DMAC, 66 Buckingham Gate, London SW1E 6AU, UK
Tel: +44 (0) 20 7824 5520

www.dmac-diving.org
info@dmac-diving.org

Exposure Index for Pulmonary Oxygen Toxicity in Surface-Oriented Diving

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1 Introduction and Scope

Divers will normally breathe hyperoxic gas mixtures during diving. Hyperoxia is known to have a toxic effect on several systems (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 a large number of 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). However, 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 recognized 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 recognized to cause short-term and long-term effects on pulmonary function. The precise interaction between these mechanisms remains largely unknown. The majority of 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 proper monitoring of hyperoxic *exposure*. The objective is to minimize pulmonary oxygen toxicity (POT) in *surface-oriented occupational diving*. The principles should be equally applicable for military and recreational diving, but guidance for these groups is outside the DMAC scope. The procedures and threshold limits should not be applied for saturation diving or hyperbaric oxygen treatment. 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. 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 were 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) has, as mentioned earlier, suggested UPTD exposure limits for multiday diving, but these limits have not been scientifically validated.

2.3 Arieli K-index

Arieli and coworkers have in a series of works (7, 8, 9, 10) analyzed previous data and have proposed a new index "K" (termed "Arieli K" in this document). The Arieli K-index (*Equation 2*) has a better fit to VC changes after short exposures relevant for surface-oriented diving and allows for the calculation of recovery from pulmonary oxygen toxicity (6).

$$K = t^2 \times pO_2^{\,4.57}$$

Equation 2 Arieli K-index (K) as a function of exposure time (t) in h and pO_2 in Atm. from (10)

The expected relative percentage reduction in VC will be $8.2x10^{-3}$ of the K-value. Another and somewhat more complex formula allows the calculation of recovery from POT. These are presented in Appendix II. Recovery from a hyperoxic exposure with high pO_2 will be faster than exposure with low pO_2 even if K was identical at the end of this exposure. Risberg and van Ooij (6) reviewed alternative exposure indexes for POT. They concluded that Arieli K was the best predictor of VC and should replace UPTD.

2.4 Equivalent Surface Oxygen Time (ESOT)

Based on the review of Risberg and van Ooij (6), DMAC decided to issue a Guidance Note explaining the operational implementation and threshold limits of Arieli K in commercial surface-oriented diving. Hyperoxic exposure to and recovery from a dive with a constant pO_2 can be calculated and charted relatively easily. However, the calculation of K for multi-level pO_2 dives require either complex calculation or equally careful use of tables and charts, The complexity is due to the raised power of time in the Arieli K equation.

A recent work (11) explains how hyperoxic exposure monitoring can be facilitated using an alternative index termed Equivalent Surface Oxygen Time (ESOT) as shown in *Equation 3*.

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

Equation 3 Equivalent Surface Oxygen Time (ESOT) as a function of time (min) and pO_2 in Atm.

ESOT will predict hyperoxic VC changes identical to Arieli K (Appendix II), but is a more intuitive and less computationally involved index than Arieli K. We therefore recommend it for use in operational monitoring of hyperoxic exposure in surface-oriented diving.

2.5 Hyperoxic Exposure Level in Surface-oriented Diving

Single air and nitrox dives (surface-oriented diving) will generally have a low level of pulmonary oxygen toxicity whether toxicity is expressed as UPTDs or ESOT (*Table 1*). Recognized 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 is planned, and when 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 (12). 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 (13) 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 seven or five 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 Air/02 BG: Air	DC: 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	2	10	Not recommended	5	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 pO2=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.*

$SurDO_2$ and closed bell decompression (TUP) with nitrox as a breathing gas may challenge the Repex exposure limits for multiday diving (*Table 1*). Typically, a multi-day break would be advised after four consecutive days of diving after some of the dives with the highest hyperoxic exposures.

2.6 The Benefits of Replacing UPTD with ESOT

Risberg and van Ooij (6) concluded that Arieli K should replace UPTD for tracking POT in surface-oriented diving. The main benefit of replacing UPTD with Arieli K is a more accurate estimate of POT for such exposures. Arieli K is expected to better predict POT development after multiple exposures to various pO_2 values. The estimation of POT recovery is much better validated in the equation for Arieli K than the Repex model.

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 (F_iO_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. In contrast, use of Arieli K will require either computations or tables (both complex to use) to integrate exposures from various levels of pO_2.

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

3 Recommended Maximum Exposure Levels

Arieli (10) 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 and van Ooij (6) we suggest a maximum exposure level of ESOT=660 for a maximum of two consecutive days of diving. Two days off diving should be allowed after this exposure. We recommend a maximum of five consecutive days of diving, followed by two days off if the daily (24 h) exposure level is ESOT=500 or less. The daily exposure may reach ESOT=420 if two days off diving are allowed after ten consecutive days of diving. Intermittent breathing of compressed air ("air break") has been shown to delay the development of POT and recovery of POT will take place faster in resting divers. It is thus acceptable to relax these limits in resting divers breathing hyperoxic gas with intermittent air breaks. There is a paucity of studies on POT after successive multiday surface-oriented dives, in particular dives with short exposures to $pO_2<1.3$ Atm. It may be acceptable to allow more than ten 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. Appendix 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 summarizes hyperoxic threshold values. Surface intervals shorter than listed in the table should call for calculation of residual ESOT as explained in Appendices I and II.

Daily maximum ESOT	Maximum number of successive days of diving	Minimum surface interval (h)
>660	†	24
501-660	2	12
420-500	5	12
<420	10	12

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 ESOT after the preceding dive. Shorter surface intervals are allowed but will require the calculation of residual ESOT as explained in Appendix I and II. †: K exceeds recommended threshold values even for single dives. "Daily" should be interpreted as a 24 h period.

Subject to HSE bottom time limitations,[1] 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.

[1] Note that the maximum bottom time limitations published by the International Marine Contractors Association (IMCA) are identical to those of the HSE – see IMCA D 014 *IMCA International Code of Practice for Offshore Diving*, Appendix 2.

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.

4 Conclusion

We advise that the ESOT should replace UPTD as an exposure measure for POT in surface-oriented diving. Diving should be planned to keep ESOT lower than 660 for any single dive. For multiday diving, daily exposure should be limited to ESOT=660, 500 and 420 for a maximum of two, five and ten consecutive days of diving respectively. 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.

5 References

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APPENDIX 1 – 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 pO_2. 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 $ESOT_{bottom\ phase}$ = 0.21 x 180 = 38. $ESOT_{15\ msw}$ = 8.12 x 15 = 122 and $ESOT_{12\ msw}$ = 6.06 x 30 = 182. The grand ESOT=38 + 122 + 182 = 342.

The equations for exact calculation of ESOT are presented in Appendix 2.

Table for calculating residual ESOT when planning repetitive hyperoxic exposures.

Particular attention should be paid for monitoring repetitive hyperoxic exposures. The ESOT after a 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 *Table 4* below or *Equation 7* 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.

Surface interval (h)	**pO_2 (Atm)**							
	1.2	1.3	1.4	1.5	1.6	1.9	2.2	2.5
1	98 %	96 %	94 %	92 %	91 %	86 %	81 %	76 %
2	96 %	92 %	89 %	86 %	82 %	73 %	65 %	58 %
3	94 %	89 %	84 %	79 %	75 %	63 %	53 %	44 %
4	92 %	85 %	79 %	73 %	68 %	54 %	43 %	34 %
5	90 %	82 %	75 %	68 %	62 %	46 %	35 %	26 %
6	88 %	79 %	70 %	63 %	56 %	40 %	28 %	20 %
7	87 %	76 %	66 %	58 %	51 %	34 %	23 %	15 %
8	85 %	73 %	62 %	54 %	46 %	29 %	18 %	12 %
9	83 %	70 %	59 %	50 %	42 %	25 %	15 %	9 %
10	82 %	67 %	56 %	46 %	38 %	21 %	12 %	7 %
11	80 %	65 %	52 %	42 %	34 %	18 %	10 %	5 %

Table 4 Residual ESOT expressed as percentage of the ESOT achieved after the first dive depending on the surface interval (h) and pO_2 (Atm) during the first dive. For a multi-segment dive, pO_2 having the greatest impact on ESOT should be chosen. Use pO_2=1.1 Atm for dives with pO_2 less than tabulated.

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 Atm, EAD=12 msw. Surface interval 5h. 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 a 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. $ESOT_{Dive1}$ = 2.16 x 160 = 346. Next find the column for pO_2=1.4 Atm in *Table 4*. Locate the row for a 5h surface interval. You find the crossing cell to hold "75%". After the 5h surface interval $ESOT_{residual}$ = 346 x 0.75 = 260. The second dive (pO_2=1.4 Atm, exposure time 60 min) will have $ESOT_{Dive2}$ = 2.16 x 60 = 130. The total hyperoxic exposure burden for both dives are ESOT = 260+130 = 390. This dive plan can be completed for ten successive days before a break of two days without hyperoxic exposure is needed (*Table 2*).

APPENDIX 2 – RELEVANT FORMULAS APPLICABLE FOR ACCURATE CALCULATION OF ESOT AND EXPECTED VC REDUCTION

ESOT is a simple transformation of "Arieli K" (10).

$$ESOT = 60 \times \sqrt{K}$$

Equation 4 Transformation of Arieli K (K) (10) to ESOT.

ESOT can be calculated according to *Equation 5*.

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

Equation 5 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 5*.

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

Equation 6 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 7*.

$$ESOT_{rec} = ESOT_i \times e^{(0.21-0.192 \times pO_2) \times t_{rec}}$$

Equation 7 Residual ESOT ($ESOT_{rec}$) after a normoxic recovery period of t_{rec} (h) depending on pO_2 (Atm) of the proceeding exposure. Use pO_2=1.1 Atm for exposures subceeding this level.

Decrement in VC can be estimated based on ESOT as shown in *Equation 8*.

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

Equation 8 Predicted reduction in Vital Capacity (ΔVC) (%) depending on ESOT after competed exposure

Reference is given to the manuscript by Arieli (10) and Risberg et al. (11) presenting the original formulas developed to calculate "Arieli K" and ESOT during exposure, recovery and predictors of Vital Capacity change.