Original articles

Correction for adiabatic effects in the calculated instantaneous gas consumption of scuba dives

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Abstract

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Introduction: In scuba-diving practice, instantaneous gas consumption is generally calculated from the fall in cylinder pressure without considering the effects of water temperature (heat transfer) and adiabatic processes. We aimed to develop a simple but precise method for calculating the instantaneous gas consumption during a dive.

Methods: With gas thermodynamics and water/gas heat transfer, the instantaneous released gas mass was modelled. In addition, five subjects made an open-water, air, open-circuit scuba dive to 32 metres' sea water. Depth, cylinder pressure and water temperature were recorded with a dive computer and gas consumption was calculated and compared using different methods.

Results: After descent in open-water dives, the calculated gas mass in the cylinder was the same as calculated from cylinder data, suggesting that the model is adequate. Modelled dives showed that adiabatic effects can result in considerable overestimate of the gas consumption, depending on the dive profile, exercise-dependent pulmonary ventilation and the cylinder volume. On descending, gas thermodynamics are predominantly adiabatic, and the adiabatic correction of ventilation is substantial. During the dive, the adiabatic process (at the start 100%) decreases steadily until the end of the dive. Adiabatic phenomena are substantially different between square and saw-tooth profiles. In the emergency situation of a nearly empty cylinder after a square-wave dive involving heavy physical exertion, the adiabatic effect on the cylinder pressure is generally > 20%. Then, with a strongly reduced consumption at the start of the ascent, heat inflow produces an increase of cylinder pressure and so more gas becomes available for an emergency ascent.

Conclusion: Adiabatic effects, being indirectly dependent on exercise, the profile and other conditions, can be substantial. The developed method seems sufficiently accurate for research and possibly for reconstruction of fatalities and is implementable in dive computers.

Key words

Gases; gas supply; universal gas law; thermodynamics; models; ascent; computers – diving

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Introduction

In scuba-diving practice, instantaneous and total dive gas consumption is generally calculated from retrieved cylinder pressures, implicitly assuming isothermal gas thermodynamics in the cylinder. This classical method is correct for the post-dive calculation when at the time of cylinder pressure readings, the temperature of the gas in the cylinder is the same pre- and post-dive. Calculation of instantaneous gas consumption is more complicated. This requires data on the actual temperature in the cylinder; however, this cannot be calculated from the universal gas law ($PV = nRT$) applied to the cylinder gas (V – volume, P – pressure, n – gas mass, R – universal gas constant, T – absolute temperature).

Thermodynamically, there are two extreme conditions: the purely isothermal and the purely adiabatic one. When the cylinder is considered as a system with an infinitely fast heat transfer between cylinder gas and ambient water (T is water temperature) the process of gas release is isothermal; the universal gas law holds and n can be calculated. However, when the cylinder is considered as thermally isolated, the gas temperature T decreases: the process is adiabatic. Now, n and T are unknown. In practice, the problem is more complicated since such pure conditions do not exist. Any pressure drop involves a mixed isothermal/adiabatic process.

Various types of dive computer (DCS) provide some measure of the level of consumption during the dive, but ignore adiabatic pressure and temperature effects. With constant depth, pulmonary ventilation and ambient temperature, the gas in the cylinder always cools down due to adiabatic expansion. Cold stress and work load increase ventilation and, thereby, increase the adiabatic effect. This particularly applies in situations with, for example, strong currents, heavy exercise or emergency stress. The longer the gas release (with some flow) lasts, the greater the drop in temperature; this also applies for depth since gas flow increases with depth. When not considering the effect of cooling due to adiabatic expansion, the calculated consumption can be substantially overestimated.

Points that need to be considered for correct reconstruction of the instantaneous consumption are:

- Cooling of the gas in the cylinder due to adiabatic expansion;
- Heat transfer from the ambient water to the gas in the cylinder that may counteract the adiabatic cooling;
- Heat transfer between gas and water due to a change in water temperature (with depth) resulting in heating or extra cooling of the gas;
- 'Quasi-consumption' when the buoyancy control device (BCD) is inflated.

Since, in the present theoretical design and in actual dives, the gas mass that leaves the cylinder is of interest, corrections to obtain the physiological consumption (especially the quasi-consumption for pressure equalizing the lungs) are omitted. During the actual dives, 'quasi-consumption' can be avoided by preventing the BCD from being inflated with cylinder gas. Taking the first three points into account, it can be shown that the released gas mass can be calculated with a simple computation from three quantities: cylinder pressure, water temperature and depth, provided that the half-time (assuming an exponential mechanism) of the heat transport process is known. We also will show that the three quantities can be obtained with non-expensive but sufficiently accurate equipment. From the release, the instantaneous ventilation, expressed in ambient L·min^{-1} (aL·min^{-1}) at 37°C (the alveolar temperature), can be calculated with the necessary corrections during the descent: BCD-correction, equilibration of the lung, airways, sinuses, mouthpiece and mask.

To evaluate the method of calculation and its usefulness it is applied to both theoretical dives and actual open-sea dives. Attention will be paid to the following model parameters: profile, ambient gas flow (mimicking level of exertion), cylinder volume and water temperature. In summary, the aim of this study, new in diving-related computation and relevant for diving physiology, is to develop a simple, cheap but accurate method to calculate gas consumption at any moment during a dive.

Methods

MODELLING

From the universal gas law $PV = nRT$ and the expression of thermodynamics, $PV^{\gamma} = constant$ where γ is the thermodynamic C_P/C_V ratio, it can be calculated that:

$$P_{a,j} = n_j^{\gamma}.(R/V)^{\gamma}.T_{j-1}^{\gamma}.P_{t,j-1}^{(1-\gamma)} \quad [1]$$

where C_P and C_V are the specific heat at constant pressure and constant volume respectively $(C_P = C_V+R)$, $P_{a,j}$ the j-th cylinder pressure after j-th inspiration (j = 1, 2 …) and adiabatic cooling due to decrease of the cylinder pressure, n_j – gas mass, T_j – measured water temperature and $P_{t,j}$ – measured cylinder pressure. With an exponential approximation of heat transfer to the cylinder gas, it can be calculated that for the j-th time interval Δt it holds that:

$$2^{-\Delta t/h}.P_{t,j-1}(n_j/n_{j-1})^{\gamma} + n_j.(1-2^{-\Delta t/h})RT_jV^{-1} - P_{t,j} = 0 \quad [2]$$

where h is the half time of heat transfer between ambient water and gas in the cylinder (assumed homogeneous temperature). Since Eq. [2] has no analytic solution in n_j, n_j must be solved numerically. From n_j, the instantaneous gas volume flow is known and hence the consumption.

Before presenting the results of actual and simulated dives, the contribution of the adiabatic effect in the mixed process, hence with heat transport, is calculated for model simulations with a constant depth, a constant flow (in ambient units), and a constant water temperature (T) of 300 K (27°C). These outcomes are compared with the isothermal condition used in dive computers (DCs). With a given constant consumption, being Δn mol/Δt, after rewriting Eq. [2], the cylinder pressure can be found with:

$$P_{t,j} = P_{t,j-1}.2^{-\Delta t/h}((n_0 - j\Delta n)/(n_0 - (j-1)\Delta n))^{1.4} + (1 - 2^{-\Delta t/h})RT(n_0 - j\Delta n)V^{-1} \quad [3]$$

with n_0 the gas mass at the start of the dive and h = 80 s (when V = 0.012 m^3). h was estimated from pool experiments (≈ 20°C cylinder/water temperature difference) and was close to a physical model estimate (personal communication, van Grol HJ, 2014). h is slightly dependent on cylinder dimensions and material and on current (swimming against a current). With h = 0, i.e., infinitely fast heat transfer, the process is pure isothermal and, with $h = \infty$, i.e., no heat transfer, the process is pure adiabatic.

The mixed process can be quantified by three variables, the absolute adiabatic pressure effect, (*AP_effect*, bar), the relative adiabatic effect (*A_effect*, %) and the adiabatic fraction (*A_fraction, %*):

$$AP\_effect = P_{iso} - P_{mixed} \quad [4a]$$

(subscript iso means isothermal)

From a practical point of view, the evolution of *AP_effect* is the most relevant adiabatic phenomenon since it is a measure of the 'extra' pressure that becomes available when the gas is warmed to the ambient temperature:

$$A\_effect = 100(P_{iso} - P_{mixed})/P_{iso} = 100(T_{iso} - T_{mixed})/T_{iso} \quad [4b]$$

This equality directly follows by applying the universal gas law. *A_effect* gives the relative decrease of pressure and temperature relative to the isothermal pressure and temperature:

$$A\_fraction = 100(P_{iso} - P_{mixed})/(P_{iso} - P_{adia}) \quad [4c]$$

(subscript adia means adiabatic)

By applying the gas law, the consumption per minute (Eq. [2] and [3] use Δt, here 4 s) of the actual dives was calculated with $\tilde{V}$ = 387 (n_{j-1} - n_j)/(0.1 depth +1) aL·min^{-1} (body temperature, depth in msw). Since air and nitrox have the same C_P/C_V

ratio (γ = 1.4) and the same thermal conductivity, all results also apply to nitrox. This does not hold for helium mixtures since decompression of helium gives adiabatic heating above 51 K (the Joules-Thomson effect), not cooling. Consequently, the adiabatic effects of helium and nitrogen (or oxygen) counteract each other. Therefore, adiabatic phenomena in cylinders containing heliox or trimix do not need to be considered.

OPEN-WATER DIVES

Five, fit subjects volunteered to make a single, recreational, no-decompression, air scuba dive. Ethical approval was not required by the Medical Ethical Committee of the University of Amsterdam (Project W15_204, Decision #15.0262). However, all subjects provided informed consent. The intended profile characteristics and the conditions were: descent rate 20 m·min^{-1}, maximal diving depth (MDD) 30 meters' sea water (msw) for 2 min, with a gradual saw-tooth ascent over 40 min; 12-L aluminium cylinders, wetsuits and the same UWATEC *Galileo Luna* DC. Depth (resolution 0.01 msw; error at most -0.3 msw), cylinder pressure P_t (resolution 0.25 bar), and water temperature T_j (resolution 0.4°C, error at most -0.4°C) were retrieved from the Galileo with sample intervals (Δt) of 4 s. The subjects were accompanied by an experienced buddy.

Before starting the descent, the cylinders were temperature equilibrated with the ambient water temperature for 8 min. At MDD, the BCD, not used until then, was orally inflated by the buddy. After leaving MDD, the subject buddy-breathed for about 7 min to equilibrate the temperature of his/her cylinder (eliminating the effect of adiabatic cooling), in order to validate the model calculation of the consumption at the instant of leaving MDD. During the remainder of the dive, subjects breathed from their own cylinder.

In the open sea, temperate (summer) and tropical water temperature generally decreases with depth. The half time of the Galileo temperature sensor appeared too large (ca. 40 s with a swimming speed of 1200 m.h^{-1}) to obtain precise recordings of the changing water temperature during the descent in order to validate the method. Since the ascent was so slow (1–2 msw·min^{-1}), the temperature recorded was considered to be water temperature. These logged temperatures (as a function of depth) were also used for the depth-temperature relation during the descent.

Results

MODELLING

As a reference, a ventilation flow rate of 17 aL·min^{-1} was used (see Results, open-sea dives). With an isothermal process ($h = \infty$), a constant depth, constant gas flow and constant ambient temperature during the whole simulation, P_t diminishes linearly with time (ignoring the small effect of the breathing cycle). P_t is proportional to the level of gas flow and to ambient absolute pressure.

Figure 1

Evolution of adiabatic effect. Adiabatic effect (reverse-plotted at left axis) and pure isothermal cylinder pressures (right axis). The upper stippled straight line presents the isothermal cylinder pressure P_t (right axis) at a depth of 1 msw and a flow rate of 17 aL·min^{-1}. The lower stippled straight line is for 34 msw depth with 42.5 aL·min^{-1}. The upper and lower solid curves show the difference in cylinder pressure between the mixed and the isothermal process relative to the isothermal pressure (left axis, in %; same depths and flow rates); cylinder volume 12-L

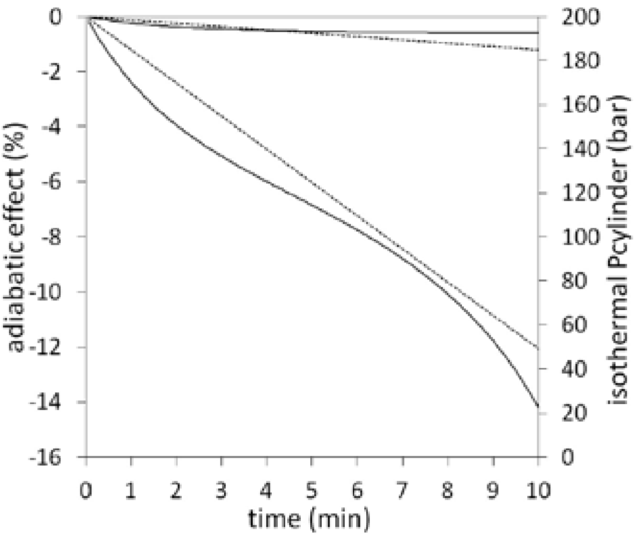
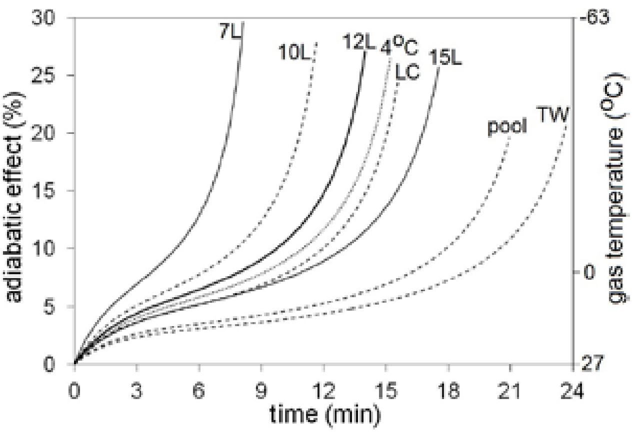


Figure 1 (P_t at right axis; stippled curves), illustrates this for 1 msw with 17 aL·min^{-1} and for 34 msw with 42.5 aL·min^{-1} (ratio of absolute pressures = 4 and ratio of ambient flows = 2.5). With any adiabatic release, the P_t always diminishes faster than with a pure isothermal process. The solid curves shown in Figure 1a (left axis) give *A_effect* for the two depths. The upper solid curve (1 msw, 17 aL·min^{-1}) indicates that for this low release the adiabatic cooling is nearly compensated for by heat inflow from the surrounding water. The lower solid curve indicates (with the 10x faster gas release) that *A_effect* cannot be ignored. Yet, between 5 and 10 min heat inflow dominates; *A_fraction* ≈ 35%. At 5 min with isothermia, the pressure left is 125 bars, whereas in the mixed case it is 8.5 bars lower. Here, *AP_effect* becomes smaller after 6 min, but *A_effect* is still increasing (from 6.5% at 5 min to 13.5% at 10 min).

Figure 2 shows the influence of cylinder volume, water temperature, depth and consumption on *A_effect* (left axis) under constant conditions (mimicking a square-wave dive with descent and infinitely fast ascent). The adiabatic cooling (right axis) is presented for a water temperature of 27°C. At the moment that a cylinder pressure of 50 bar is reached, the effect is about 9% and > 20% with an 'out of air' situation (10 bar reached; the top end of the curves). Even in shallow

Figure 2

Adiabatic effect as function of time with various cylinder volumes, water temperatures and exertion levels. 7-L, 10-L, 12-L and 15-L cylinder volume with 34 aL·min^{-1} at 34 msw and 27^{O}C; 4^{O}C – the same for 12-L cylinder but 4^{O}C water temperature; LC – low consumption (26 aL·min^{-1}), 34 msw, 27^{O}C; TW – temperate water 13^{O}C, 10-L cylinder, 26 aL·min^{-1}, 20 msw; Pool – 27^{O}C, 51 aL·min^{-1}, 3.8 mfw. N.B. All dashed curves are for 10-L cylinder. Right axis gives the cylinder gas temperature for the curves with 27^{O}C water temperature



water, high gas consumptions give a similar effect as with an ordinary dive (20 msw, 25 aL·min^{-1}) in temperate water (compare 'pool' and 'TW' curves).

Figure 3 presents *A_effect* for the four combinations of 17 and 42.5 aL·min^{-1} and 1 and 34 msw. At 1 msw, irrespective of the consumption level (curve 1 and curve 3) and with 17 aL·min^{-1} at 34 msw (curve 2) *A_effect* is almost irrelevant. With 42.5 aL·min^{-1} at 1 msw, after 10 min *A_effect* is only about 3% lower than the isothermal pressure (curve 3). However, at 34 msw a 15% difference is seen (curve 4) and during 10 min *A_fraction* changed from 100 to 33%.

The simulation of curve 5 is basically the same as for curve 4, but periods of 30 s at a ventilation rate of 72 aL·min^{-1} were inserted at 2 and 6 min. The second 30-s period gives a large, long-lasting adiabatic effect that can only be counteracted by a very low gas consumption. After t = 10 min, with a consumption of 10.6 aL·min^{-1} (swimming speed nearly zero[1]), the temperature increases quickly because heat inflow overwhelms the ongoing but small adiabatic cooling effect.

The above examples respect constant-consumption simulations. The next one shows a calculated simulated dive to 34 msw with descent and ascent included for a pure adiabatic, pure isothermal and a mixed process (Figure 4). After t = 5 min, the consumption changes from 17 to 42.5 aL·min^{-1}, resulting in a larger difference between the adiabatic and isothermal pressures and a sudden large increase in *AP_effect* (thick dashed curve). During the descent, the thermodynamics of the gas is predominantly

Figure 3

Evolution of the adiabatic effect (left axis) and absolute cylinder gas temperature (right axis). Curves: #1 1 msw / 17aL·min^{-1}; #2 34 msw / 17 aL·min^{-1}; #3 1 msw / 42.5 aL·min^{-1}; #4 34 msw / 42.5 aL·min^{-1}; #5 as #4 but two 30 s periods of 72 aL·min^{-1} and after t = 8 min 10.6 aL·min^{-1}; #6 as #4 but h = 20 s; for further explanation see main text

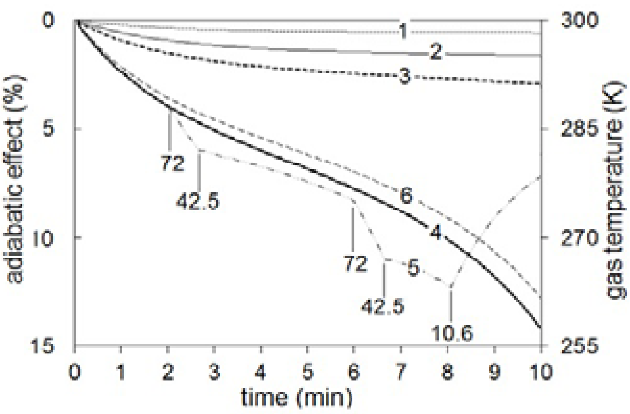
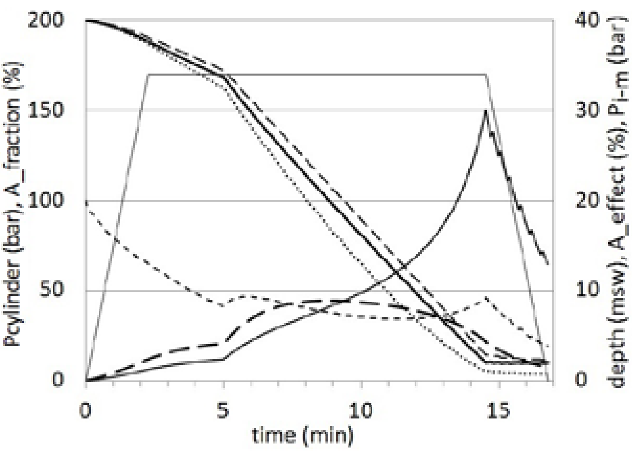


Figure 4

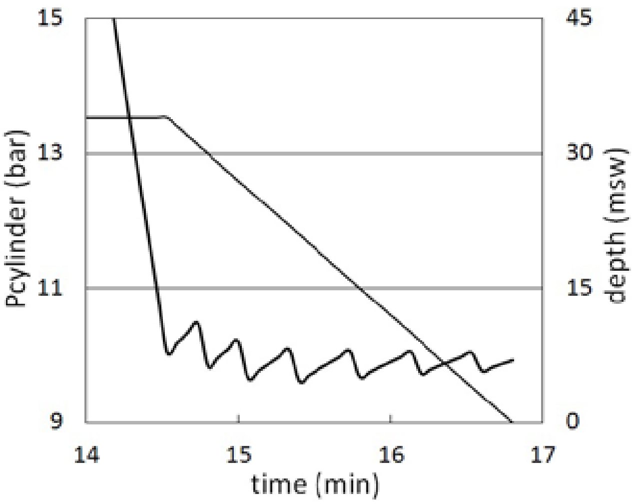
Model simulation starting with 17 aL·min^{-1} and, after 5 min, 42.5 aL·min^{-1} (water temperature 300 K, 12-L cylinder, 15 msw·min^{-1} descent and ascent speed, maximum depth 34 msw). Thin straight solid line, square profile (right axis); dashed curve, pure isothermal cylinder pressure (left axis); thick solid curve, cylinder pressure mixed process; stippled curve, pure adiabatic cylinder pressure, thin curve *A_effect* (right axis), thin stippled curve *A_fraction* (left axis), thick dashed line *AP_effect* (indicated by $P_{i\text{-}m}$)



adiabatic (*A_fraction* 100–65%). At the end of this dive, the isothermal and adiabatic components are nearly the same (Figure 4). In a cylinder pressure-versus-time diagram (as in Figure 4), this is apparent by comparing the isothermal, the adiabatic and the mixed-pressure curves with each other. The latter curve always lies in-between the two former curves. At the start, the mixed and adiabatic curves coincide (theoretically); during the dive the mixed curve creeps towards the isothermal one. During the ascent from square-wave dives and after leaving the MDD of a 'saw-tooth' dive, the

Figure 5

Cylinder pressure during the ascent from 34 msw; at t = 14.5 min, the blocking pressure of the first stage (10 bar) is reached and the emergency ascent starts; for further explanation see text



A_effect diminishes, unless the cylinder pressure approaches 10 bar, then, *A_fraction* (Figure 4) rises. *AP_effect* shows a flat maximum somewhere near the middle of the dive.

At 14.5 min total diving time, P_t = 10 bar, assumed to be the first-stage blocking pressure. However, theoretically it is possible to ascend by taking (sucking) breaths with well-controlled, long, slow expirations. The extra breathable air is provided by the temperature increase in the cylinder due to heat inflow from the surrounding water. Consequently the first-stage pressure supply becomes > 10 bar during the interval between inspirations. This additional air is proportional to the first-stage blocking pressure. In practice, the availability of spare gas is more complicated. For instance, the flow through the first stage is not a yes/no situation; the blocking pressure may decrease with ambient pressure and a rise in water temperature increases the warming up of the cylinder. Altogether, this may add a few minutes breathing time before complete 'shut off' of the air supply. This could represent the difference between surviving and drowning. In such an emergency situation, Figure 5 illustrates how from a depth of 34 msw theoretically one can make a controlled emergency ascent (ignoring stops).

OPEN-WATER DIVES

The dives (visibility ca. 35 m, negligible current, surface temperature 26.8–27.6°C, descent 23 m·min^{-1}, MDD 31–37 msw, temperature at MDD 22.5–25.6°C) were of low exertion, with an almost passive descent and, after leaving MDD, gas consumption was 17 aL·min^{-1} (≈ 2.5 METS; ≈ 9 mL O_2·kg^{-1}). Table 1 gives the modelled consumed gas mass (in mol) just before leaving MDD and the consumption calculated with the gas law on the basis of measured cylinder pressure and gas temperature (assumed to be the same as the water temperature) at the end of the buddy-breathing period. The difference is small (0.16%) and insignificant (paired Student's t-test, P = 0.25). If the release is assumed to be isothermal, then there is an overestimate of gas consumption. For the five dives this was on average 4.4 aL·min^{-1} during the descent (Table 1), about a quarter of the reference consumption of 17 aL·min^{-1}. At MDD the overestimate was about the same but after leaving MDD it slowly diminishes. At MDD the process was still predominantly adiabatic (*A_fraction* 80–90%).

Two dives performed in a pool at 4 metres' fresh water depth and with swimming speed of about 33 m·min^{-1}, the cylinder was emptied. The final adiabatic cooling was 60°C and *A_fraction*, initially falling, then increased to 31% by the end of the dive. After warming of the cylinder, the extra air supply was in accordance with the calculated amount, illustrating the above-mentioned principle of Figure 3.

Discussion

Adiabatic cooling of the gas in a diving cylinder during a dive results in an underestimate of the remaining gas supply. Adiabatic effects are not considered in commercially available dive computers. For a precise estimate of gas consumption during a dive, adiabatic effects on the cylinder gas should be taken into account as shown by modelling the adiabatic behaviour and by validating the model with actual dives. The adiabatic behaviour is complicated and

Table 1

Calculated and measured gas masses used for the descent and 2-min bottom stay of the five dives and overestimate of consumption during descent related to isothermal process

Dive	Modelled gas mass (mol)	'Measured' gas mass (mol)	Isothermal over-estimate consumption (aL·min^{-1})
D1	94.90	94.40	4.8
D2	89.89	89.69	3.4
D3	81.37	81.26	3.7
D4	88.16	88.20	6.0
D5	96.53	96.61	4.1
Mean (SD)	90.17 (6.01)	90.03 (5.97)	4.4 (0.9)

dependent on many parameters. Therefore, in some respects the modelling described has several weak points.

STUDY WEAKNESSES AND STRENGTHS

The derivation of Eq. [2] and applicability of a dive computer (Galileo) fulfils the aim of the study. The usefulness of Eq. [2] was established by the negligible difference in the modelled gas mass and the directly calculated gas mass after leaving MDD. A 50% increase of half time *h* resulted in an almost ten times larger deviation, indicating that the value of *h* used for 12-L aluminium cylinders filled with air (or nitrox) is realistic. However, a small error in *h* is acceptable (Figure 3, curve 6).

Part of the modelling was performed assuming a gas consumption of 42.5 aL·min^{-1} at 34 msw with bouts of 72 aL·min^{-1}. The question arises whether this is realistic. Taking 180 aL·min^{-1} at atmospheric pressure as the 15 s maximal voluntary ventilation (MVV15), $MVV15_{34msw} = 180p^{-0.4} = 96$ aL·min^{-1}; (where p is absolute pressure (bar)).[2] This is a conservative estimate; after a 9-min, 200-watt load at 36 msw an MVV15 of 160 aL·min^{-1} has been reported.[3] The sustained MVV was not given, but one should need about 38 aL·min^{-1} (extrapolated from sustained MVV exercise data). At sea level in air, the sustained MVV (> 4 min) is between 60 and 90% of MVV15.[4–6] We conclude that the consumption of 42.5 aL·min^{-1} is about 65% of $MVV15_{34msw}$ and allows heavy work; swimming speed 27 m.min^{-1} (calculated from ref. 7, ventilation/$\dot{V}O_2$ conversion factor 25; body mass 70 kg; close to thermal equilibrium).[7] The above shows that the chosen gas consumption rates are realistic assuming a diver's high level of fitness ($\dot{V}O_{2max} > 40$ mL.kg^{-1}.min^{-1}). With cold stress (TW dive of Figure 2), which requires some 8 aL·min^{-1} extra (calculated from ref. 8), 25 aL·min^{-1} is needed,[8] whereas the swimming speed is subjectively very low (approximately 10 m.min^{-1}).

A disputable point is the practical value of the 'extra adiabatic' spare gas in an 'out-of-air' situation. Only specific training in breathing control under safe conditions (deep pool, etc.) would increase the chances of survival.

By implementing the method in dive computers, a realistic estimate of the instantaneous gas consumption can be obtained during a dive. For a precise correction during the descent, the water temperature sensor-technology should preferably have a half time < 10 s. An initially non-equilibrated cylinder gives an error in the consumption (about $100\Delta T/T_{water}$% with ΔT water-cylinder temperature difference) that fades away with the half time *h*. In practice, this is a minor drawback. Another inaccuracy, the gas needed to equalize the lung, etc., and to inflate the BCD, can be corrected for with a simple algorithm (by using biometric data and suit thickness). Another algorithm can adjust *h* for cylinder size and material, and the consumption level (via a feedback). Summarising, a high quality DC with the above features is an adequate device to perform the adiabatic correction.

DEPENDENCY ON CONDITIONS AND APPLICATION

The evolution of *A_effect* and *A_fraction* is complicated since they are strongly dependent on depth and the diver's gas consumption (level of exercise; compare 10L with LC curve in Figure 2). Therefore, general 'rules' can hardly be given. Increasing cylinder volume decreases A_effect substantially (Figure 2). High versus low water temperature (compare 12-L with 4^{O}C curve in Figure 2) and changes in water temperature during the dive are of minor importance. All the curves of Figure 2 have similar shapes. They coincide well after axis transformation in both directions. However, the major phenomenon is the decrease of *A_ratio* and increase of *A_effect* up to a cylinder pressure of some tens of a bar. For lower pressures, the effect may reverse. Generally, *AP_effect* has a flat maximum at 5–10 bar somewhere near the middle of the dive.

The descent is the most prominent part of the dive with respect to the adiabatic correction that can amount to more than 5 aL·min^{-1}. The increase in depth is the major cause. With a saw-tooth profile (the open-sea dives) the correction becomes progressively less important after leaving MDD. Finally it diminishes to some percent of the gas supply of the cylinder just before surfacing. These results for saw-tooth-like profiles strongly contrast with those of square profiles where adiabatic cooling at the start of the ascent can be many tens of degrees. However, the adiabatic effect diminishes less with a low swimming speed since *h* increases with decreasing swimming speed, resulting in stronger adiabatic behaviour.

In diving history, especially recreational diving, fatalities are not always well explained. Even nowadays, divers descend in two minutes to some 50 m depth on air. Sometimes a fatality happens shortly after the descent. Consumption calculations during the descent, that generally have large overestimates when not corrected, can shed light on the cause of the fatality (e.g., hypercapnia). In other cases there may have been a high consumption at great depths in combination with a low water temperature. Then, the low gas temperature resulting from adiabatic cooling might have caused blockage of the regulator (plastic components) due to freezing, resulting in the calamity. (With 4^{O}C water temperature, 34 aL·min^{-1} and 12-L cylinder, within 72 s the gas temperature cools to -2^{O}C (Figure 2). For such dives, the adiabatic correction after DC data retrieval gives a better reconstruction of actual gas consumption. However, in general, the adiabatic correction has a limited value for forensic aims or accident reconstruction. In cardiorespiratory physiological research the actual gas consumption gives a more complete view of the physiology during the dive.

Conclusions and recommendations

In this study, model parameters were validated by means of pressure measurements during actual dives. The theoretical analyses show that even with moderate gas flows, the adiabatic correction is relevant when aiming to closely follow the evolution of the gas content of a cylinder. This holds especially for the descent and for deep, square-wave dives (> 30 msw). Moreover, the model shows that decreasing cylinder volume and increasing the gas flows strongly increases the adiabatic effect. Both the modelled and actual dives with a saw-tooth profile indicate that, with low exertion, the adiabatic effect is restricted to about 4% near the end of the dive. Square-wave dives give the largest effect; at the moment that a cylinder pressure of 50 bar is reached, the effect is about 9% and with 'out of air' > 20%. After high pulmonary ventilation, 'out of air' means there is still some reserve that enables the diver to reach the surface, due to the substantial adiabatic effect that has cooled the gas in the cylinder. It is recommended that managing an 'out of air' situation is a subject in diving education.

The developed method seems sufficiently accurate for research and for specific cases of fatality reconstruction and is implementable in DCs. Unfortunately in practice, accuracy does not hold for temperature recording by DCs due to the long half time of the sensor technology and its strong dependency on current (swimming speed). In contrast, cylinder pressure is measured accurately and without delay. However, due to the adiabatic effect it does not allow an accurate extrapolation to the remaining gas supply. As a result, it gives an underestimate of the remaining bottom time, a quantity provided by some modern DCs. The 'extra' gas with an out-of-air, heavy exertion deep dive can be considered as a beneficial side effect of a DC that actually fails to correct for the adiabatic effect. The adiabatic effect can be minimized for cold water diving by an optimal choice of cylinder size; for most recreational diving, a 12-L aluminium cylinder is suitable. The cylinder should be mounted as freely as possible in the BCD to facilitate heat inflow.

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