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Exposure Index for Pulmonary Oxygen Toxicity in Surface-Oriented Diving

DMAC 35 Rev. 1 – February 2025

Supersedes DMAC 35, which is now withdrawn

Revision before February 2030

The practical implementation of this guidance note is presented in Appendix III. The body of this document contains the background, but Appendix III can be read independently.

Version History

Date	Reason	Revision
February 2025	Revised maximum exposure levels including revised allowance for multi-day diving. Inclusion of chapter describing limitations and caveats. Added executive summary for operational use (Appendix III). Editorial changes and reorganisation of text.	Rev. 1
June 2023		Initial publication

1 Introduction and Scope

Divers will normally breathe hyperoxic gas mixtures during diving. Hyperoxia is known to have a toxic effect on several organs (1). The most significant effects are those on the lungs and CNS.

Van Ooij and coworkers have published a comprehensive review of pulmonary oxygen toxicity (POT) in diving (2). Symptoms present as tracheobronchitis with cough, chest pain and dyspnea. However, these subjective symptoms are difficult to identify in the early phase. Measurements of vital capacity (VC) reduction have traditionally been used to assess POT, though many other lung function parameters have been investigated. However, none of these has yet proven superior to vital capacity (VC) measurements when sensitivity, specificity, coefficient of variation and resource constraints are considered (2). There is a large variation in sensitivity to pulmonary oxygen toxicity. No index can do better than predicting the mean or median expected effect of hyperoxia. Within a group exposed to hyperoxia, there will be individuals with minimal as well as profound pulmonary toxicity of the very same hyperoxic dose.

It should be recognised that the pulmonary effects of diving are imposed by other mechanisms in addition to hyperoxia. Increased breathing gas density affecting breathing resistance, immersion with redistribution of blood, and venous gas embolism ultimately affecting pulmonary endothelium are some of the mechanisms recognised to cause short-term and long-term effects on pulmonary function. The precise interaction between these mechanisms remains largely unknown. Most studies on POT have been completed in the dry environment of pressure chambers, not accounting for other effects of immersed diving.

The scope of this document is to provide guidance on the proper monitoring of hyperoxic *exposure*. The objective is to minimise pulmonary oxygen toxicity (POT) in *surface-oriented occupational diving*. The principles should be equally applicable for military and recreational diving, as well as for hyperbaric oxygen therapy, but guidance for these applications is outside the DMAC scope. The procedures and threshold limits should not be applied for saturation diving. The document will not review the *monitoring* of the pulmonary function of divers. The reader is advised to search other sources for the discussion of acute CNS toxicity.

2 Oxygen Exposure Indices

2.1 Unit Pulmonary Toxic Dose (UPTD)

In 1970 Bardin and Lambertsen (3) presented the now well-known formula (Equation 1) for the calculation of the Unit Pulmonary Toxic Dose (UPTD) as a measure of oxygen exposure. The index was based on the seminal thesis of Clark and Lambertsen (4) published the same year in which the authors demonstrated how hyperoxia would affect pulmonary vital capacity (VC). UPTD is calculated per Equation 1 below.

$$UPTD = t \times \sqrt[-1.2]{\frac{0.5}{pO_2 - 0.5}}$$

Equation 1 Pulmonary hyperoxic exposure measure (UPTD) as proposed by Bardin and Lambertsen (3). pO_2 in breathing gas in Atm. t: Exposure time in min.

A 2% reduction in VC can be expected after an exposure of 615 UPTDs, while 1425 UPTDs would be expected to cause a median reduction of 10% in VC. The UPTD-term was later largely replaced by OTU – Oxygen Toxicity Unit – to recognise extrapulmonary hyperoxic effects, but OTU would be calculated identically to UPTD. Exposure limits for POT were published by Hamilton et al. in 1988 in the Repex report (5). They suggested that 850 UPTD would be an acceptable limit for one day of exposure, while additional days of diving would require a gradual reduction in daily exposure. Multiday exposure exceeding ten days should limit daily exposure to 300 UPTD per day. The scientific basis for these recommendations was limited, and they were mainly based on "expert opinion".

2.2 Validity and Limitations of the UPTD Concept

The UPTD concept has survived for more than 50 years – replacing it would thus require valid reasons. The UPTD index is not an accurate predictor of POT after short-lasting (<5h) exposures exceeding 1 Atm (6). This is the most relevant exposure time for surface-oriented diving. The UPTD index is not related to a recovery function. Due to this, the UPTD index can't be used directly to calculate the surface interval needed to allow sufficient recovery before the next hyperoxic exposure. Hamilton et al. (5) have, as mentioned earlier, suggested UPTD exposure limits for multiday diving, but these limits have not been scientifically validated.

2.3 Equivalent Surface Oxygen Time (ESOT)

Arieli and coworkers proposed a new toxicity index (Arieli K) (7) that predicted development of POT with better accuracy than the UPTD/OTU (6). However, calculation of the Arieli K index is computationally demanding and for this reason Risberg et al. (8) introduced an alternative index: The Equivalent Surface Oxygen Time (ESOT, Equation 2).

$$ESOT = t \times pO_2^{\,2.285}$$

Equation 2 Equivalent Surface Oxygen Time (ESOT) as a function of time (min) and pO_2 in Atm.

A study of Risberg et al. (9) demonstrated that the Arieli K model (7) would not accurately predict *recovery* after POT. The authors recommended an alternative, ESOT-based model (Equation 5) as detailed in Appendix II.

We recommend using the ESOT index when monitoring and charting hyperoxic exposure in surface-oriented diving.

2.4 Hyperoxic Exposure Level in Surface-oriented Diving

Single nitrox dives (surface-oriented diving) and repetitive air dives will generally have a low level of pulmonary oxygen toxicity whether toxicity is expressed as UPTDs or ESOT (Table 1). Recognised decompression tables used in commercial surface-oriented diving will limit oxygen exposure well below the stipulated UPTD and ESOT limits with a possible caveat for multiday diving. The need for assessment of POT in surface-oriented diving is evident when multi-day exposure to nitrox diving, in-water oxygen decompression, closed bell transfer under pressure (TUP) or surface decompression with oxygen ($SurDO_2$) diving techniques are employed.

Table 1 lists the maximum UPTD a diver may acquire during a single dive with either air or Nitrox (pO_2=1.4 Atm) as the breathing gas, decompressing according to US Navy Diving Manual Rev 7A (10). The oxygen exposure will depend on whether the decompression takes place as in-water air-breathing or $SurDO_2$. As can be seen, the hyperoxic load will be minimal with HSE bottom time restrictions and air as the breathing gas. For single dives, no HSE-approved exposure will exceed 615 UPTD.

Multiday diving with nitrox as a breathing gas may exceed the recommended Repex exposure limit, though dependent on the breathing gas, decompression method and number of days of consecutive diving (Table 1). There is no restriction on the number of consecutive days of diving if air is breathed during the dive if the HSE bottom time limitations (11) and Repex recommendations (5) are applied. If nitrox with pO_2=1.4 Atm is breathed in the bottom phase, a break should be put in place after four days of consecutive diving depending on whether decompression was based on in-water air decompression or $SurDO_2$.

	DC: IW air BG: Air	DC: IW Nitrox BG: Nitrox	DC: $SurDO_2$ BG: Air	DC: $SurDO_2$ BG: Nitrox	DC: TUP or IW Air/O_2 BG: Air	DC: IW TUP Air/O_2 BG: Nitrox
Profile (msw/min)	27/60	12/240	15/180	12/240	24/180	24/180
UPTD	36	463	143	476	312	517
# consecutive diving days UPTD/Repex	>10	4	>10	4	10*	4
ESOT	33	582	344	719	436	739
# consecutive diving days ESOT	No limit	1	7	Not recommended	7	Not recommended

*Table 1 Maximum oxygen exposure expressed in Unit Pulmonary Toxic Dose (UPTD) and ESOT for in-water decompression (IW), Surface Decompression with Oxygen ($SurDO_2$) and Transfer Under Pressure (TUP) profiles according to USN Diving Manual Rev 7A (see text). Profiles with the largest UPTD tabulated with maximum depth and bottom time. Bottom times for the various combinations are restricted according to HSE regulations. DC: Decompression mode. BG: Breathing gas bottom phase. Nitrox presumed to be open circuit and adjusted to give pO_2=1.4 Atm in the bottom phase (Nitrox 63 for 12 msw schedule, Nitrox 41 for the 24 msw schedule). Exposures exceeding recommended limits for single and multiday diving are indicated by light and dark colours, respectively. The maximum number of consecutive diving days recommended according to the Repex procedure (5) is shown in row "# consecutive diving days UPTD/Repex". The maximum number of consecutive days recommended per ESOT dose is shown in the bottom row. *Number of consecutive diving days based on UPTD=310. The above depth-bottom time combinations are "worst case" scenarios. For other combinations, the results will be different.*

2.5 The Benefits of Replacing UPTD with ESOT

ESOT will predict the development of POT with better accuracy than the traditional UPTD/OTU index (6, 8). While the Arieli K toxicity index (7) will predict POT development identical to ESOT (8), the Arieli K index is impractical for use in operational diving. ESOT is a mathematical transformation of Arieli K that allows a simpler calculation of hyperoxic exposure than Arieli K and is more intuitive for the user. ESOT=1 is the hyperoxic exposure reached after 1 min of breathing 100% O_2 (FiO_2=100%) at surface pressure. ESOT is, in this respect, comparable to UPTD. In a multi-pO_2 segmented dive, the ESOT from each segment can simply be summed up to reach the total hyperoxic exposure for the dive. The main benefit of replacing UPTD with ESOT is a more accurate estimate of POT for such exposures. The estimation of POT recovery is better validated in the ESOT model than in the Arieli K and Repex model(9).

We recognise that UPTD has been accepted as a de-facto standard for hyperoxic exposure in the past. The fact that UPTD is used extensively should not by itself be a reason for continuous use when scientific evidence strongly supports that ESOT will predict POT more accurately for most exposures and recovery periods.

3 Recommended Maximum Exposure Levels

Arieli (12) suggested a maximum exposure of K=250 (ESOT=949). Though this would be expected to limit median VC reduction to 2%, it would probably cause POT symptoms and significant spirometric changes in a high proportion of working divers. Based on the arguments of Risberg et al. (9) we suggest a maximum exposure level of ESOT=660 for single exposures. Two days off diving should be allowed after exposures ranging ESOT 501-660. We recommend a maximum of five consecutive days of diving, followed by two days off if the daily (24 h) exposure level is between ESOT=451 and 500. The daily exposure may reach ESOT=450 if two days off diving are allowed after seven consecutive days of diving. Intermittent breathing of compressed air ("air break") during hyperoxic exposure has been shown to delay the development of POT. A minimum 12 h inter-day (overnight) normoxic interval should take place for multiday exposures. POT recovery will occur faster if the diver is resting during the hyperoxic exposure. It is thus acceptable to relax these limits when resting divers breathing hyperoxic gas with intermittent air breaks. There is a paucity of studies on POT after successive multiday surface-oriented dives, particularly with short exposures to pO_2<1.3 Atm. It may be acceptable to allow more than seven successive days of diving for such exposures, but the advice of a diving physician should be sought in each case.

As long as HSE bottom time restrictions are adhered to, there is no need to calculate ESOT for air dives with in-water decompression. Such dives are not expected to cause any relevant POT. Air in-water decompression dives can even be done on the two days prescribed "off diving".

The POT of a dive will be affected by previous hyperoxic exposures. Appendices I and II explain how ESOT should be calculated for repetitive exposures. While a high residual ESOT after a previous dive is expected to reflect a clinically significant POT, it is questionable whether a low residual ESOT after a long surface interval will have a relevant additive or synergistic effect on later exposures. Table 2 summarises hyperoxic threshold values. Surface intervals shorter than listed in the Table 2 should call for calculation of residual ESOT as explained in Appendix I and II. Any surface interval longer than 12 h will "zero" the "ESOT clock".

Maximum number of successive days of diving	Daily maximum ESOT	Minimum inter-day recovery time (h)
1	660	48
5	500	12
7	450	12
>7	To be assessed by a diving medical advisor	

*Table 2 Hyperoxic exposure limits for commercial surface-oriented diving adhering to HSE bottom time limitations. The maximum number of successive diving days and minimum surface interval for repetitive exposures depending on maximum ESOT achieved on any day in the dive series. Shorter surface intervals are allowed but will require the calculation of residual ESOT as explained in Appendix I and II. "Daily" should be interpreted as a 24 h period. These limits are **not** applicable for hyperbaric oxygen (HBO) treatment.*

Subject to HSE bottom time limitations, the practical consequences of this guidance would mainly be limitations on the number of successive nitrox $SurDO_2$ and nitrox TUP dives (Table 1). If more than five consecutive days of nitrox diving with in-water decompression are planned, some limitations will apply if pO_2 exceeds 1.3 Atm *and* bottom time exceeds 180 min. Inert gas load (repetitive group designator) rather than hyperoxic exposure will tend to restrict bottom time for a repetitive dive following a dive with high hyperoxic exposure. Open-circuit nitrox diving adhering to HSE bottom time limitations will only be a concern with a F_iO_2>>40% – irrespective of decompression mode. These guidelines will not restrict the number of consecutive days of air dives with staged in-water decompression. The guideline should be considered by occupational divers using rebreathers (e.g. scientific divers), but dives planned by technical recreational divers and military divers using rebreathers with high F_iO_2 or fixed pO_2 are beyond the scope of this document. The recommended hyperoxic occupational exposure limits are not intended for use in relation to hyperbaric oxygen (HBO) treatment since such treatment takes place with resting, non-immersed patients breathing hyperoxic gas intermittently.

4 Limitations and Caveats

This document is intended for general guidance. It should be recognised that there is a large individual susceptibility to POT. Some persons will tolerate high pO_2 for a long time with minimal pulmonary toxicity while others may suffer pulmonary symptoms even after short exposures. The diving supervisor should contact the diving medical advisor if divers report respiratory symptoms – even if the exposure limits are respected. The exposure limits should be respected when no other advice is available. However, they are not intended to prohibit adjustment based on specific risk assessment supported by qualified diving medical advice. Such adjustments could be considered for multiday exposures, dives with shorter overnight interval than 12 h and in particular dives with intermittent hyperoxic exposure (SurDO_2 and O_2 breathing with air breaks). Such exceptions should be assessed on an individual basis.

5 Conclusion

We advise that the ESOT replace UPTD as an exposure measure for POT in surface-oriented diving. Exposure limits presented in Table 2 should replace the historical "Repex" limits(5). Diving should be planned to keep ESOT lower than 660 for any single dive. For multiday diving, daily exposure should be limited to ESOT=500 and 450 for a maximum of five and seven consecutive days of diving, respectively. A twelve-hour overnight normoxic interval should be planned for multiday exposures. Two days off diving should be planned for after multiday hyperoxic exposures. Air in-water decompression dives are not expected to cause POT and can take place even on the two days "off diving". These limits should only be relaxed if a risk assessment, reviewed by a competent diving physician, has concluded that the exposures will not increase the likelihood or extent of POT.

6 References

1. Clark JM, Thom SR. Oxygen under pressure. In: Brubakk AO, Neuman TS, editors. Bennett and Elliott's Physiology and Medicine of Diving. 5th ed: Saunders; 2003. p. 358-418.
2. van Ooij P-JAM, Sterk PJ, van Hulst RA. Oxygen, the lung and the diver: friends and foes? European Respiratory Review. 2016;25(142):496-505.
3. Bardin H, Lambertsen CJ. A quantitative Method for Calculating Cumulative Pulmonary Oxygen Toxicity. Use of the Unit Pulmonary Toxic Dose (UPTD). University of Pennsylvania, Institute for Environmental Medicine; 1970.
4. Clark JM, Lambertsen CJ. Pulmonary oxygen tolerance in man and derivation of pulmonary oxygen tolerance curves [Thesis]: University of Pennsylvania; 1970.
5. Hamilton RW, Kenyon DJ, Peterson RE, Butler GJ, Beers DM. REPEX: Development of Repetitive Excursions, Surfacing Techniques, and Oxygen Procedures for Habitat Diving. U.S. Department of Commerce. National Oceanic and Atmospheric Administration; 1988. Report No.: National Undersea Research Program Technical Report 88-1A.
6. Risberg J, van Ooij PJ. Hyperoxic exposure monitoring in diving: A farewell to the UPTD. Undersea Hyperb Med. 2022;49(4):395-413.
7. Arieli R, Yalov A, Goldenshluger A. Modeling pulmonary and CNS O(2) toxicity and estimation of parameters for humans. J Appl Physiol (1985). 2002;92(1):248-56.
8. Risberg J, van Ooij PJ, Matity L. From UPTD to ESOT: Monitoring hyperoxic exposure in surface-oriented diving. Undersea Hyperb Med. 2023;50(3):301-6.
9. Risberg J, van Ooij P, Matity L. Recovery from pulmonary oxygen toxicity: a new (ESOT) model. Undersea Hyperb Med. 2024 [Accepted].
10. Supervisor of Diving. U.S. Navy Diving Manual Revision 7 Change A. Washington, D.C.; 2018. Report No.: SS521-AG-PRO-010.
11. Health and Safety Executive. Commercial diving projects offshore. Diving at work Regulations 1997. Approved Code of Practice and guidance: Health and Safety Executive; 2014.
12. Arieli R. Calculated risk of pulmonary and central nervous system oxygen toxicity: a toxicity index derived from the power equation. Diving Hyperb Med. 2019;49(3):154-60.

Appendix I – Tables for Calculating ESOT after a Surface-Oriented Dive

Table for Calculating ESOT After Single Or Multi-Segmented pO_2 Exposures

pO_2 (Atm)	*k*	Time (min)							
		15	30	60	90	120	150	180	240
0.5	*0.21*	3	6	12	18	25	31	37	49
0.6	*0.31*	5	9	19	28	37	47	56	75
0.7	*0.44*	7	13	27	40	53	66	80	106
0.8	*0.60*	9	18	36	54	72	90	108	144
0.9	*0.79*	12	24	47	71	94	118	141	189
1	*1.00*	15	30	60	90	120	150	180	240
1.1	*1.24*	19	37	75	112	149	186	224	298
1.2	*1.52*	23	46	91	137	182	228	273	364
1.3	*1.82*	27	55	109	164	219	273	328	437
1.4	*2.16*	32	65	129	194	259	324	388	518
1.5	*2.53*	38	76	152	227	303	379	455	606
1.6	*2.93*	44	88	176	263	351	439	527	702
1.9	*4.33*	65	130	260	390	520	650	780	1040
2.2	*6.06*	91	182	364	545	727	909	1091	1454
2.5	*8.12*	122	243	487	730	974	1217	1461	1948

Table 3 ESOT index tabulated as a function of exposure time in min (columns) and pO_2 (Atm) in the breathing gas (rows). The dive should be planned to keep ESOT<660. For other exposure times, ESOT can be calculated as the product of k and exposure time (min).

This table does not consider the risk for CNS Oxygen toxicity (CNS OT). CNS OT should be considered independently of POT.

How to use this table

The table can be used for dives with a constant or variable pO2. Consider a $SurDO_2$ dive with compressed air to 15 msw for 180 min according to US Navy Diving Manual. The hyperoxic exposure in the bottom phase with a pO_2=0.5 Atm is ESOT=37. After surfacing the diver will be recompressed to 15 msw for 15 min followed by 30 min O_2 breathing at 12 msw. The air break can be ignored. The 15 msw exposure will give ESOT=122. The 12 msw exposure adds additional ESOT=182. The total exposure burden will be 37+122+182=341.

Alternatively, the ESOT may be calculated using the k-column in Table 3. During the bottom phase (pO_2=0.5 Atm) k=0.21. Multiply with exposure time to reach ESOTbottom phase = 0.21 x 180 = 38. ESOT15 msw = 8.12 x 15 = 122 and ESOT12 msw = 6.06 x 30 = 182. The grand ESOT=38 + 122 + 182 = 342.

The equations for exact calculation of ESOT are presented in Appendix II.

Method for Calculating Residual ESOT when Planning Repetitive Hyperoxic Exposures with Inter-Exposure Interval Shorter than 12 H

Particular attention should be paid for monitoring repetitive hyperoxic exposures. The ESOT after repetitive exposure may be affected by the remaining pulmonary injury after the first dive unless the surface interval (SI) is sufficiently long (Table 2). If the SI is shorter than that listed in Table 2 the residual ESOT remaining after the first dive must be calculated. The residual ESOT can be calculated using Figure 1 below or Equation 5 in Appendix II. Once the residual ESOT has been calculated, it can be added to the ESOT of the repetitive dive. The principle is similar to that used when planning repetitive dives: a residual nitrogen time is added to the actual bottom time.

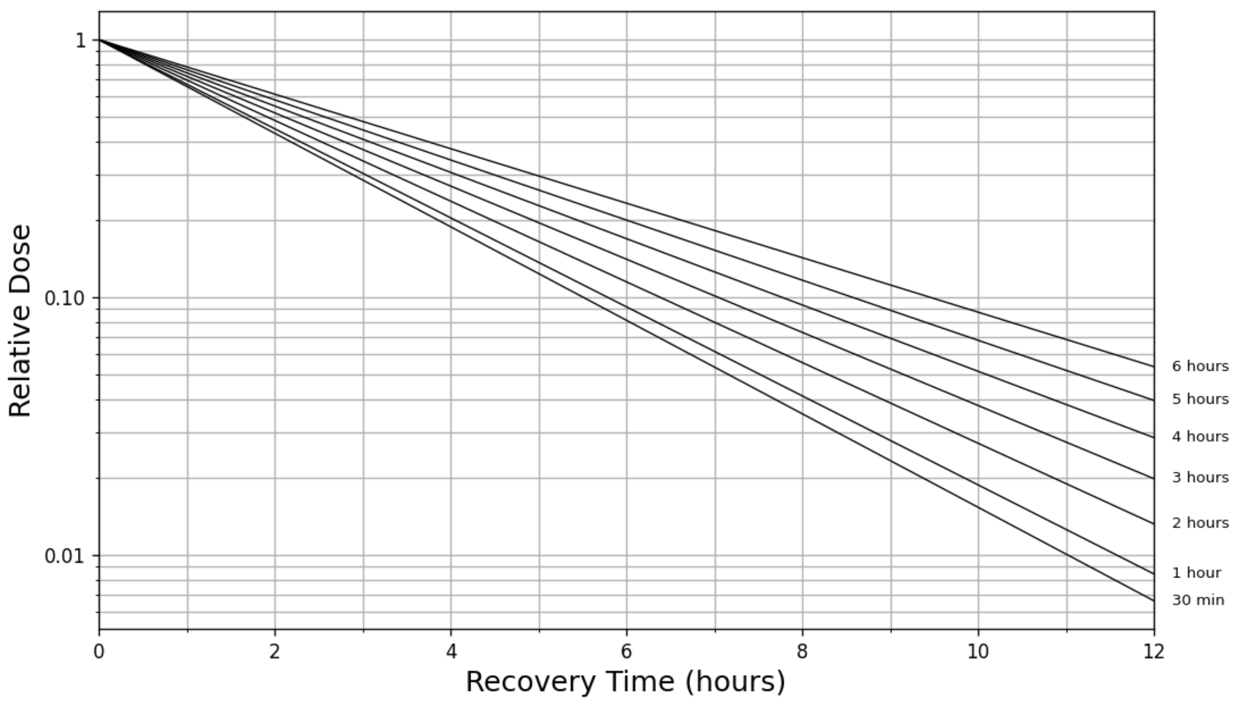

Figure 1 Recovery after hyperoxic exposures ranging 0.5 – 6 h. The remaining POT, expressed as a relative dose on the Y-axis, will decrease as a function of recovery time (X-axis). To use this graph, choose the line with a time equal or longer than the first exposure time. Locate the recovery time (inter-exposure time) on the x-axis and note the relative dose on the Y-axis. Multiply the ESOT of the first exposure with the relative dose to estimate ESOT value at the start of the next exposure. That ESOT value should be added to the ESOT of the succeeding exposure to evaluate the accumulated hyperoxic exposure. This figure should not be used for more than two succeeding exposures on the same day (24 h).

Example: Two dives to 21 msw with Nitrox 45 are planned as no-decompression dives according to USN Diving Manual Rev 7. pO_2=1.4 tm, EAD=12 msw. Surface interval 5 h. The maximum bottom time for a no-decompression dive to 12 msw is 163 min. We will plan the first dive for a bottom time of 160 min. Initially prepare the calculation of repetitive Group (RG) and Residual Nitrogen Time (RNT) to calculate the allowed bottom time for the second dive. The first dive will have a RG=O being reduced to RG=J after 5h which, in turn, will give an RNT=97 min. To avoid staged decompression the second dive should have a bottom time not exceeding 63 min. We will plan the second dive with a bottom time of 60 min.

Then start calculating the oxygen exposure. Use Table 3 and follow the row for pO_2=1.4 Atm in and find k=2.16. ESOTDive1 = 2.16 x 160 = 346. Next go to Figure 1. There is no line for a bottom time of 160 min, you have to choose between 2 h and 3h. For this example, let us make a conservative approach and choose 3 h. The hyperoxic load will be reduced to approximately 20 % of initial value after the 5 h surface interval. ESOTresidual=346 x 0.2 = 69. The second dive (pO_2=1.4 Atm, exposure time 60 min) will have ESOTDive2 = 2.16 x 60 = 130. The total hyperoxic exposure burden for both dives are ESOT = 69+130 = 199. This dive plan can be completed for seven successive days before a break of two days without hyperoxic exposure is needed (Table 2). It should be remembered that a minimum of 12 h continuous normoxic recovery is required every day (24 h).

Appendix II – Relevant Formulas Applicable for Accurate Calculation of ESOT and Expected Vc Reduction

ESOT can be calculated according to Equation 3.

$$ESOT = t \times {pO_2}^{2.285}$$

Equation 3 Formula for calculating ESOT as a function of exposure time (t) in min and pO_2 in Atm.

Multiple successive exposures/pO_2 segments can be calculated as a summary of all individual segments according to Equation 4.

$$ESOT_{Acc} = ESOT_1 + ESOT_2 + \cdots ESOT_n$$

Equation 4 Accumulated ESOT ($ESOT_{Acc}$) for n successive dive segments can be calculated as the sum of ESOT for each dive segment.

Recovery of ESOT can be calculated according to Equation 5.

$$ESOT_{rec} = ESOT_i \cdot e^{-r \cdot s^{t_{exp}} \cdot t}$$

Equation 5 Residual ESOT ($ESOT_{rec}$) after a normoxic recovery period of t (h) depending on exposure time (t_{exp}, h) of the proceeding exposure. r=0.439 s=0.906.

Equation 5 can be used to calculate ESOT recovery between two hyperoxic exposures on the same day (24 h). t_{exp} should include the total hyperoxic exposure time for each day, and a minimum of 12 h recovery is needed to ignore the residual POT from preceding hyperoxic exposures – e.g. to calculate the accumulated ESOT after three succeeding hyperoxic exposures, it is necessary to set t_{exp} to the total exposure time for the first two exposures. Recovery during the second inter-exposure interval will thus be slower than the recovery during the first inter-exposure interval.

Decrement in VC can be estimated based on ESOT as shown in Equation 6.

$$\Delta VC = 0.0082 \times \left(\frac{ESOT}{60}\right)^2$$

Equation 6 Predicted reduction in Vital Capacity (ΔVC) (%) depending on ESOT after competed exposure

Reference is given to the manuscript by Arieli (12) and Risberg et al. (8,9) presenting the original formulas developed to calculate "Arieli K" and ESOT during exposure, recovery and prediction of Vital Capacity change.

Appendix III – Executive Summary and Examples Using DMAC 35 for Typical Commercial Diving Schedules

Scope

This procedure describes how oxygen exposure should be monitored to limit development of pulmonary oxygen toxicity (POT). It is applicable for surface-oriented diving when the diver breathes oxygen-enriched breathing mixtures (F_iO_2>21%). Divers breathing compressed air only are not expected to develop POT and there is no need to calculate oxygen exposure for such diving. This summary is intended for practical/operational use. Refer to the main contents of DMAC 35 for detailed discussion.

Methods

Calculate Oxygen Exposure by Means of ESOT Method

For single exposures, the oxygen exposure can be calculated according to Table 4 below.

pO_2 (Atm)	*k*	Time (min)							
		15	30	60	90	120	150	180	240
0.5	*0.21*	3	6	12	18	25	31	37	49
0.6	*0.31*	5	9	19	28	37	47	56	75
0.7	*0.44*	7	13	27	40	53	66	80	106
0.8	*0.60*	9	18	36	54	72	90	108	144
0.9	*0.79*	12	24	47	71	94	118	141	189
1	*1.00*	15	30	60	90	120	150	180	240
1.1	*1.24*	19	37	75	112	149	186	224	298
1.2	*1.52*	23	46	91	137	182	228	273	364
1.3	*1.82*	27	55	109	164	219	273	328	437
1.4	*2.16*	32	65	129	194	259	324	388	518
1.5	*2.53*	38	76	152	227	303	379	455	606
1.6	*2.93*	44	88	176	263	351	439	527	702
1.9	*4.33*	65	130	260	390	520	650	780	1040
2.2	*6.06*	91	182	364	545	727	909	1091	1454
2.5	*8.12*	122	243	487	730	974	1217	1461	1948

Table 4 ESOT index tabulated as a function of exposure time in min (columns) and pO_2 (atm) in the breathing gas (rows). For other exposure times, ESOT can be calculated as the product of k and exposure time (min).

Repetitive Exposures

Same-day repetitive exposures call for special procedures. Refer to the main contents of DMAC 35.

Single-Day and Multi-day Exposure Limits

Single-day exposures should not exceed 660 ESOT. Allowance for multi-day exposure depends on maximum achieved daily (24 h) exposure dose as listed in Table 5 below. Following a multi-day exposure, the diver should have two recovery days without diving or air diving only.

Maximum number of successive days of diving	Daily maximum ESOT	Minimum inter-day recovery time (h)
1	660	48
5	500	12
7	450	12
>7	To be assessed by a diving medical advisor	

Table 5 Hyperoxic exposure limits for commercial surface-oriented diving. The maximum number of successive diving days and minimum surface interval for repetitive exposures depending on maximum ESOT achieved on any day of a dive series. Shorter surface intervals are allowed but will require the calculation of residual ESOT as explained in the main contents of DMAC 35. "Daily" should be interpreted as a 24 h period. A multi-day exposure should be followed with two recovery days.

Examples

Example 1 – Nitrox In-Water Decompression Dive

Consider this dive:

- Depth: 24 msw
- Bottom time: 120 min
- Breathing gas: Nitrox 40 (40% O_2 balance N_2)
- Equivalent air depth: 16 msw
- Table depth: 18 msw
- Decompression: 36 min@ 3msw (DCIEM table)

Calculate:

- pO_2
  - Bottom depth: pO_2 = 3.4 × 0.4 = 1.4 atm
  - 3 msw staged decompression stop: pO_2 = 1.3 atm × 0.4 = 0.5 atm
- Calculate ESOT by means of Table 4:
  - Bottom phase: The 120 min column lists ESOT=259 for pO_2=1.4 atm
  - Decompression: There is no 36 min column, but multiply the exposure time with the appropriate cell in "k" column to get the answer: 36 × 0.21 = 8 ESOT
  - Total: 259 + 8 = 267 ESOT

The final result, ESOT=267 is much lower than the threshold limit for 7 consecutive days of exposure (Table 5). If the diver is expected to dive this profile for more than seven consecutive days, the diving medical advisor should be contacted. The diver should otherwise have two days off or air diving only.

Example 2 – SurDO_2 Dive with Nitrox as Bottom Gas

Consider the same dive but with SurDO_2 decompression:

- Depth: 24 msw
- Bottom time: 120 min
- Breathing gas: Nitrox 40 (40% O_2 balance N_2)
- Equivalent Air Depth: 16 msw
- Table depth: 18 msw
- Decompression: SurDO_2 (DCIEM table): No in-water staged decompression, but 30 min O_2 @ 12 msw in DDC

Calculate:

- pO_2
  - Bottom depth: $pO_2 = 3.4 \times 0.4 = 1.4$ atm
  - DDC BIBS O_2 breathing at 12 msw: pO_2=2.2 atm
- Calculate ESOT by means of Table 4:
  - Bottom phase: The 120 min column lists ESOT=259 for pO_2=1.4 atm
  - Chamber BIBS breathing pO_2=2.2 atm row and 30 min column: ESOT=182 (You may alternatively multiply the exposure time with “k”: 30 * 6.06 = 182 ESOT)
  - Total: 259 + 182 = 441 ESOT

The final result: ESOT=441 is less than the 7-days threshold of 450 ESOT (Table 5). If the diver is expected to dive this profile for more than seven consecutive days, the diving medical advisor should be contacted. The diver should otherwise have two days off or air diving only.