UNDERSEA & HYPERBARIC MEDICINE

From UPTD to ESOT: Monitoring hyperoxic exposure in surface-oriented diving

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ABSTRACT

Risberg J, van Ooij PJ, Matity L. From UPTD to ESOT: Monitoring hyperoxic exposure in surface-oriented diving. Undersea Hyperb Med. 2023 Third Quarter; 50(3):301-306.

A recent review suggested that the measure $K = t^2 \times pO_2^{4.57}$ (t is exposure time in h, pO_2 in atm) should replace unit pulmonary toxic dose (UPTD) as an exposure index for pulmonary oxygen toxicity (POT) in surface-oriented diving. K would better predict reduction in vital capacity (VC) during exposure and allow prediction of recovery. Although K is more accurate estimating VC changes than UPTD, the calculation of K is more extensive, particularly when estimating hyperoxic exposure for dives with multiple pO_2 segments. Furthermore, and in contrast with UPTD, K is difficult to interpret on its own given its non-linear dimension of time. We suggest that a new metric: ESOT (equivalent surface oxygen time) should be used to replace UPTD. $ESOT = t \times pO_2^{2.285}$ (t is exposure time in minutes, pO_2 in atm). ESOT=1 is thus the hyperoxic exposure reached after one minute of breathing 100% O_2 at surface pressure. Hyperoxic monitoring by ESOT is more practical than K to apply in an operational environment, with no loss of accuracy in POT prediction. In addition, it intuitively allows interpreting hyperoxic exposures on its own, analogous to UPTD. The daily hyperoxic threshold limits suggested by Risberg and van Ooij for two, five and an unlimited number of successive diving days would translate to ESOTs of 650, 500 and 420 respectively.

Keywords: enriched air – nitrox; hyperbaric oxygen; hyperoxia; lung function; models; occupational diving; oxygen; pulmonary function; unit pulmonary toxic dose

INTRODUCTION

Increased oxygen partial pressure (pO_2) is known to have a toxic effect on many cellular processes and organ functions [1]. In diving, the acute effect on CNS and chronic effect on lungs are well recognized. Van Ooij [2] has reviewed how hyperoxia may cause symptoms, changes in spirometric indices and changes in composition of exhaled gas. Symptoms and findings of pulmonary oxygen toxicity (POT) have been reported by many, with decrement in vital capacity (VC) as the most frequently reported measure of the dose-response pattern. Bardin and Lambertsen [3] introduced the unit pulmonary toxic dose (UPTD) as the exposure measure best describing the reduction in VC. The UPTD is commonly referred to as oxygen toxicity unit (OTU) outside the scientific environment. Risberg and van Ooij [4] recently published a review of alternative exposure indices applicable to predict VC changes due to POT. They concluded that UPTD should be replaced by K ("Arieli K") as suggested by Arieli [5] for exposures relevant to surface-oriented diving. They found Arieli K to predict VC changes after exposure better than UPTD. In addition, Arieli K could be used to predict POT recovery.

Arieli K is calculated as shown in Equation 1.

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

Equation 1. **Arieli K (K) expressed as a function of exposure time (t, hours) and pO_2 (Atm).**

A multi-segmented hyperoxic exposure could be calculated according to Equation 2.

$$K = [(t_1 \times pO2_1^{2.285}) + (t_2 \times pO2_2^{2.285}) + \cdots + (t_n \times pO2_n^{2.285})]^2$$

Equation 2. **Arieli K (K) for n number of discrete succeeding hyperoxic segments ($pO2_i$, Atm) each with t_i (h) exposure time.**

Recovery would take place as expressed in Equation 3.

$$K_{rec} = K_{pre} \times e^{(0.42-0.384 \times pO2_{pre}) \times t}$$

Equation 3. **Krec: Remaining K after a normoxic period (t, hours) depending on pO_2 of the preceding dive ($pO2_{pre}$, Atm) and K immediately after the preceding exposure (K_{pre}). In a multi-segmented dive, pO_2 of the dive segment having the largest effect on K should be used. For dives with pO_2<1.1 Atm, a $pO2_{pre}$=1.1 atm should be used.**

K after two successive hyperoxic exposures with an intermediate normoxic interval can be calculated using Equation 4 below.

$$K = K_{rec} + K_s + 2\sqrt{K_{rec} \times K_s}$$

Equation 4. **K after two successive exposures. K_{rec}: Remaining K immediately preceding the second exposure. K_s: K of the second exposure.**

The reduction in VC after a hyperoxic exposure could be calculated as shown in Equation 5.

$$\Delta VC = 0.0082 \times K$$

Equation 5. **Reduction in vital capacity (ΔVC, %) after a hyperoxic exposure. Hyperoxic exposure burden expressed as Arieli K (K).**

While Equations 1-4 adequately allow calculation of hyperoxic exposure, recovery and effect on VC, the Arieli K index is impractical for use in operational planning of dives. The raised power of exposure time calls for complex calculation of multi-segmented dives (Equation 2). This fact was recognized when the Diving Medical Advisory Committee (www.dmac-diving.org) drafted a guidance note recommending the use of Arieli K for future hyperoxic exposure monitoring. Though calculus can be omitted using tables designed for multi-pO_2 segment diving, these tables required careful training, experience and attention to avoid errors. A relatively complex dive chart was developed to allow stepwise progress in calculation of accumulated hyperoxic exposure after multi-segment dives.

METHOD

Recognizing the practical challenges in tracking hyperoxic exposure for multi-segment pO_2 dives, we investigated whether the exposure index could be calculated easier without loss of the relationship between pO_2 and exposure time on VC reduction as suggested by Arieli [5].

RESULTS

Equivalent surface oxygen time

We suggest a simplification of the exposure index in the form of equivalent surface oxygen time (ESOT) as presented in Equation 6 below.

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

Equation 6. **Relationship between ESOT and Arieli K (K).**

This simple mathematical transformation of K will allow the exposure index to be expressed as a single dimension of exposure time (Equation 7).

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

Equation 7. **Equivalent surface oxygen time (ESOT) expressed as a function of exposure time (t, min) and pO_2 (atm)**

A unit of ESOT is the hyperoxic exposure achieved after breathing 100% O_2 at surface pressure for one minute. In this respect it is analogous to UPTD.

If needed, ESOT may be transformed from UPTD such:

$$ESOT = UPTD \times pO_2^{2.285} \times \left(\frac{0.5}{pO_2 - 0.5}\right)^{\frac{5}{6}}$$

Equation 8. **Relationship between ESOT and UPTD.**

ESOT allows a much simpler calculation of multi-segment dives (Equation 9 below) compared to Arieli K (Equation 2).

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

Equation 9. **Accumulated hyperoxic exposure ($ESOT_{acc}$) after n succeeding hyperoxic segments, each segment causing a discrete ESOT value.**

As can be seen, the accumulated ESOT for all dive segments can be calculated by simply adding the individual ESOTs.

Recovery of ESOT during a surface interval can be expressed as shown in Equation 10 below.

$$ESOT_{rec} = ESOT_{pre} \times e^{(0.21\text{-}0.192 \times pO2_{pre}) \times t}$$

Equation 10. **Residual ESOT ($ESOT_{rec}$) after a surface interval (t, hours) following a hyperoxic exposure of $ESOT_{pre}$ depending on pO_2 during the preceding exposure ($pO2_{pre}$, atm). For dives with pO_2<1.1 atm, a $pO2_{pre}$=1.1 atm should be used.**

Calculation of ESOT after two successive hyperoxic exposures with an intermediate normoxic interval can be calculated using Equation 11 below. As can be seen the calculation is easier than that of K (Equation 4).

$$ESOT = ESOT_{rec} + ESOT_s$$

Equation 11. ESOT after two successive exposures. $ESOT_{rec}$: Remaining ESOT immediately preceding the second exposure. $ESOT_s$: ESOT of the second exposure.

Finally, the relationship between VC reduction and ESOT is expressed as shown in Equation 12.

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

Equation 12. **Reduction in vital capacity (ΔVC, %) depending on ESOT.**

DISCUSSION

Discussing the accuracy and limitations of Arieli K as an exposure index for POT is beyond the scope of this manuscript, and the reader is advised to review previous reports [4-6]. We have previously recommended to replace UPTD/OTU with Arieli K for POT exposure monitoring in surface-oriented diving [4], and the objective of this work was to investigate whether a transformation of the original equation could facilitate operational implementation of an alternative index.

We found that the most important benefit of using ESOT instead of Arieli K is the ease of calculating complex multi-segmented hyperoxic exposures. Additionally, the ESOT term, expressing equivalent oxygen toxicity relative to exposure at surface pressure, allows a simpler transition for operational diving personnel used to monitor exposure with UPTD, since the meaning of the exposure is being preserved. (1 ESOT referring to exposure to 100% O_2 at surface pressure for one minute, i.e., identical meaning to that of 1 UPTD). The mathematical translation of Arieli K into ESOT (Equation 6) preserves the underlying relationship between the independent variables pO_2 and exposure time on the dependent variable VC change.

Appendix 1 holds tables facilitating calculation of ESOT exposure and recovery.

Risberg and van Ooij [4] suggested daily hyperoxic exposure limits of K=120, 70 and 40- to 50 for two, five and unlimited successive days of exposure respectively. These K- values can be transformed (Equation 6) to rounded ESOT figures of 660, 500 and 420 respectively. However, institutional policy should decide appropriate threshold levels and minimum surface intervals between hyperoxic exposures. The Diving Medical Advisory Committee (DMAC) has recently published a guidance note holding exposure limits for surface-oriented diving [8]. VC change (Equation 12) could otherwise be used to define such thresholds.

Risberg and van Ooij [4] reviewed alternative hyperoxic exposure indices relevant for tracking POT in surface-oriented diving and concluded that Arieli K would be the best predictor of VC changes and should replace UPTD. We have no reservation concluding that ESOT should replace Arieli K given the advantages discussed above and the fact that ESOT will predict VC changes with the same underlying relationship to pO_2 and exposure time as Arieli K (Equation 12). However, as pointed out by Risberg and van Ooij [4], Arieli K should not be applied as a hyperoxic exposure index in saturation diving nor hyperbaric oxygen therapy. The same limitation will apply for ESOT. Though Arieli K (and thus ESOT) will predict VC changes more accurately than UPTD for most relevant scenarios in surface-oriented diving, the data substantiating this relationship is limited [7]. It should be recognized that the Arieli K recovery equation (Equation 3) may give some counterintuitive results. Short-lasting, repetitive, multiday exposures to low pO_2 are predicted to cause higher accumulating POT than similar-length exposures to higher pO_2. This should be addressed in future studies.

CONCLUSION

We recommend that ESOT should be applied for hyperoxic exposure monitoring in surface-oriented diving. ESOT will predict VC changes caused by POT better than UPTD.

Acknowledgment

Dr. Lyubisa Matity is recognized for identifying the ESOT as a simplified exposure index.

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APPENDIX 1

ESOT may either be calculated using Equation 7 and 9 or retrieved using Table 1. When Table 1 is used "kp" should be multiplied by the exposure time (min) to find the appropriate ESOT for the hyperoxic segment. If the exposure consists of multiple segments all ESOTs should be added to find the total exposure burden. A 30-minute exposure to pO_2=1.2 atm will give ESOT = 30 x 1.52 = 46. Alternatively, ESOT may be found in the cell intersecting the appropriate pO_2 row and time column. If the exposure time is not charted, ESOT may be found by addition. For a 30-minute exposure to pO_2=1.2 atm the cells for 10 and 20 minutes should be added giving ESOT = 15 + 30 = 45. There may be small differences in the estimation of ESOT comparing tabulated values and calculation using k due to rounding error. Table 2 can be used to find the expected reduction in vital capacity based on ESOT from the preceding exposure.

Recovery after a hyperoxic exposure may be expressed as a reduction in ESOT depending on pO_2 during and surface interval after the last exposure. Equation 10 may be used, alternatively Table 3. If Table 3 is used, find the cell intersecting the appropriate row for surface interval and the column for pO_2 dominating the hyperoxic exposure. Residual ESOT is expressed as the fraction of ESOT developed immediately after the hyperoxic exposure. If a subject

pO_2 (atm)	k_p	time (min)						
		5	10	20	40	80	160	320
0.5	***0.21***	1	2	4	8	16	33	66
0.6	***0.31***	2	3	6	12	25	50	100
0.7	***0.44***	2	4	9	18	35	71	142
0.8	***0.60***	3	6	12	24	48	96	192
0.9	***0.79***	4	8	16	31	63	126	252
1	***1.00***	5	10	20	40	80	160	320
1.1	***1.24***	6	12	25	50	99	199	398
1.2	***1.52***	8	15	30	61	121	243	485
1.3	***1.82***	9	18	36	73	146	291	583
1.4	***2.16***	11	22	43	86	173	345	690
1.5	***2.53***	13	25	51	101	202	404	808
1.6	***2.93***	15	29	59	117	234	468	937
1.9	***4.33***	22	43	87	173	347	694	1387
2.2	***6.06***	30	61	121	242	485	970	1939
2.5	***8.12***	41	81	162	325	649	1298	2597

Table 1. **Table to find ESOT for a hyperoxic exposure based on pO_2 and time. ESOT for exposure times not listed may be found by adding ESOTs (e.g., ESOT for a 60-minute exposure may be found by adding ESOT for a 20- and a 40-minute exposure). Alternatively, ESOT may be calculated by multiplying "kp" for the appropriate pO_2 with exposure time (in minutes).**

ESOT	ΔVC
100	0.0 %
200	0.1 %
300	0.2 %
400	0.4 %
500	0.6 %
600	0.8 %
700	1.1 %
800	1.5 %
900	1.8 %
1000	2.3 %

Table 2. **Estimated reduction in vital capacity (ΔVC, %) depending on ESOT of the preceding dive.**

was exposed to pO_2=1.6 atm with ESOT=200 immediately after the dive, ESOT would be reduced to 200 x 46% = 92 after eight hours of surface interval. Table 3 and Equation 10 are practical tools for handling repetitive diving with 0-12h surface intervals but will be challenging and provide unrealistic results when planning multiday diving due to the exponential decay of ESOT. $T_{1/2}$=34h for ESOT decay after exposure to pO_2=1.2 atm and would suggest that even short exposures would cause POT after successive multiday diving. The institutional policy should determine a minimum surface interval allowing POT of the preceding exposure to be ignored (zeroing ESOT). The Diving Medical Advisory Committee (DMAC) has recommended a 24-, 12- and 8-hours minimum surface intervals to zero ESOT after preceding exposures exceeding ESOTs of 660, 500 and 420 respectively [8].

Table 4 may be useful for transforming UPTD to ESOT.

If UPTD is known for each segment of a multi-pO_2 segmented exposure, the accumulated ESOT may be calculated according to Equation 13 below.

$$ESOT_{acc} = \sum_{i=1}^{n} UPTD_i \times PO_{2i}^{\ 2.285} \times \left(\frac{0.5}{PO_{2i}\text{-}0.5}\right)^{\frac{5}{6}}$$

Equation 13. **Equation to calculate accumulated ESOT for an exposure with n discrete levels of pO_2 (atm) when UPTD of each segment is known.**

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 3. Recovery after hyperoxic exposure is expressed as the residual fraction of ESOT depending on pO_2 of the hyperbaric exposure and (normoxic) surface interval.

pO_2	UPTD 10	20	40	80	160	320
0.6	12	24	48	95	190	381
0.7	9	19	38	76	152	304
0.8	9	18	37	74	147	294
0.9	9	19	38	76	151	303
1	10	20	40	80	160	320
1.1	11	21	43	85	171	342
1.2	11	23	46	92	183	367
1.3	12	25	49	98	197	394
1.4	13	26	53	106	211	423
1.5	14	28	57	113	227	454
1.6	15	30	61	121	243	486
1.9	18	37	74	147	294	588
2.2	22	44	87	175	350	699
2.5	26	51	102	204	409	818

Table 4. Table to convert UPTD (first row) to ESOT for exposure to a constant pO_2. Cell contents may be added for UPTDs not tabulated (e.g. add contents in the "20" and "40" columns to find ESOT for UPTD=60). This table cannot be used for calculating accumulated ESOT for a multi-pO_2 segmented exposure. Equation 13 should be used for such a purpose.