From UPTD to ESOT. Monitoring pulmonary oxygen toxicity in surface-oriented diving

Jan Risberg

Pieter-Jan van Ooij Lyubisa Matity

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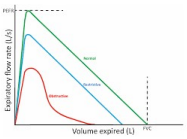
Why care?



HSE

Medical examination and assessment of working divers (MA1)

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Relevance – when should calculation of POT be considered?

Presumed adherence to IMCA/HSE/NORSOK U-100:2015

Breating gas bottom	In-water decompression	SurD	TUP	Saturation
Air				
Nitrox				
Heliox				

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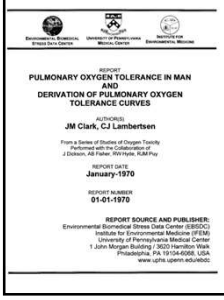
Clark and Lambertsen 1970



REPORT
PULMONARY OXYGEN TOLERANCE IN MAN AND DERIVATION OF PULMONARY OXYGEN TOLERANCE CURVES

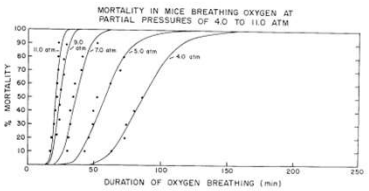
AUTHOR(S)
JM Clark, CJ Lambertsen

From a Series of Studies of Oxygen Toxicity Performed with the Collaboration of J Dickson, AB Fisher, WH Hyde, RJM Puy

REPORT DATE
January-1970

REPORT NUMBER
01-01-1970

REPORT SOURCE AND PUBLISHER:
Environmental Biomedical Stress Data Center (EBSDC)
Institute for Environmental Medicine (IFEM)
University of Pennsylvania Medical Center
1 John Morgan Building, 3620 Hamilton Walk
Philadelphia, PA 19104-6068, USA
www.uphs.upenn.edu/ebsdc



Marshall&Lambertsen, J Appl Physiol 1961

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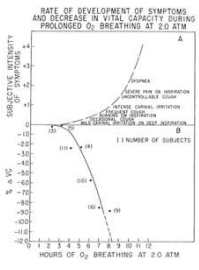
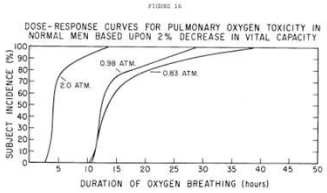
Clark and Lambertsen 1970





pO_2=0.83 Atm (N=6)
pO_2=0.98 Atm (N=4)
pO_2=2.0 Atm (N=11)

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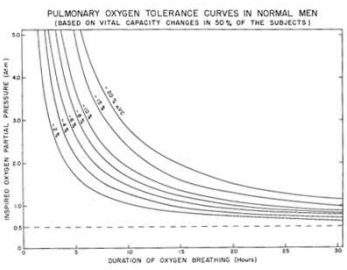
Clark and Lambertsen 1970



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Bardin & Lambertsen 1970
UPTD – Later OTU

$$UPTD = t \times \sqrt[-1.2]{\frac{0,5}{P - 0,5}}$$

$$\Delta VC(\%) = -0,01 * (UPTD - 415)$$

A Quantitative Method for Calculating Cumulative Pulmonary Oxygen Toxicity Use of the Unit Pulmonary Toxicity Dose (UPTD)

H. Bardin and C.J. Lambertsen

Institute for Environmental Medicine
University of Pennsylvania
April, 1970

UPTD	Corresponding ΔVC in 50% of subjects
615	-2
825	-4
1035	-6
1230	-8
1425	-10
1815	-15
2190	-20

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Hamilton et al. 1988 (Repex)

Duration (days)	Average daily exposure (UPTD)	Accumulated period exposure (UPTD)
1	850	850
2	700	1400
3	620	1860
4	525	2100
5	460	2300
6	420	2520
7	380	2660
8	350	2800
9	330	2970
10	310	3100
11>	300	3300>

We did not invent this information. The information was developed by others it came from experience with oxygen exposure and was the best that we could find. Our only contribution is to fit it together to show how the daily dose can be determined as a function of mission duration.

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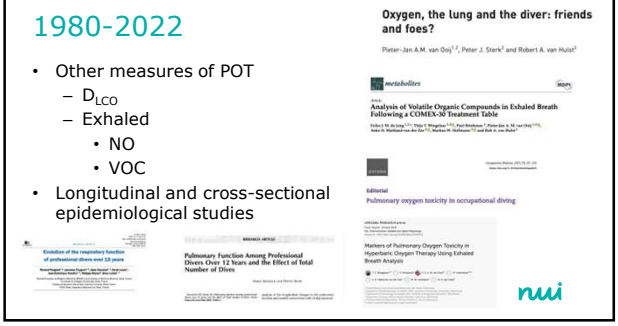
1980-2022

- Other measures of POT
  - D_{LCO}
  - Exhaled
    - NO
    - VOC
- Longitudinal and cross-sectional epidemiological studies



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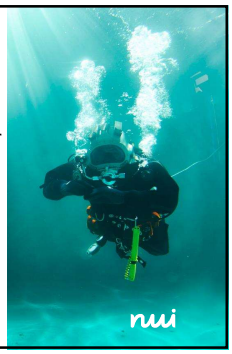
ESOT

- Equivalent Surface Oxygen Time (min)
- 1 ESOT = The hyperoxic exposure reached after breathing pO_2=1 Atm for 1 min.
  - Conceptually similar to UPTD/OUT
    - 60 ESOT
      - Exposure for pO_2=1 Atm for 60 min (1h)
      - Exposure for pO_2=1.4 Atm for 31 min

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



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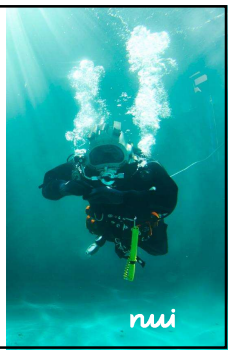
Summary – exposure limit

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

Minimum surface interval: The time required in normoxia or air diving only to ignore/zero ESOT from the preceding exposure



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UNDERSEA & HYPERBARIC MEDICINE

Hyperoxic exposure monitoring in diving: A farewell to the UPTD

Jan Risberg, PhD, MD [1]; Pieter Jan van Ooij, PhD, MD [2]

[1] NUI, Bergen, Norway [2] Diving Medical Center, Royal Netherlands Navy, Den Helder, The Netherlands

CORRESPONDING AUTHOR: Jan Risberg - jrs@nui.no

ABSTRACT

Risberg J, van Ooij P-J. Hyperoxic exposure monitoring in diving: A farewell to the UPTD. Undersea Hyperb Med. 2022 Fourth Quarter; 49(4): 395-413.

Depending on pO_2 and exposure time hyperoxic breathing gas may cause injury in many organs including the lungs. Pulmonary oxygen toxicity (POT) may be asymptomatic, but will initially present as a tracheo-bronchitis in symptomatic subjects. A number of objective measurements of POT have been investigated, but the decrement in vital capacity (VC) has remained the most accepted outcome measure. The unit pulmonary toxic dose (UPTD) has been established as the most common exposure index for POT in diving. UPTD is calculated based on the pO_2 and exposure time. A literature search identified five models predicting POT, but no model would accurately predict VC change for the full range of pO_2, variation and exposure time relevant for surface-oriented diving. Nevertheless, compared to UPTD, the K-index ($K = t^{*}pO_2^{0.5}$, where t = time (hours) and pO_2 = inspired pO_2 (atm)) suggested by Arieli performed better for pO_2 < 150 kPa and allowed estimation of recovery. We recommend that the Arieli K-index should replace UPTD as the POT exposure index for all surface-oriented diving. Based on the limited data available we suggest a daily threshold of K = 120 for a maximum of two diving days followed by two days of recovery. For five consecutive days of diving, we recommend that the threshold should not exceed K=70 and two recovery days should be allowed. For multiday diving without days of recovery, the daily exposure should probably be limited to K = 40-50. ∎

KEYWORDS: diving; oxygen; pulmonary function; pulmonary oxygen toxicity; UPTD

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Summary of indices reviewed

Index	Originally proposed	Exposures included	pO_2 range (kPa)	Relationship between pO_2 and time vs VC change	Outcome measure	Recovery function	Comment
UPTD	**Bardin and Lambertsen 1970 [4]**	**21**	**84-203**	**(Rectangular hyperbola)**	**(VC)**		**Relationship between pO_2 and time expressed as UPTD (rectangular hyperbola). Relationship between UPTD and VC was not mathematically expressed but tabulated.**
Unnamed	Harabin 1985 [22]	440	25-203	Linear	VC		
Repex	Hamilton et al. [24]				(VC)	+	The Repex report holds recommendations for limiting UPTD's for multiday exposure, i.e. inherent expectations of POT recovery
FR(1)-VC(2) FR(2)-VC(2)	Vann 1988 [7]	794	25-203	Exponential	VC	+	
Arieli K	**Arieli et al. 2002 [8]**	**56**	**106-304**	**Exposure: Power Recovery: Exponential**	**VC**	**+**	
ROT	Shykoff 2015 [5]	1352	130-140	Exposure: Exponential Recovery: Sigmoidal	FVC, FEV_1, $FEF_{25-75\%}$ or pulmonary symptoms	+	POT expressed as a likelihood function.

Risberg and Van Ooij, UHM 2022;49(4):395-413

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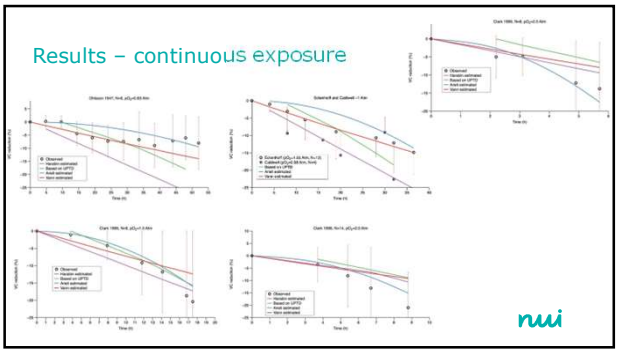
Results – continuous exposure



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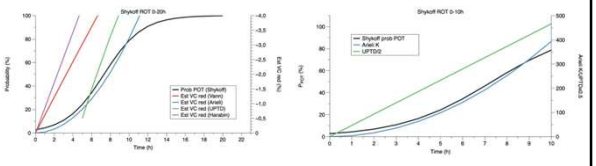
Results 130-140 kPa continuous exposure



Shykoff 2015, N=1352
>5200 manhours in water

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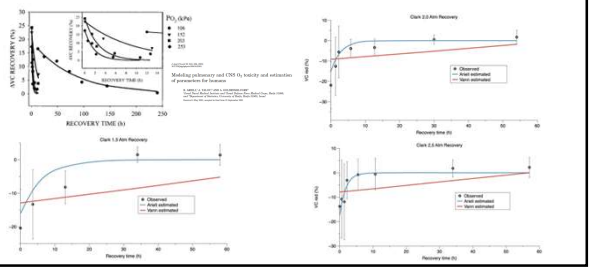
Results – recovery 150-250 kPa



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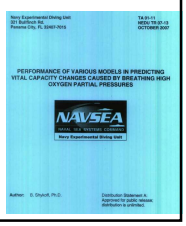
Our conclusions

Exposure	pO_2 (kPa)	Time (h)	Time:VC relationship	Estimate precision	
				UPTD	K
Continuous	<100	<5h	0	-	-
Continuous	<100	>>5h	Lin	↑	↓
Continuous	130-140	0-10 h	Exp*	↑	-
Continuous	150	0-10 h	Exp	-	-
Continuous	200-250	0-5 h	Exp	↓	-
Itermittent	200	0-4 h	0	↑	↑
Recovery	150-250	0-24h	Sigm or Exp		-

Model	Cont. Exp.		Cont. + Intermitt. Exp.	
	E	E+R	E	E+R
UPTD (4)	35 %		32 %	
Proportional (7, 15)	35 %	33 %	33 %	33 %
Proportional healing (7)	75 %	60 %	71 %	56 %
Power (8)	66 %	61 %	25 %	53 %

Risberg and Van Ooij, UHM 2022;49(4):395-413



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Arieli K and ESOT – the difference

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

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

pO_2: Atm
t: h

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

pO_2: Atm
t: min

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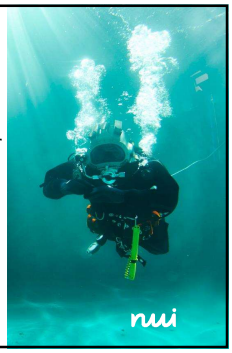
ESOT

- Equivalent Surface Oxygen Time
- 1 ESOT = The hyperoxic exposure reached after breathing pO_2=1 Atm for 1 min.
  - Conceptually similar to UPTD/OTU

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

pO_2: Atm
t: min



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Summary – exposure limit

ESOT after dive	Maximum number of successive days of diving	Minimum surface interval (h)
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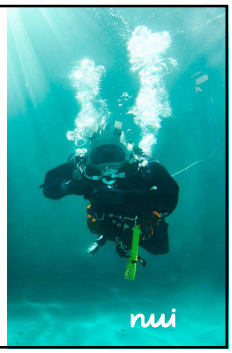
Minimum surface interval: The time required in normoxia or air diving only to ignore/zero ESOT from the preceding exposure



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Do we need hyperoxic monitoring in surface-oriented (non-sat) diving?

	BG: Air DC: IW air	BG: Air DC: SurDO$_2$	BG: Air DC: TUP Air/O$_2$
Profile (msw/min)	27/60	15/180	24/180
UPTD	36	143	312
# consecutive diving days (Repex)	>10	>10	10

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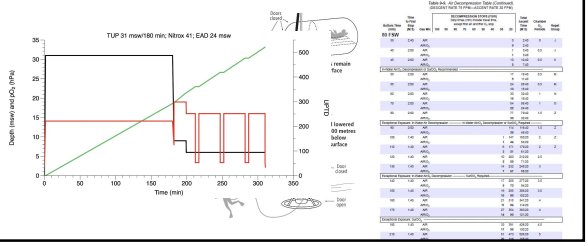
With Nitrox bottom gas and TUP or SurDO$_2$ – yes we need monitoring.



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Nitrox + TUP or SurDO2 calls for hyperoxic monitoring

	BG: Air DC: IW air	BG: Nitrox DC: IW nitrox	BG: AirDC: SurDO$_2$	BG: Nitrox DC: SurDO$_2$	BG: Air DC: TUP Air/O$_2$	BG: Nitrox DC: TUP Air/O$_2$
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 (Repex)	>10	5	>10	4	10	4

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Calculation of multi-pO_2 segmented dives

- A dive with these segments
  - 180 min with pO2=1.3
  - 17 min with pO_2=1.9 Atm
  - 96 min with pO2=1.6 Atm
- Calculus
  - 180 min 1.3 Atm
    - 328
  - 17 min 1.9 atm
    - 65
  - 96 min 1.6 Atm
    - 303
- Total
  - 696 (328+65+303)

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

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To calculate it exactly

- Segments
  - 180 min 1.3 Atm
    - 180 x 1.82 = 328
  - 17 min 1.9 atm
    - 17 x 4.33 = 74
  - 96 min 1.6 Atm
    - 96 x 2.93 = 281
- Total
  - 683 (328+74+281)

pO_2 (Atm)	k
0.5	0.21
0.6	0.31
0.7	0.44
0.8	0.60
0.9	0.79
1	1.00
1.1	1.24
1.2	1.52
1.3	1.82
1.4	2.16
1.5	2.53
1.6	2.93
1.9	4.33
2.2	6.06
2.5	8.12

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A DMAC Guidance note for operational support


The Diving Medical Advisory Committee

Exposure Index for Pulmonary Oxygen Toxicity in Surface-Oriented Diving

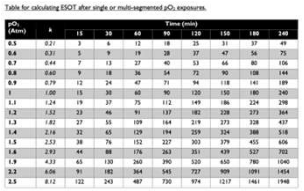
Table for calculating ESOT after single or multi-segmented pO_2 exposures.

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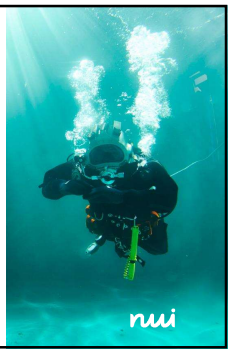
Summary – part 1

- ESOT is a simple mathematical transformation of Arieli K
- ESOT respects the Arieli K relationship between pO_2 and time on ΔVC
- ESOT simplifies hyperoxic exposure monitoring compared to Arieli K
- Similar to UPTD
  - ESOT is a single dimension of time
  - ESOTs may be added for different pO_2 segments of a dive
  - ESOT express the POT of a 1 min exposure to pO_2=1 Atm



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The tricky part
Recovery and threshold limits

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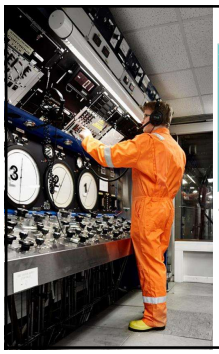

Which exposure limit?

Author	ESOT	Finding
Arieli 2019	937	ΔVC ↓2%
Shykoff 2015	937	P_{POT}=57%
Shykoff 2018	715	POT 50% after one exposure (P_{POT} 34%) "Well tolerated" for 5d, no accumulation <9d
Shykoff 2008	502	FEV1 0.16 %/d, 18d for 25% of divers to have significant spirometric change (P_{POT} 16%)
Thorsen 1998 Pott 2019	632-665	No PFT changes after 21-25 sessions
Ornhagen 1989	615	No PFT changes after seven days

- If 2 d recovery*
  - 1-2 d exposure: ESOT=660
  - 5 d exposure: ESOT=500
  - 10 d exposure; ESOT=420

*: "Recovery"=Normoxia or air dive only

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The practical consequence

	BG: Air DC: IW air	BG: Nitrox DC: IW nitrox	BG: AirDC: SurDO$_2$	BG: Nitrox DC: SurDO$_2$	BG: Air DC: TUP Air/O$_2$	BG: Nitrox DC: TUP Air/O$_2$
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 (Repex)	>10	4	>10	4	10	4
ESOT	33	582	344	719	436	739
# of consecutive diving days ESOT	No limit	2	10	Not recommended	5	Not recommended

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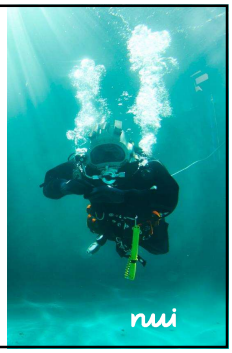
Summary – part 2

- Extremely limited data on >5 successive days of hyperoxic exposure
- Exposure limits are heavily based on Shykoffs 130-140 kPa exposures
- Suggested limits are probably conservative due to
  - Divers are resting during decompression
  - Air breaks are provided during decompression
- Suggested threshold limits will mainly affect number of successive days with Nitrox as breathing gas with SurDO$_2$ and TUP decompression



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Limitations and caveats

- Very limited data available on multiday exposures and in particular
  - Multiday exposure with low hyperoxic load
  - Recovery
- Arieli K/ESOT behaves unexpected for multiday exposures ranging 1.1 – 1.4 Atm

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