambient pressure, the water will be supersaturated. It will start to de-saturate. It is this off-gassing process that is the critical factor in decompression theory. Decompression theory is to predict until which level of saturation controlled off-gassing is still possible. It is to predict the quantity of nitrogen that can leave the body in a controlled manner (5A) when ascending directly to the surface and which quantities require a de-saturation in steps (5B), known as decompression-stops.

Saturation is a slow process. This can be observed if we pressurize an apple. Leave the apple in the chamber for several minutes and then "bring it up to the surface". You will be able to see and hear gas coming out of the apple for several minutes.



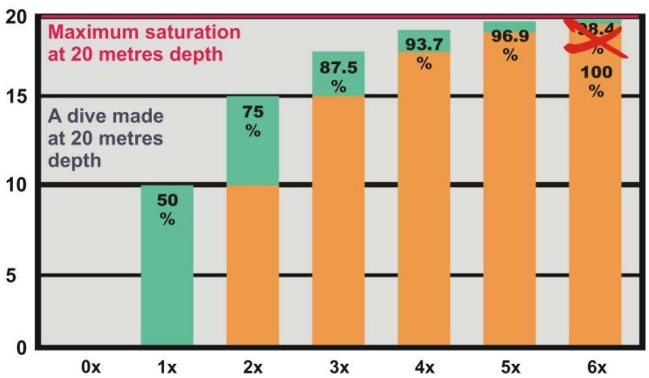
The first step is thus to calculate how much nitrogen a certain dive profile would store in each part of your body, or better, in each tissue. Already this first step is "impossible". How much nitrogen a certain part of the body is taking up depends on several factors. The distance between capillaries in that specific tissue, the density of the tissue and other secondary factors all play a role. These factors vary from tissue to tissue, from person to person, from day to day and in some cases even from minute to minute.

There is no way we can take all the variables into account. Even if we could, there would be no way to make measurements to confirm that our calculations are correct. The calculations are based on assumptions of how different tissues would behave. These "tissues" do not have a direct relationship with the "real tissues" in the body. This is why we give them the more neutral name of "compartments". Although there is no direct relationship between these theoretical compartments and our body tissues, we do know that blood is a fast tissue and bone a slow one. We can however not measure how slow or how fast they really are.

Compartments

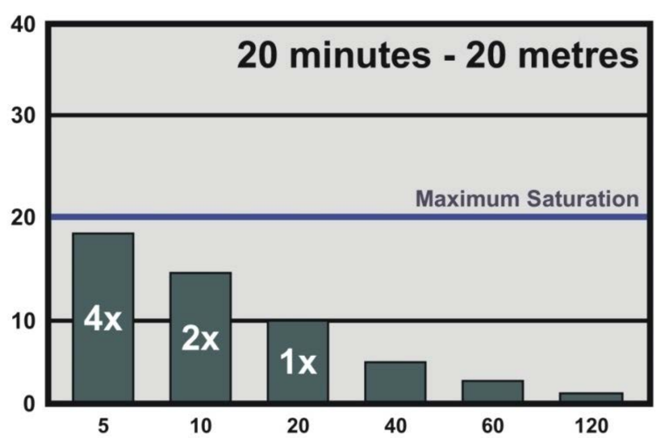
To simulate the saturation characteristics of the different tissues in the body, Haldane introduced a model with 5 different compartments. These 5 compartments would all saturate with nitrogen in the same manner, but at a different speed. The name of the compartment indicates its speed. In the Haldanian model we find 5, 10, 20, 40 and 75 minute compartments. The US Navy later changed the 75 minute compartment to an 80 minute compartment and added a 120 minute compartment (a 6-compartment model).

The model we are going to be using for the following examples is a 6 compartment model with a 5, 10, 20, 40, 60 and 120 minute compartment. This is not a "real" model, meaning that it is not tested and not used in a dive table or dive computer. It serves the purpose of explaining decompression theory. Different dive computers use a different set of compartments. This can involve a different number of compartments with different values. The way the computer calculates the saturation and de-saturation of the individual compartments hardly varies. The Haldanian model is still in use in virtually all dive tables and dive computers.



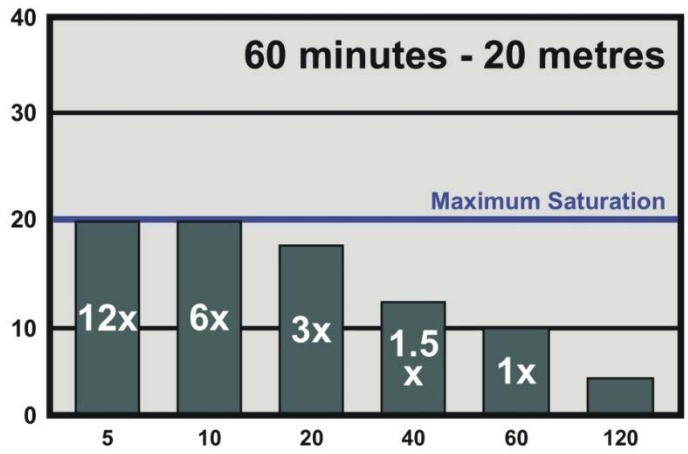
Haldane has stated that a difference in nitrogen pressure between a tissue and its surroundings is reduced to half of its previous value in one "period". The period being the name of the tissue. If you would descend to a depth of 20 metres, eventually all tissues would saturate to the nitrogen partial pressure found at that depth. The 5 minute tissue would do this in half an hour – 6 times 5 minutes. After 5 minutes the saturation would be completed for 50% (reducing the difference in nitrogen partial pressure by half), after 10 minutes 75% (reducing the "new" difference in pressure by half) after 15 minutes 87.5%, after 20 minutes 93.7%, after 25 minutes 96.9% and after half an hour 98.4%. Of course we could continue calculating to 99.2%, 99.6%, 99.8% and so on, but we don't. It is widely accepted that 6 steps or tissue half-times (98.4%) bring us so close to "complete saturation" or "equilibrium" that the 98.4% is considered 100%.

The models behind dive tables and dive computers calculate saturation in 6 steps. Following the same steps, the 60 minute compartment would take 6 hours to saturate (6 times one hour).



In order to simplify, we will not work with nitrogen partial pressure in the coming examples. We will simply indicate saturation at a certain depth, meaning that we are saturated to the partial pressure of nitrogen in air at that depth. Starting at 0 metres does not mean that we do not have nitrogen in our body at the surface. It simply means that we are saturated to the nitrogen partial pressure in air at 0 metres (which would be 0.8 bar).

With the previous information in mind, we can now calculate the saturation in the individual compartments at any given moment during a dive. The first example is a 20 minute dive at a depth of 20 metres. The 5 minute compartment has completed 4 periods (20 divided by 5). As all compartments, the 5 minute compartment works toward complete saturation (the nitrogen partial pressure at 20 metres). In four steps the saturation went from 10, 15 and 17.5 to the nitrogen partial pressure at 18.75 metres. The 10 minute compartment completed 2 periods, which brings the saturation to 15 metres and the 20 minute compartment completed one period and is thus saturated to the nitrogen partial pressure at 10 metres. The slower the compartment, the less nitrogen it has taken up at this point in the dive.



If we now look at the situation after 60 minutes at a depth of 20 metres, we see an interesting aspect of decompression theory. The 5 minute compartment completed 12 periods (60 divided by 5). As we have learned before, we stop calculating after 6 periods because that is the moment we consider complete saturation to be reached. This means that the 5 minute compartment was saturated 30 minutes into the dive. With respect to saturation and off-gassing nothing has happened in the last 30 minutes of the dive. We see that the 10 minute compartment has just now reached saturation and that the other compartments are still on the way. Following this logic, we can see that it would take 12 hours to complete the saturation process for this model. 12 hours is the time needed for the 120 minute compartment to reach saturation.

Although this explains how we calculate the quantity of nitrogen absorbed by the individual compartments, it does not tell us if it is safe to make a direct ascent to the surface. We know how much nitrogen has to be off-gassed by the individual compartments, but we do not know if this can be done in a controlled manner. This means that we need to add the tolerance to additional nitrogen for each individual compartment. This is the maximum quantity of nitrogen that the given compartment can eliminate in a controlled manner.

M-values

The tolerance each individual compartment has to excess nitrogen is called an M-value (maximum value). The faster the compartment, the higher the tolerance is. The set of M-values we use are also referred to as M_0-values, meaning that it is the maximum excess nitrogen to allow a direct ascent to 0 metres. That is the surface at sea level. For a return to an environment with another pressure than the surface at sea level, another set of M-values would apply.

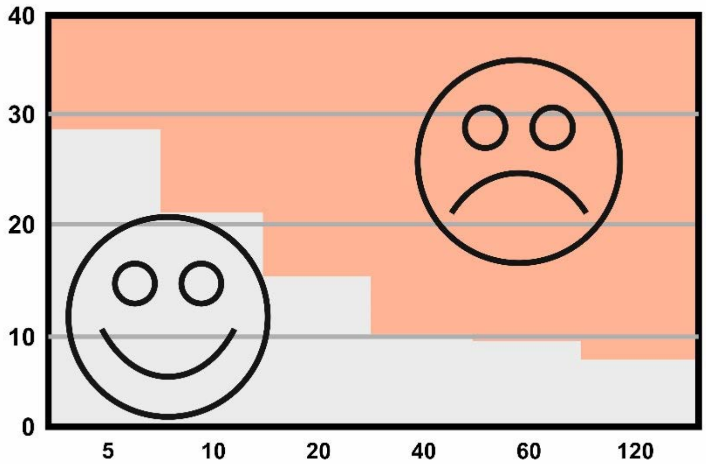
In literature, M-values are frequently given in the unit msw (metres of sea water). As divers are more used to bar as a unit for pressure, we will use bar here. The US Navy allows a maximum nitrogen partial pressure in the 5 minute compartment of 3.17 bars and only 1.58 bars in the 120 minute compartment. M-values are not standardised. Different tables and dive computers use a different set of M-values and are thus hard to compare.

US Navy Compartments	5	10	20	40	120
M_0-values	**3.17 bar**	**2.68 bar**	**2.19 bar**	**1.7 bar**	**1.58 bar**

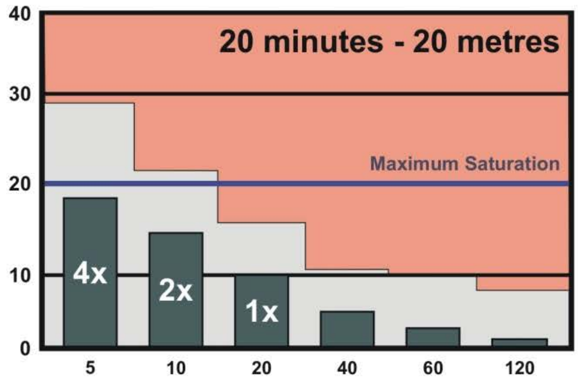
The pressures indicated here are converted from fsw and rounded. In our graphic representations of M-values, we indicate the depth at which the maximum nitrogen partial pressure is reached. For the 5 minute compartment, this would be a depth of approximately 28 metres (based on our 80/20 mix and an M-value of 3.04 bars). The M-values indicated in the examples in this book are just for the purpose of explaining decompression theory and do not represent tested data.

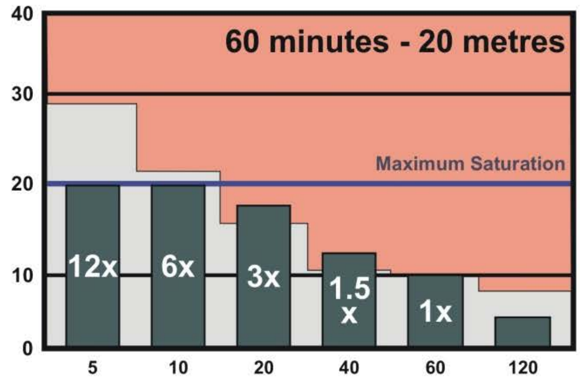
Where virtually all specialists agree on the way to calculate saturation and de-saturation, the opinions on M-values (and ascent procedures) vary. In part this is due to the intent of the model. The US Navy was testing its tables to see if subjects developed symptoms of decompression sickness. Other researchers have tested their tables to measure bubble formation in the veins with use of Doppler bubble detectors. As not all bubbles lead to symptoms of decompression sickness, the different methods will not come up with the same values. The difference in M-values is a main reason for the variation in values different makes of dive computers give for the same dive.

In most dive computers, the M-values are fixed values, but some have programmed a protocol to "punish" diver behaviour (yo-yo dives, rapid ascents, etc.) with more conservative of M-values. When the diver starts showing non-recommended behaviour, the maximum allowed nitrogen partial pressure for the individual compartments is reduced. The number of factors that can be taken into account by such a protocol is limited. The protocol can detect non-recommended dive profiles and could also take water temperature into account. It cannot measure factors related to the diver such as illness, fatigue, dehydration and others. An air integrated computer can detect overexertion by a sudden increase in breathing gas consumption, but that protocol would then also be activated by a regulator free-flow, filling a lift bag or air-sharing (alternate air source or buddy breathing) exercises in a course.



No matter what testing and philosophy there are behind the mathematical model, there will be a set of M-values against which a dive can be compared. As long as saturation stays within tolerable levels, the diver can make a direct ascent to the surface. When the diver exceeds the limits, he is obliged to make decompression stops before making the final ascent to surface. These decompression stops are meant to reduce the quantity of nitrogen in the individual compartments to tolerable levels.



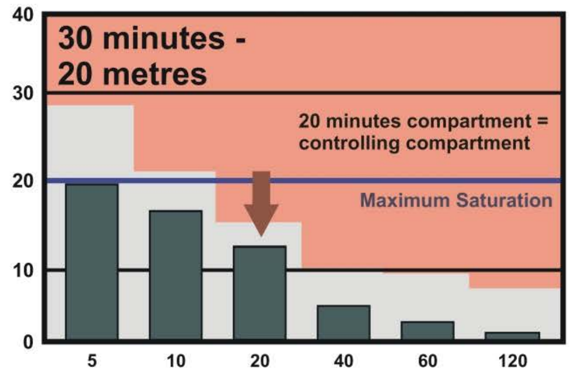


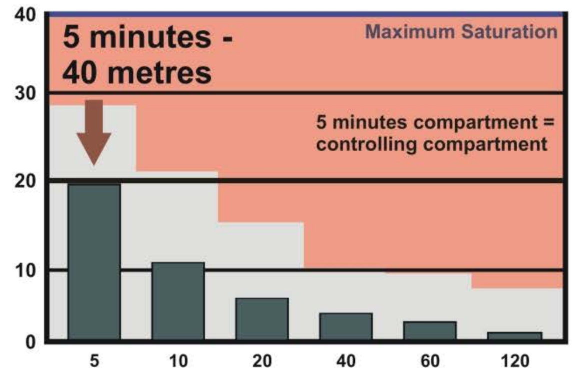
If we now compare the dives we have seen in the section on saturation to the M-values, we see that the 20 minute dive at a depth of 20 metres will allow a direct ascend to the surface. The 60 minute dive at 20 metres requires decompression and does not allow a direct ascent to the surface.

Controlling Compartment (or Tissue)

A computer does not only tell you if a direct ascent to the surface is possible, but also informs you how much more time is available for a dive at the given depth. To provide this data, the computer is basing itself on the “controlling compartment”. The controlling compartment is not the same for all dives. Dives at different depths are controlled by different compartments. Basically the computer works as follows: the computer will “ask” each compartment how many minutes he would need at the current depth to reach its M-value. The computer will then take the shortest answer and display that number as remaining dive time on the display of the computer.

When looking at a 40 metre dive, we will see that the 5 minute compartment saturates fast compared to the other compartments. It is clear that this compartment will give the shortest answer on the question of how many minutes more it will take to reach the M-value. In this case the 5 minute compartment is the controlling compartment.



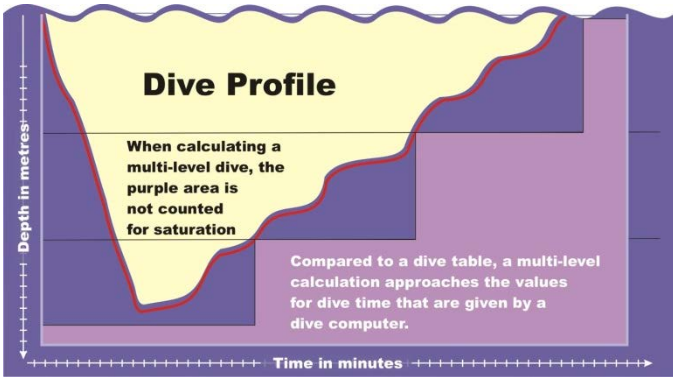


When we then look at a dive at a depth of 20 metres, we see that it is not possible that the 5 minute compartment controls this dive. Even if the 5 minute compartment reaches complete saturation at 20 metres depth (which is the case after 30 minutes), the quantity of nitrogen is still far from the M-value for this compartment. For dives shallower than the M-value for a given compartment, that compartment does not play a role. When asked the question on the remaining time, these compartments will answer that they can stay at this depth endlessly, which is obviously not the shortest answer. Deep dives are controlled by fast compartments. Shallow dives are controlled by slow compartments.

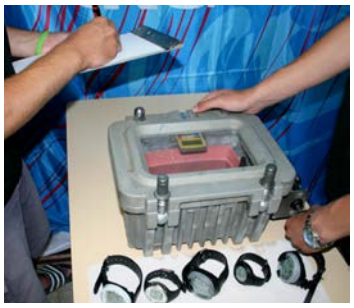
Then what about dives with varying depth? Well, they use different controlling compartments for different depths. This is often referred to as multi-level diving. It is recommended that the dive begins at its deepest point and that the diver then progressively goes to shallower depth (although there is debate that reverse dive profiles are acceptable, it is still the current recommendation to start at the deepest point of the dive whenever possible). At the deepest point of the dive, a fast compartment will be controlling. When the diver ascends to shallower depth, at some point he will be shallower than the M-value of the controlling compartment. At that moment this compartment will respond "endless" and the next slower compartment becomes controlling compartment as it is now this compartment that gives the shortest answer. You can sometimes observe this on your dive computer. The remaining dive time will jump and all of a sudden be several minutes longer than a second before.

It is this switch from faster to slower compartments that allows us so much more dive time with a computer than with a table. The table considers you to be at the maximum depth of the dive for the duration of the dive. The sum of the remaining dive time and the dive time displayed on your computer at the deepest point of your dive (in the beginning of the dive) would be the dive time a dive table (based on the same mathematical model) would allow for a dive with that maximum depth. The table does not give credit for continuing the dive at a shallower depth. The computer does.

Some dive tables allow the calculation of multi-level dives. When progressing to shallower depth, at some point such tables can be "switched" to a slower controlling compartment (the horizontal lines in the drawing). Such tables tell you beforehand at which depth you can gain additional dive time by switching to a slower compartment. The computer does not. Additional time the computer is giving you comes as a "surprise". A computer with fixed M-values will always give the additional time at the same depth. That is the depth where you go shallower than the M-value of the controlling tissue. This means that you could do a little test with your computer to find out at which depth your computer switches to another compartment. The values you find will then apply to all future dives. That way you know to which depth you need to ascend in order to take benefit of a longer dive time.



Simulate a dive to 40 metres in a small pressure chamber. Ascend in steps of 1 or 2 metres and note the dive time and the remaining dive time. Once you are done, add the dive time to the remaining dive time for each depth. You can now enter the depth and the sum of the dive time and remaining dive time in a computer program on your PC. A graphical representation of the data allows you to see that the total dive time (dive time + remaining dive time) increases when going to shallower depth. In part this is explained by the slower saturation at shallower depth. At some points you notice that the rate at which the total dive time is increasing becomes faster. These are the points at which the computer is switching to a slower controlling compartment. A computer with fixed M-values will always do this at the same depth. The list of depths you created with this test will apply to all future dives with that computer.



To avoid that the computer gets into a decompression obligation, you need to work relatively fast. It is best to work in a team. This "test" can also be done during a dive. Just note the same data on a slate while you ascend.

On the following pages a form provides data collected during a M-value test. The empty form can be used to test your own dive computer.

M-value Identification for Dive Computers

Computer 1:				Computer 2:			
Depth in metre	Dive time	Remaining dive time	Total	Depth in metre	Dive time	Remaining dive time	Total
10				10			
11				11			
12				12			
13				13			
14				14			
15				15			
16				16			
17				17			
18				18			
19				19			
20				20			
21				21			
22				22			
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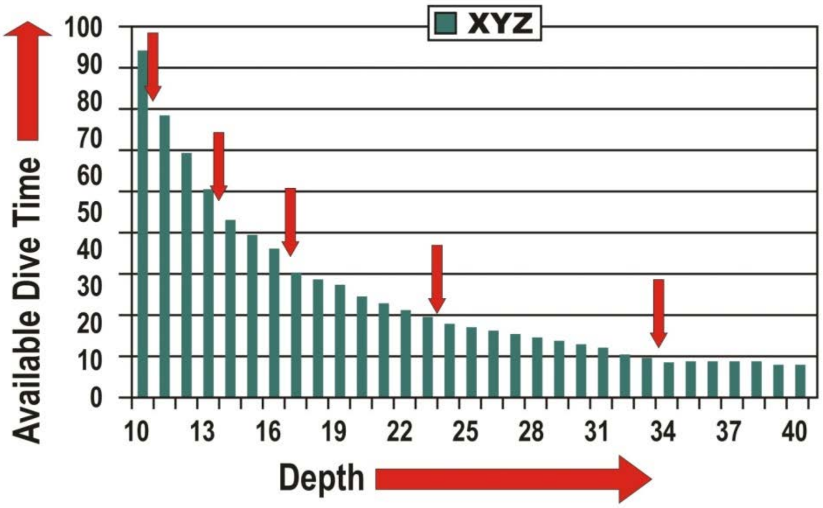
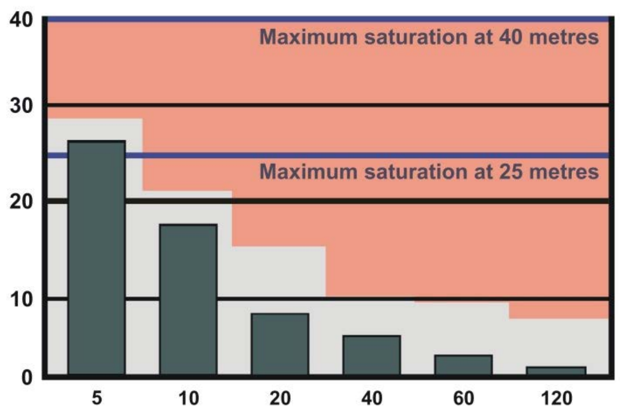
28				28			
29				29			
30				30			
31				31			
32				32			
33				33			
34				34			
35				35			
36				36			
37				37			
38				38			
39				39			
40				40			

M-value Identification for Dive Computers

Computer 1:	XYZ			Computer 2:	DC11		
Depth in metre	Dive time	Remaining dive time	Total	Depth in metre	Dive time	Remaining dive time	Total
10	18	76	94	10	11	89	100
11	18	58	76	11	10	63	73
12	17	49	66	12	10	49	59
13	17	39	56	13	9	38	47
14	16	32	48	14	9	35	44
15	16	28	44	15	8	31	39
16	15	25	40	16	8	23	31
17	14	20	34	17	7	18	25
18	13	19	32	18	7	14	21
19	13	17	30	19	7	5	12
20	12	16	28	20	6	5	11
21	12	14	26	21	6	5	11
22	11	13	24	22	6	5	11
23	11	11	22	23	5	5	10
24	10	10	20	24	5	5	10
25	10	9	19	25	4	5	9
26	9	9	18	26	4	5	9
27	8	9	17	27	4	5	9
28	8	8	16	28	3	5	8
29	7	8	15	29	3	5	8
30	7	7	14	30	3	5	8
31	6	7	13	31	2	5	7
32	5	7	12	32	2	5	7
33	5	6	11	33	2	5	7
34	4	6	10	34	2	5	7
35	4	6	10	35	1	5	6
36	3	7	10	36	1	5	6
37	3	7	10	37	1	5	6
38	3	7	10	38	1	5	6
39	2	7	9	39	1	5	6
40	1	8	9	40	0	5	6

The red arrows indicate at which points the sum of the dive time and remaining dive time start to increase faster. This is the point where the computer starts calculating with another compartment. You can place a ruler on the graphic along the top of the bars to better see the rate of increase. The gradual increase in dive time between the red arrows is the result of ascending to a shallower depth. Although it is still the same compartment that is controlling the dive, the shallower depth reduced the rate of the nitrogen absorption and thus increases the remaining dive time.



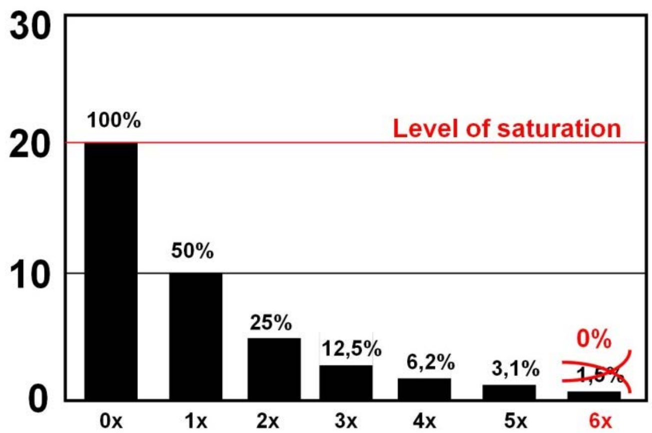


A diver moves to a shallower depth after having been to 40 metres. At 25 metres, his second depth, the 5 minute compartment says it can stay at this depth endlessly (at 40 metres is still said there are only a few minutes of dive time left).

Increase in dive time on a dive computer when progressing to shallower depth comes from the switch from a faster to a slower controlling compartment. Some divers think that the increase in dive time comes from the off-gassing already completed at shallower depth, but this is not the case. Of course there can be some off-gassing going on, but this is not reflected in the remaining dive time displayed on the computer. If there is off-gassing going on, this will be in the faster compartments. These are the only ones that are saturated higher than your current depth. In shallower depth these compartments are not the controlling compartment. The data they provide is that they can stay at this depth endlessly. The computer will only display the shortest answer to its question: how long does it take at this depth to reach the M-value. The shortest answer can only come from a compartment in the process of saturating. A compartment that is neither saturated, nor reached its M-value, but still has the potential to reach the M-value.

If there is off-gassing taking place in faster compartments while you are still diving, it will be at a limited speed. The rule – a given difference in pressure between a tissue and its surroundings is reduced to half in one period – is still true. If a tissue is saturated at 30 metres and you are at 20 metres, it does not off-gas at the same speed it would when you were at the surface. The pressure gradient between 30 en 20 metres will be reduced to half. Not the pressure gradient between 30 and 0 metres. But again, even if off-gassing is going on, it will not be reflected in the data the computer is giving on its display because the off-gassing compartments will tell the computer “they can stay endless at the current depth” (this holds true for dives within the no-decompression limit).

Surface Interval

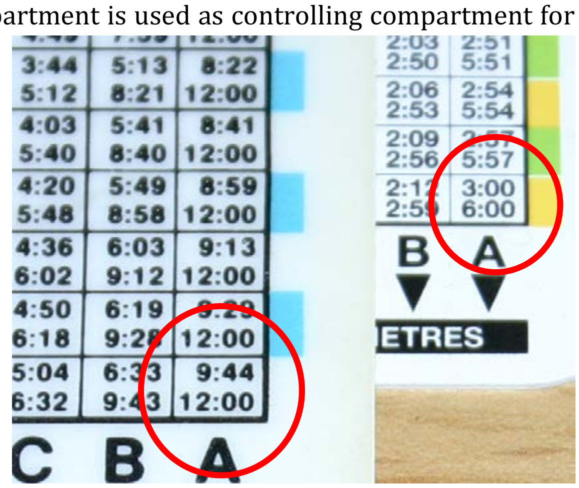


Long ago, repetitive diving required a diver to add the dive time of the two dives and to fulfil decompression obligations as if the two dives were a single dive. There was no procedure to receive credit for an interval between dives. This changed with the revised edition of the US Navy tables in 1956. The US Navy decided on the 120 minute compartment as the controlling compartment for the surface interval. It established a system with letters (A-N) to express the level of saturation in the 120 minute compartment. These were called pressure groups or repetitive dive groups.

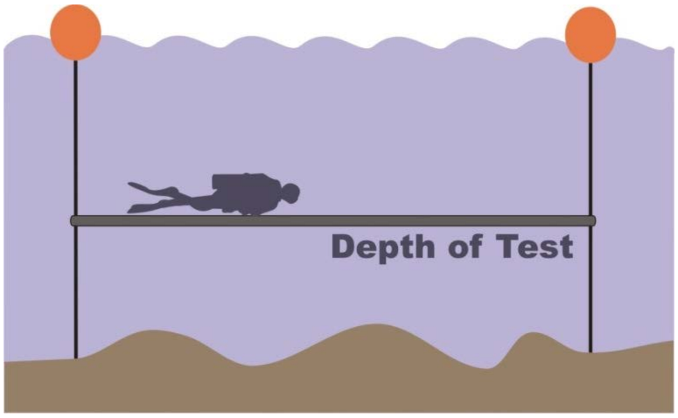
Off-gassing is assumed to go in the same manner as saturation. A difference in pressure between a tissue and its surroundings is reduced to half in one period. Using the 120 minute compartment to control the surface interval thus meant that off-gassing was completed after 12 hours (6 times 120 minutes). The faster compartments are off-gassing faster than the 120 minute compartment and are thus taken into account when off-gassing is controlled by a slow compartment. Compartments slower than 120 minutes might be a concern. They are not taken into account by a 120 minute controlling compartment for the surface interval.

Buhlmann later introduced the EE (exponential – exponential) model for surface intervals. He argued that off-gassing of each compartment would work according to the same period as the saturation. A 5 minute compartment would completely saturate in 30 minutes and also the off-gassing would be completed in 30 minutes. The theory implies that the compartment controlling the dive would also be controlling the surface interval.

With dive tables it is not so hard to find out what compartment is used as controlling compartment for the surface interval. It is enough to look in the last box of the surface interval credit table. When this box marks 12 hours, the controlling compartment is the 120 minute compartment (12 hours divided by 6 steps = 2 hours or 120 minutes). When this same box marks 6 hours, the 60 minute compartment is controlling compartment for the surface interval (6 hours divided by 6 steps = 1 hour or 60 minutes).



Both the US Navy and the Buhlmann models for surface intervals were criticized over the years and new protocols were introduced. A main problem for the introduction of new models is that there is hardly any test data available for the effects of multiple dives during multiple days. The main objection against the US Navy protocol was that the 120 minute compartment penalized recreational dive profiles too much and thus restricted repetitive dives more than needed. The objection against the Buhlmann model was that it did allow repetitive dives which had been found to produce cases of decompression sickness during test dives. This especially on repetitive short and deep dives.

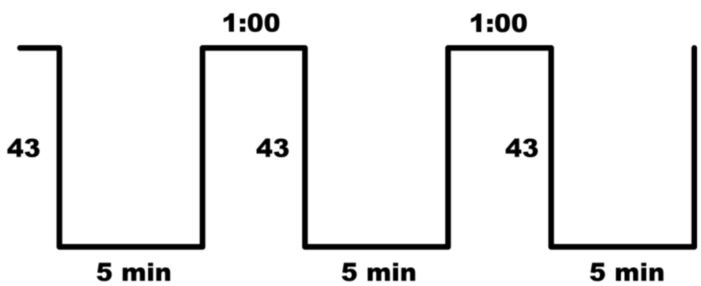


The testing of dive tables is not always pleasant. It is not a matter of "just making a nice dive" and then being tested either clinical or with a doppler detector afterward. We know that cold and workload have a negative effect on the development of decompression sickness. This means that the dive may not be "too relaxed" and that the water temperature in which the tests are taking place needs to be low. In most cases the dive itself needs to follow a predetermined profile. The bottom, with all its interesting wild life, is not suitable. Because of varying depths and because we would need to do test dives on different depths on the same location another solution is required. For this reason many test dives are made along a rigid bar hanging between two buoys. The divers just circle the bar until the intended dive time is completed and then come back to the surface along one of the lines anchoring the buoys. Just imagine if you were the diver testing the no-decompression limit for a 10 metre dive. You would be circling the metal bar (in cold water) for hours.

Years later Spencer introduced the 60 minute compartment as controlling compartment for the surface interval. It was argued to be better adapted to the needs of recreational divers. The 60 minute compartment only functions if we refrain from extremely long dives (the reason why sometimes no dive times are given for depths shallower than 10 metres) and if we do not make decompression dives. As both are not normal practice for recreational divers, leaving these options out was not considered to be a problem. Basically the table needs to avoid long dives in order to use a faster compartment to control the surface interval. For most dives even the 40 minute compartment could be used to control the surface interval, but that would require being even more conservative on the allowed dive times for dives at shallow depth.

Repetitive dives and multiple dives during several days have always been a concern. Dive tables and dive computers have their limitations with respect to extreme exposure. There are many procedures and recommendations in place to motivate divers to limit their exposure during diving vacations. Often these recommendations are not programmed in the dive computer software and require the diver to use common sense.

Especially diving instructors and underwater photographers are at risk. Diving professionals and photographers tend to spend a big part of the day underwater. Because of their activities they tend to stay at shallow depths. They either do several dives in a day or make few dives, but with a long exposure.



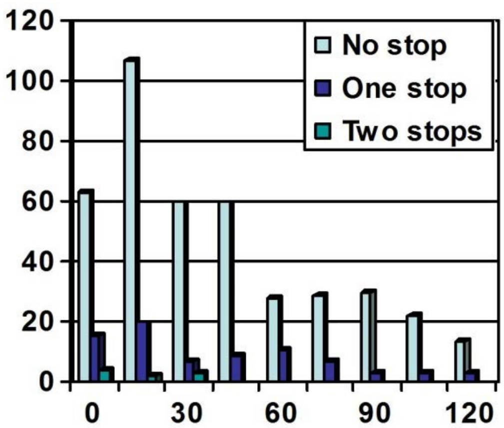
In 1982 Leitch and Barnard published that they found symptoms of decompression sickness in one subject after a second dive and in multiple subjects after a third dive in a test protocol for a series of 3 dives. All dives were to a depth of approximately 43 metres for 5 minutes. Between the dives the subjects made a surface interval of 1 hour. It should also be noted that extra *precautions (not required by tables) were made, such as reducing nitrogen content in the breathing gas and extra stops during ascent. When simulating these dives with an original EE model dive computer, all three dives will be allowed. One could even reduce the surface interval to 36 minutes (6 times 6 minutes, which is sometimes used as the fastest compartment in dive computers) and it would still work. A dive at that depth is controlled by the fastest compartment. If that same compartment is used to control the off-gassing process, the computer is ready to repeat that same dive after a relatively short surface interval. Traditional EE models have virtually no memory of a previous deep dive after a short surface interval. In most of today's EE model dive computers, the protocol is altered to exclude this type of repetitive deep diving.*

Ascents

Probably the most discussed issue in decompression theory is ascents. This goes to the extent that some computers give opposite recommendations with respect to the ascent speed compared to others. Some allow higher ascent speeds at greater depth and want you to slow down when approaching the surface, while others want you to slow down at greater depth to do a "deep stop".

The early recommendation was to get out of deep water soon to avoid additional saturation. When we limit ourselves to the concept of saturation and off-gassing, combined with M-values, this recommendation makes sense. The more you limit your time at depth, the less the compartments will be saturated, the less nitrogen needs to leave the body. This theory assumes that nitrogen is in solution during the dive and during ascent. It assumes that avoiding decompression sickness means avoiding bubble formation.

After it was found that bubbles do develop in divers who dive within the limits of their dive table and that these divers in most cases do not develop symptoms of decompression sickness, it was a logical next step to take extra precautions to avoid (or limit) bubble formation. Initially tests put emphasis on relatively shallow safety stops and lower ascent speeds. This resulted in recommendations to do a safety stop at the end of every dive and requirements to do a safety stop for certain dive profiles.



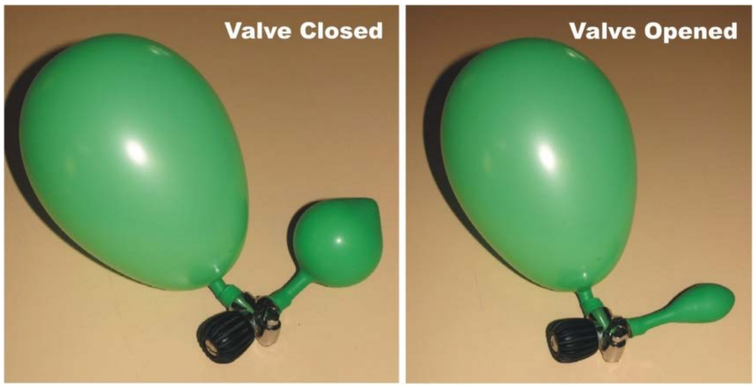
In test dives it was shown that making a safety stop for dives within the no-decompression limit could reduce the amount of bubbles enormously. For the "one stop" profiles a stop of 2 minutes at 3 metres was made. For the "two stop" profiles a first 1 minute stop at 6 metres was made, followed by a 4 minute stop at 3 metres.

Critics call the procedure to get out of deep water soon and then stop in shallower depth "bend and mend". The expression sounds nice and is used on many occasions. It is expressing the opinion that the problem of decompression sickness finds its origin in greater depth and that the problem should be dealt with there, before ascending to shallower depth. Evidence for neither of the opinions is conclusive (2006). There are dive computers that follow the "get out of deep water" approach and others that follow the "deep stop" approach to ascents.

The bulk of research on the concept of deep stops started after a biologist claimed that he felt better after a deep dive in which he collected fish, than after deep dives on which he just observed. The key to this would be the need to make regular stops during the entire ascent in order to puncture the swimming bladder of the collected fish. The work of Dr. Bruce Wienke (RGBM) is most quoted and most used in dive computers for recreational diving.

The idea behind RGBM (Reduced Gradient Bubble Model) and similar models is that avoiding bubble formation is not possible, because you already have micro-bubbles in your body before your dive. These micro-bubbles are too small to be detected by a Doppler bubble detector. The minimum size of bubble Doppler can detect is said to be 10 micron. The idea behind these models is thus on one side to avoid the formation of new bubbles, by following the concept of saturation, off-gassing and M-values. This is combined with an attempt to keep existing bubbles small by following an ascent protocol with deep stops.

As the name of the model suggests, it is based on the pressure gradient between the bubble and its surroundings. Imagine a small section of pipe with a valve in the middle that would allow us to open and close the passage through the pipe. Imagine the section of pipe is closed and we connect an inflated balloon on each side. One inflated to almost its maximum and the other only partly inflated. What would happen to the balloons if we would open the valve? Our first thought would be that the balloons "equalize" and become equal in size. When thinking again, we will probably come up with the correct answer. The smaller balloon will get smaller and the bigger one gets bigger. You know it. When inflating a balloon the start is the hard bit. Once the balloon is of a certain size it gets easier to inflate. The surface tension of the balloon reduces when it gets bigger. When you just inflated the first breath of air into a balloon, it tends to pop out of your mouth due to the pressure inside the balloon.



Similar to the balloon, the smaller a bubble is, the higher its surface tension and thus the higher the pressure inside the bubble in relation to its surrounding pressure (when the bubble is small enough, the pressure inside can be as much as 0.5 bar higher than the surrounding pressure). As long as the bubble is small enough to maintain a high internal pressure, it will not absorb additional nitrogen and thus will not get bigger. As the bubble has a higher inside pressure as its surroundings, it will allow nitrogen to get out and dissolve in the bloodstream.

The problem caused during the ascent is a combination of two factors. These are the immediate effect of reduced pressure (Boyle) on the size of the bubble and the delayed process of off-gassing nitrogen from the bloodstream. When moving to shallower depth, pressure reduces. This will increase the size of the bubble according to Boyle's law. Additional increase in size results from a reduced surface tension (the bubble was smaller than it should have been according to Boyle's law, because of its high surface tension – that surface tension reduces when the bubble gets bigger). We are thus dealing with a bubble that increases its size because of both the reduced surrounding pressure and because of its reduced pressure gradient between the inside of the bubble and its surrounding.

The second factor is the delay with which the partial pressure of nitrogen in the bloodstream adapts itself to the new partial pressure at a shallower depth. The nitrogen partial pressure in your blood will not be equivalent to the nitrogen partial pressure in the breathing gas at the depth where you are. It will be equivalent to the partial pressure in the breathing gas at the depth where you took the breath that saturated the blood that is now surrounding the bubble. During an ascent, that breath can have been taken several metres deeper than the depth where you are now.

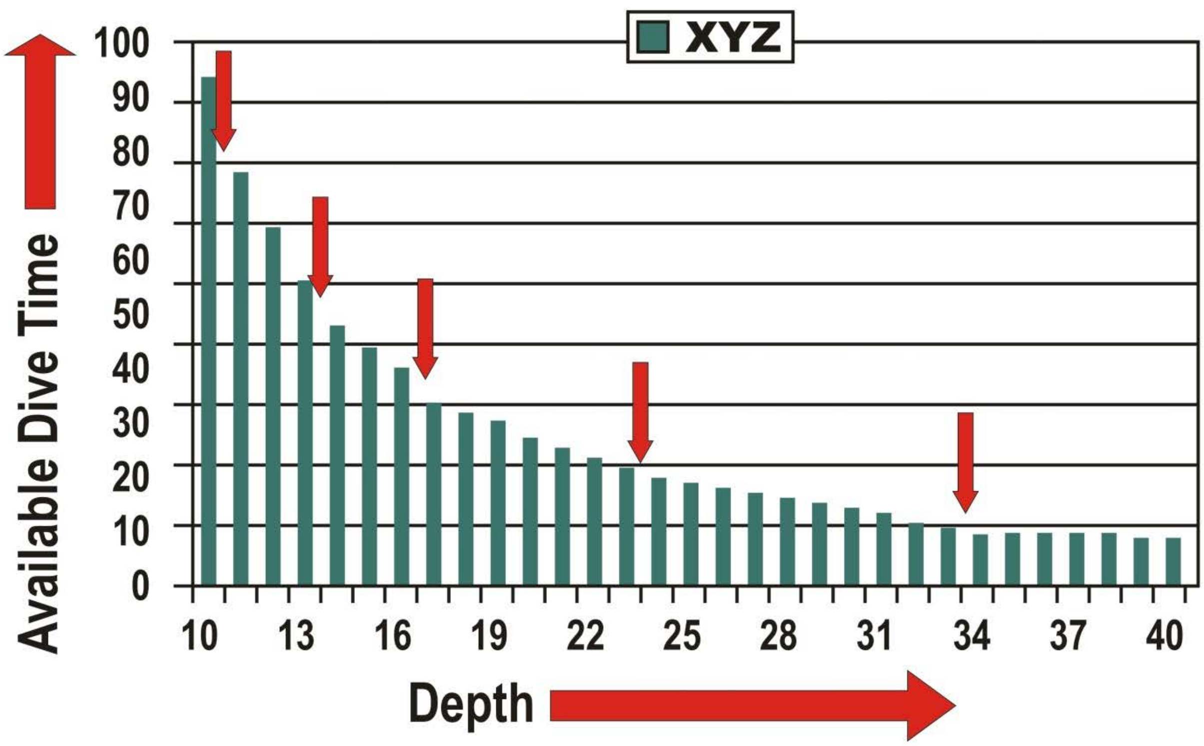
Without losing ourselves in endless calculations, we can imagine what will happen. A small bubble with a high internal pressure (and a tendency to off-gas) will get bigger and lose its internal pressure. The partial pressure of nitrogen in the bubble reduces. At the same time the partial pressure of the nitrogen dissolved in the blood will be higher than the "normal" partial pressure of nitrogen at that depth. At some point the partial pressure of the nitrogen in the blood will be superior to the partial pressure of the nitrogen in the bubble and the bubble will have the tendency to take up nitrogen and get bigger.

Deep stops are thus meant to provide for a moment where the nitrogen partial pressure in the blood can become equal to that in the breathing gas at that depth. This would allow the bubble to off-gas the nitrogen it has just taken up and reduce its size to become small enough to restore its surface tension and thus its internal pressure.

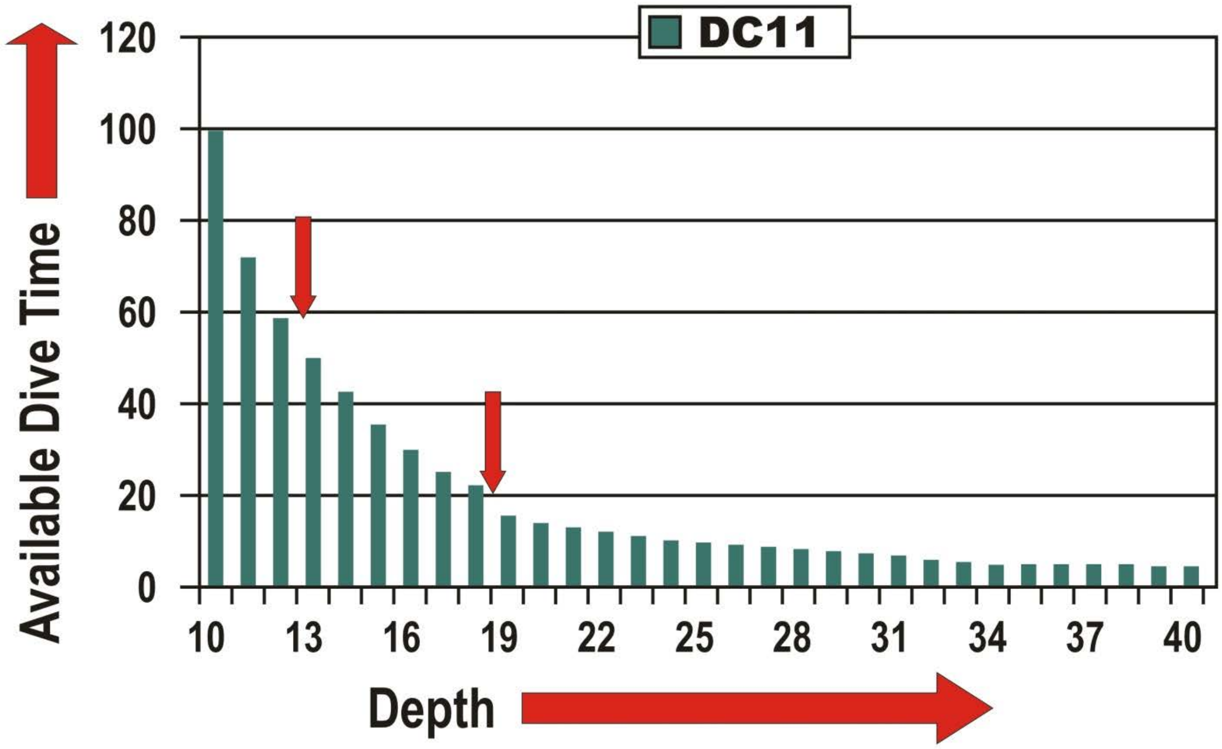
Let's keep in mind that bubble dynamics is not really a concern in most recreational dives. At the end of most dives, we tend to follow the slope of the bottom or the reef and only do a direct ascent to the surface for the last bit. These "ascents" along the slope of the reef or bottom are typically slow, because we are still "diving". We stop to look at marine life; we follow an interesting depth line; and so on. It is only on seldom occasions (such as a wreck dive) that a recreational diver makes a direct ascent to the surface out of greater depth.

On top of that, most recreational dives have a maximum depth that is shallower than the depth of a deep stop. Recreational divers are not exposed to bubble dynamics to the same extent as commercial and technical divers. Of course recreational divers need to pay attention to ascent theories and the problems related to them, but are well advised to pay equal (or more) attention to repetitive long and relatively shallow dives (and the problems related to that).

What Happens When More Compartments are Added to a Model?



As we have seen in the section on M-values, the computer switches to slower controlling compartments when ascending to shallower depth. The more compartments there are in a model, the more frequent such a switch to a slower compartment will take place. If there are not enough compartments in the model (in the range of compartments that are likely to control a recreational dive), we will see less realistic values, like in the DC11 dive computer in the chart earlier in this book (which has not been on the market since a long time).



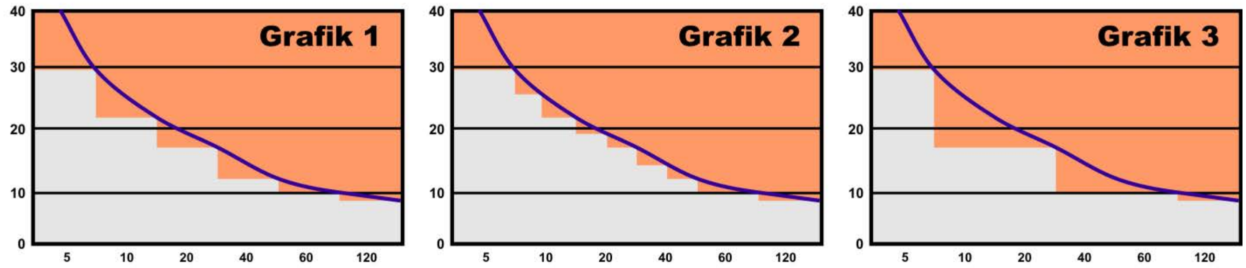
Compartments slower than the controlling compartment for the surface interval have no relevance for the calculation of the dive time. If such a slow compartment would have been taken into consideration for the dive time at shallow depth, it must also be taken into consideration for the surface interval.

Compartments slower than the compartment for the surface interval are needed for calculations for multiple dive profiles, total de-saturation time and flying after diving. For dive time and the number of switches to a slower compartment, in most cases only the compartments ranging from 1 to 60 minutes play a role (the DC11 had 6 compartments, but they ranged from 6 to 600 minutes).

We could actually imagine the “real” range of M-values in the shape of a curve. With hundreds of M-values, the values would be so close together that they would form a line, such as the blue line in the illustration. When limiting the number of compartments, the line will have small steps. Obviously these are on the “safe side”.

It could be argued that fewer compartments would be safer, because it will keep you further away from the critical line. It does not. There are always points at which the “real M-value line” is touched. You never know at which depth there is a margin and at which depth there is not.

With a bigger number of compartments faster than 60 minutes, the M-values will always be close to the curve of “real M-values”. Your margin will always be more or less the same. This means that there is a clear situation to which the diver can add extra conservatism, knowing that the margin for safety that



the computer is giving is more or less constant, regardless of your depth.

A low number of compartments as we have seen in the data from the test of the DC11 will result in big “jumps” in remaining dive time. The computer does not give credit for an extended depth range and then all of a sudden gives a lot of credit when switching to a compartment that is much slower.

Many computers give such big “jumps” close to the surface, but the ones doing this in the 20 metre depth-range are to our knowledge not on the market anymore. A big jump implies that you have not been credited enough before.

Choosing Dive Tables & Dive Computers

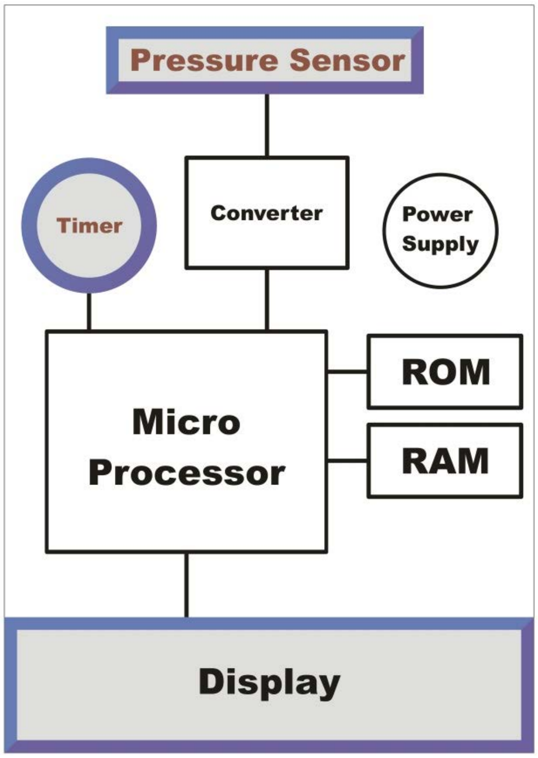
The question of why some people are more affected by decompression sickness than others is not yet answered. It does not seem realistic to expect the answer to that question in the near future. This leaves room for discussion and different opinions. In part, this difference in opinion has resulted in different mathematical models behind the various dive tables and makes of dive computers. For the time being it is not possible to say which of these models is best. There is simply not enough information available to either confirm or deny any of these models. If such information would become available, all “denied models” would disappear from the market.

Some people would say that the “safest” computer would be the best. If “safest” would be equivalent to “most conservative”, it would not be hard to make the “best computer”. You would just have to take a look at the no-decompression limits of the existing models and then create your “safest computer” by making sure you offer less time than the others for any given depth.

Your only problem would be that shortly after you have brought your “safest dive computer” on the market, the competition would come with an even safer model. Then the next “safer” model and the next would come. In the end we cannot get into the water anymore. Making computers more conservative is not the answer with respect to safety.

In recent marketing efforts for different makes of dive computers there is increased emphasis on ascent protocols. This ranges from models with higher speeds at greater depth, while slowing the ascent at shallower depth, compared with models that slow the ascent at greater depth to do a deep stop (the opposite and based on RGBM). RGBM theory in a dive computer was already available in 1991, but was not received with big enthusiasm amongst divers at that time. It more or less disappeared, to reappear in more recent models. With this new introduction, divers developed enthusiasm. However, there is little proof or statistical support that confirm the benefit from deep stops in the relatively shallow, multi-level dive profiles that are common in recreational diving.

In order to find out if there is something like “the best computer” or “the best mathematical model”, we need to explore the factors that are known (or believed) to increase the risk of decompression sickness. We need to take a look how these factors are taken into consideration in a dive computer or dive table. We should also estimate if we can expect future dive computers being programmed to take these factors into consideration.



Depth and dive time – these are the main factors on which the mathematical model is based. The computer is equipped with a pressure sensor and an internal clock to keep track of pressure (depth) and time and to calculate saturation and de-saturation based on these two factors.

Altitude – diving at altitude requires that a different set of M-values is used. The diver is returning to an environment with a lower atmospheric pressure. In such a low pressure environment, the body tissues can hold less nitrogen in solution. Virtually all dive computers support altitude diving. Some switch to altitude mode automatically. Others must be set for the correct altitude by the diver. There is not a lot of research data available for altitude diving and there are some additional concerns, other than just an adapted set of M-values. Most dive computers do not take all of these additional concerns into account.

When diving at altitude, you return to an atmosphere with a lower atmospheric pressure than at sea level. This means that both the oxygen and nitrogen partial pressure are lower than at sea level. Both have consequences, but there is not a lot of research data available. Initially one would imagine that a simple conversion of the M-value would be all that is needed. Rather than using the “normal” M_0-values, you would use a set of more conservative M-values that would allow the diver to return to a lower pressure than the atmospheric pressure at sea level. This is what most dive computers do. Other concerns include the non-acclimatized diver. This is a diver coming from sea level and traveling to a mountain lake to dive there.

The non-acclimatized diver has higher nitrogen saturation before the dive than a diver living at altitude. With respect to saturation, the first dive would already be a “repetitive dive”. Otherwise the diver should wait long enough or he would have to wait before a first dive to de-saturate the nitrogen from sea-level before entering the water. The question is if the dive computer takes this additional nitrogen into account (especially if it is a computer you have to set for altitude yourself). If it does, another question is if the computer would also take into account when you did wait long enough to “de-saturate” your sea-level nitrogen.

The reduced presence of oxygen at altitude brings some concern that circulation is changed. The general idea is that your blood must circulate faster to bring the same amount of oxygen to the body tissues. That increase circulation also alters the saturation and de-saturation of nitrogen. Since there is only limited data from testing, there is no way we can either confirm or deny this theory. It is unlikely that dive computers take this aspect into account.

There are many “rules” for diving at altitude relating to the ascent speed, depth for safety stops, maximum number of dives in a day, the sequence of dives, and so on. Most of these recommendations find their basis in experience. There are also recommendations about the use of Nitrox at altitude, but these are conflicting. Some tell you to stay away from Nitrox at altitude because its use at altitude was never tested. Others *tell you that Nitrox is a good tool to limit the negative effects of altitude diving. How many of these rules and recommendations does your dive computer take into account?*

Nitrogen content in the breathing gas – early dive computers were only suitable for air diving. Later some "special" models came on the market for diving with Nitrox. In today's dive computers, the possibility to set for different Nitrox blends is considered a standard feature of dive computers.

Nitrogen from previous dives – all dive computers have memory of previous dives. As we have seen in other sections, there are different ways of giving credit for a surface interval. No matter which model of dive computer you are using, it is recommended to pause your diving every few days to allow the slow compartments a complete de-saturation. Only limited test data on the subject of multiple dives during multiple days exists. Dive computers are not really designed for multi day/multiple dive profiles.

Flying after diving – the recommendations for flying after diving have changed often. Most dive computers give recommendations for the time you need to wait before taking a plane. The question is if the computer is taking the most recent recommendations into account. Another question is if this function on a computer is really useful. The time of your flight is in most cases already fixed before you make your last dive before that flight. Your computer will only tell you after you have made the dive how many hours it recommend you to wait before flying. For practical reasons, most dive resorts and divers use general guidelines for flying after diving, rather than the feature on the dive computer. What would make sense in a dive computer would be an option to enter your flight time before going diving and that the computer would adapt the "remaining dive time" to your time of departure, but that option does not yet exist.

Traveling to altitude after a dive – for divers there are hardly any recommendations on taking the car to a higher altitude after a dive at sea level. Some would tell you to just follow the recommendations for flying after diving, others just tell to be conservative. Dive computers normally do not have a feature for traveling to altitude after diving.

Injury and illness – injury and illness can alter circulation and have an effect on saturation and de-saturation. It is up to you as a diver to take this factor into account. Tables and dive computers have no way of knowing that you are ill or injured.

Dehydration – a typical problem divers in tropical locations have is that they do not drink enough water. Dehydration is known to have a negative effect on decompression sickness, but goes unnoticed in many cases. Dive tables and dive computers will not notice and will not take dehydration into consideration. It is up to you as the diver to do that. Two good indicators are urine and skin. If your urine is dark in colour, you are dehydrated; if it is transparent (as if it were water) you have been drinking enough water. To see if your skin is hydrated, you can just lift a bit of it on the back of your hand with your thumb and index finger. If the skins elasticity will pull it back immediately, you have been drinking enough water, if the pulled skin moves slowly into its normal position, you are dehydrated.

Age and sex – personal factors such as age and sex are normally not taken into consideration by dive computers. In some cases dive computers allow (or recommend) to change to a different set of M-values based on your age. This is done by setting the computer for altitude mode (or something similar). By changing the M-values, the computer becomes more conservative, giving shorter no-decompression limits. In most cases it does not affect other relevant factors such as ascent protocols.

Workload during a dive – exertion during a dive is known as a contributing factor for decompression sickness. Most dive computers do not take this factor into account. There are some that do. The ones that do are air-integrated computers (not all air integrated computers do this). When the computer senses an increase in air consumption that is not explained by an increase in depth, it assumes that the diver is exerting himself. The computer reacts by giving more conservative values. There are two problems with this feature. A system like this will also react if you offer air to another diver (either for training purposes or because the diver is really out of air), when you fill a lift bag or when you simply have a regulator free-flow. The other problem is that most computers with this feature do not inform you on the display that the computer went in a more conservative mode. If you noticed yourself that you have overexerted yourself and you want to dive more conservatively, you do not know if the computer already reacted or not (if you believe it did, but it did not, you are not conservative at all – if you believe it did not, but it did, and add conservatism yourself, you are double conservative).

Workload before or after a dive – dive computers have no way of taking your workload before or after the dive into account. If you know that you are going to have to exit through heavy surf, or have to climb a cliff after exiting the water, then you need to take the extra risk into consideration yourself.

Diving in cold water – although most computers have a temperature feature, the temperature is not taken into account in the dive calculations. With some it is. Those who do take water temperature into account simply give more conservative no-decompression limits. One problem is defining the temperature that should be considered “cold”. This varies as much with the exposure protection the diver is wearing as with the water temperature. A second problem is the fact that most computers that do have this feature do not inform the diver that they have switched to a more conservative mode.

Diver behaviour – there are some established “rules” in diving with respect to dive profiles. It is recommended to start at the deepest point of a dive and then work your way up. No Yo-Yo profiles. The deepest dive of the day first, etc. These can be summarized under diver behaviour. Some computers take note of certain profiles and react by reducing the no-decompression limits. Others react by indicating on the display that there is a behaviour problem, but leave it to the diver to react in an appropriate manner. Most dive computers do not react at all to diver behaviour problems.

Additional factors – alcohol or drug abuse, obesity, fatigue and so on. There is a long list of factors that are considered to have an influence on the development of decompression sickness. Dive tables and dive computers do not take these factors into account.

When looking at all these factors, it becomes clear that there is no way a dive computer can or will take all of them into account. Not the models existing today and not the models expected in the future. This means that it will always be the diver who – to a certain extent – is the one who needs to take decisions with respect to the safety of a dive and a potential need for more conservatism. This is called computer assisted diving. You take note of the recommendations the computer is giving, but take the final decision on the duration on your dive yourself.

For computer-assisted diving it is not always appropriate when the computer is “punishing” for increased gas consumption, cold water or diver behaviour. The computer does not know what has happened. Did you share your air with another diver? Do you dive in a dry suit or not? Are you an instructor doing emergency ascent training with a group of students? In the end only the diver is informed of all the factors relating to a dive. Only the diver can use this knowledge to take appropriate decisions. If a computer is “punishing” the diver for certain circumstances, at least there should be some indication of that “punishment” on the display of the computer. For divers who do not know or understand the factors increasing the risk of decompression sickness, it is of course good when a computer reacts to as many contributing factors as possible. The non-informed diver will not take any precautions himself.

For the informed and responsible diver it is better to have clear information. Knowledge of what the computer is doing and what it is not doing. This then allows for decisions with knowledge of what the computer has already added on conservatism for a certain condition or situation.

When going from the standpoint that none of the mathematical models used in diving computers has been proven “wrong”, the choice of a dive computer becomes a matter of personal preference. A model that would have been proven “wrong” would disappear from the market in a hurry (recall) to prevent claims for damages. The makes and models of dive computers currently on the market all employ a mathematical model that is validated to some extent and it is your personal choice in which type of model you have most confidence.

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