An agile implementation of the “K-value”: a severity index for CNS- and pulmonary oxygen-toxicity

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Preamble:

The K-value power functions for the central nervous system and pulmonary oxygen toxicity (CNS-OT, P-OT) are described in: [1], [2], [3], [4] & [5], pls. cf. chapter „References“.

As Ran et al. would have it ([3], abstract), there is a need for an implementation. Which is what we did ([6], [7], [8], [9]).

„Agile“ means here, in the context of IT-projects: a failure rate of 20 % is subliminally accepted … Which is why we put the software on the BETA TEST site of „**DIVE**“:

https://www.divetable.info/beta/index.htm

pls. cf. chapter „Handling of DIVE“. Error reports and enhancement requests are very welcomed, via e-mail to our head of lab: director@SMC-de.com

Overview: K-Value calculations for CNS-OT risc @ ca. 1 % & P-OT < - 2 % ΔVC:

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power functions:

$$K = t^2 * pO_2{}^c$$

CNS-OT:	**K < 26,108**	*t in min.*	*pO_2 in atm*	*c = 6.8*
P-OT:	**K < 244**	*t in hours*	*pO_2 in atm*	*c = 4.57*

recovery function:

$$K_{recovery} = K_{end} * e^{-(\tau * t_{recovery})}$$

τ = time constant: 0.079; $t_{recovery}$ in min.

K-Value Calculation, e.g. CNS-OT:

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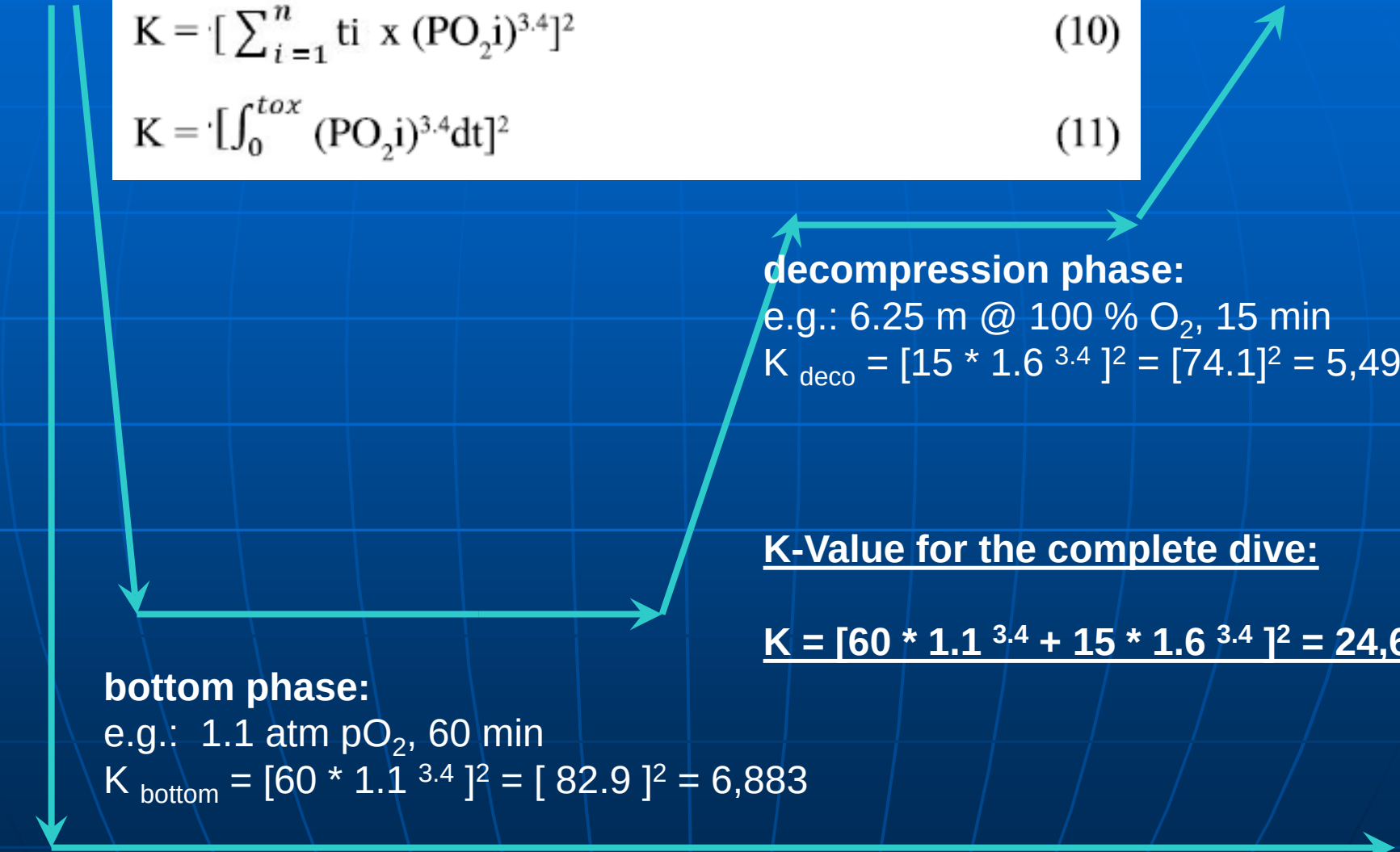
$$K = [\sum_{i=1}^{n} ti \times (PO_2 i)^{3.4}]^2 \quad (10)$$

$$K = [\int_0^{tox} (PO_2 i)^{3.4} dt]^2 \quad (11)$$



decompression phase:
e.g.: 6.25 m @ 100 % O_2, 15 min
$K_{deco} = [15 * 1.6^{3.4}]^2 = [74.1]^2 = 5,498$

K-Value for the complete dive:

$K = [60 * 1.1^{3.4} + 15 * 1.6^{3.4}]^2 = 24,684$

bottom phase:
e.g.: 1.1 atm pO_2, 60 min
$K_{bottom} = [60 * 1.1^{3.4}]^2 = [82.9]^2 = 6,883$

K-Value Calculation, e.g. CNS-OT:

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Example I: say, you have a diver down, working @ 1.1 atm pO_2, now for 60 min at the baseplate of your wind power station. Her decompression obligation becomes significant. But now you need to get her up asap due to surface surge, swell, … whatever. How can you decompress her most efficient, but quite safely?

The CNS-OT K-value for her bottom phase (pls. cf. slide #3) is: $K_{bottom} = 6{,}883$

For one decompression phase, say: 6.25 m @ 100 % O_2 we have: $K_{deco} = 5{,}498$
For these 2 stages we get: K = 24,684. So how much have you left @ 3m?
How long could you leave her instead @ 9m?

For a 1% CNS risk you have left 26,108 – 24,684 = 1,424 K-units.
Looks like a lot: but it‘s not!
This is already ca. 24,684 / 26,108 = 0.9454, i.e. more than 94 % of one K_{max}:
(pls. cf. slide # 6) so this translates to **less than 1 min @ 3 m** …

For the same accepted risk, the time frame @ 9m is approx. 8 min.

For a ca. 2 % risk, the times @ 6 and @ 9 m are, respectively: ca. 32 or 17 min.
Pls. cf. the slides # 7 & 8.

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$$K_{bottom} = t^2 * pO_2{}^c$$

$$K_{Dive} = [t * pO_2{}^{c/2} + t_{deco} * p_{deco}O_2{}^{c/2}]^2$$

α β

Since K_{bottom} is defined via known t & pO_2, as well for hyperoxic ***multi-level*** exposures ([1], Appendix A), there results a quadratic equation in the standard form for t_{deco} with the free parameters:
$p_{deco}O_2$ and $K = K_{max(CNS/P\ risc)}$:

$$[\alpha + \beta * t_{deco}]^2 - K_{max} = 0 \rightarrow$$

$$\alpha^2 - K_{max} + 2 * \alpha * \beta * t_{deco} + (\beta * t_{deco})^2 = 0$$

K_{max} definitions ([3], p. 155, 157):

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CNS-OT:

K < 26,108 @ 1 % CNS risk
K < 58,571 @ 2 % CNS risk
K < 196,811 @ 4 % CNS risk
K < 432,700 @ 6 % CNS risk

P-OT:

K < 244 @ - 2 % ΔVC
K < 1,220 @ - 10 % ΔVC

For these 6 values of K_{max} we evaluate with the already calculated 2 K-values for CNS-OT & P-OT of the topical hyperoxic exposure (= the actual dive) the following:

→ ***% of K_{max}***
→ ***time in [min*] (for CNS-OT) or *[h]* (for P-OT) to reach K_{max}**

for an intended / required *target pO_2* as a free input-parameter. The target pO_2 is the pO_2 for the final or any other decompression stage.

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From the bottom phase of the example above (pls. cf. slide # 3) we get the following output:

```
 was jetzt?k
 K-Value Plan: CNS-OT & P-OT
 Target pO2, default = 1.6:
 in [atm] !!!
 topical K CNS-OT:     6884.4        topical K P-OT:      1.5
****  K max values  ******************** CNS-OT:
 1% risk:   26108.  2% risk:   58571.  4% risk:  196811.  6% risk:  432700.
 percent of K max dose:
 1% risk: .264  2% risk: .118  4% risk: .035  6% risk: .016
 max. time [min] for 1% CNS risk:   15.9
 max. time [min] for 2% CNS risk:   32.2
 max. time [min] for 4% CNS risk:   73.0
 max. time [min] for 6% CNS risk:  116.3
****  K max values P-OT:  244      1220 ****
 percent of K max dose:
 -2% delta VC: .006 -10% delta VC: .001
 max. time [h] for - 2 % delta VC:   4.912
 max. time [h] for - 10 % delta VC:  11.509
 was jetzt?
```

→ i.e.: the final decompression should not be substantially longer than 15 min; or ca. 30 min, if you opt for a 2 % CNS risk.

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The target pO_2 (default = 1.6 atm) could be set to any other intended / required value, for e.g.: 1.9 atm:

```
 was jetzt?k
 K-Value Plan: CNS-OT & P-OT
 Target pO2, default = 1.6:
 in [atm] !!!  1.9
 topical K CNS-OT:     6884.4        topical K P-OT:      1.5
****  K max values  ******************** CNS-OT:
 1% risk:   26108.  2% risk:   58571.  4% risk:  196811.  6% risk:  432700.
 percent of K max dose:
 1% risk: .264  2% risk: .118  4% risk: .035  6% risk: .016
 max. time [min] for 1% CNS risk:    8.9
 max. time [min] for 2% CNS risk:   17.9
 max. time [min] for 4% CNS risk:   40.7
 max. time [min] for 6% CNS risk:   64.8
****  K max values P-OT:  244      1220 ****
 percent of K max dose:
 -2% delta VC: .006 -10% delta VC: .001
 max. time [h] for - 2 % delta VC:   3.317
 max. time [h] for - 10 % delta VC:   7.771
 was jetzt?
```

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References:

[1] Arieli, R., A. Yalov, and A. Goldenshluger. Modeling pulmonary and CNS O2 toxicity and estimation of parameters for humans. J Appl Physiol 92: 248–256, 2002; 10.1152/japplphysiol.00434.2001.

[2] Aviner B, Arieli R and Yalov A (2020) Power Equation for Predicting the Risk of Central Nervous System Oxygen Toxicity at Rest. Front. Physiol. 11:1007.doi: 10.3389/fphys.2020.01007

[3] Arieli R. Calculated risk of pulmonary and central nervous system oxygen toxicity: a toxicity index derived from the power equation. Diving and Hyperbaric Medicine. 2019 September 30;49(3):154-160. doi: 10.28920/dhm49.3.154-160. PMID:31523789.)

[4] Arieli, R., Shochat, T., and Adir, Y. (2006). CNS toxicity in closed-circuit oxygen diving: symptoms reported from 2527 dives. Aviat. Space Environ. Med. 77, 526–532.

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References:

[5] Wingelaar TT, van Ooij P-JAM and van Hulst RA (2017) Oxygen Toxicity and Special Operations Forces Diving: Hidden and Dangerous. Front. Psychol. 8:1263. doi: 10.3389/fpsyg.2017.01263

[6] the SubMarineConsulting Group (1991) **DIVE:** a decompression suite;

[7] Vered, Nurit; Rosenblat, Miri (2021) Synopsis: some collateral aspects of DCS, DOI: http://dx.doi.org/10.13140/RG.2.2.22131.66087

[8] Vered, Nurit; Rosenblat, Miri (2021) Synopsis: Fact Sheet & PoC https://www.researchgate.net/publication/349504991_Synopsis_Fact_Sheet_PoC_for_DIVE_Proof_of_Concept_for_a_free-shareware_decompression_suite

[9] Salm, Albi (2012) **Mother Nature is a Bitch: beyond a pO_2 of 1.6** TDM, Vol 07 / 2012, p. 16 - 22

[10] http://divingresearch.scripts.mit.edu/militarydivingdata/

Handling of DIVE Version 3_10 (1)

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An agile implementation of the "K-value": a severity index for CNS- and pulmonary oxygen-toxicity

Download free of charge from the DIVE Version 3 BETA TEST site:
the latest DIVE Version for beta testing is always staged there:

https://www.divetable.info/beta/index.htm

along with information on production date, size in bytes, new features and the checksums for verifying the download.

→ **DIVE V 3_10** is now (as per 06/2021) at an early deployment stage
(https://www.divetable.info/beta/D3_10.exe)

→ but the german manual for the old, the 3_09, still holds,
Update will follow in a couple of months:
https://www.divetable.info/DIVE_V3/DOXV3_0.pdf

Please, note: since the release train for
→ the english version (V3_04) is somewhat slower …
DIVE V 3_10 is not compatible with all older versions!

https://www.divetable.info/DIVE_V3/V3e/index.htm

The *workaround* is to use the english manual with the new 3_10:
The mnemonics to control DIVE are in english, anyway.

Handling of DIVE Version 3_10 (2)

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Example II: say, we had a tender after a HBOT session @ 2 atm pO_2, 30 min. Suddenly an urgent CO intox comes in: you need to put her again in the chamber due to lack of staff.
What would her CNS- & P-OT parameters look like?

Set the mixture to oxygen („**m**" „**1.**") (*****) and the parameters for the 1st. exposure: „**d**" „**10.1**" „**30.**" „**z**" offers all parameters relevant to the dive:

```
 was jetzt?z
Luftdruck:  1.013  PO2:  2.002 AMV: 25.0 RQ:  1.000
 O2:   1.000 He:   0.000 N2:   0.000
 CNS:   120.0 OTU:    74.7 AR =   9.00 VO2 =  0.250 Latency: N
 K Values   CNS-OT:   92230.       P-OT :     6.
 NUM FLAG: OFF   Wassertemp.:   20.00  Wasserdichte:  998.203   PRT=  11.0
Korrektur: N GFHI=   1.00 GFLO=   1.00 LAST STOP=  3.0 m First Stop =  3.0 m
Tiefe:  10.10    Zeit:     30.0 max. Tiefe=  10.10 ges. Tauchzeit=     30.0
  berechnete Kompartimentwerte mit N2 Matrix: ZH-L      He Matrix: ZH-L
 Nr.:  1 0.0044 P N2 0.0000 P HE Sum.=  0.0044 Ceil. m=  0.00 Putol:  0.000
 Nr.:  2 0.0595 P N2 0.0000 P HE Sum.=  0.0595 Ceil. m=  0.00 Putol:  0.000
 Nr.:  3 0.1516 P N2 0.0000 P HE Sum.=  0.1516 Ceil. m=  0.00 Putol:  0.000
 Nr.:  4 0.2601 P N2 0.0000 P HE Sum.=  0.2601 Ceil. m=  0.00 Putol:  0.000
 Nr.:  5 0.3705 P N2 0.0000 P HE Sum.=  0.3705 Ceil. m=  0.00 Putol:  0.000
```

The figures in line 4, designated as CNS & OTU are the values inherited from NOAA in 1991, using a linear extrapolation beyond 100 % / 1.6 atm with USN contingency exposure values [9].

(*): the **„"** are here only for clarity: for proper input, omit the „" but not the dot .
Forget the german text, focus on the pure numbers … ☺)

Handling of DIVE Version 3_10 (3)

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With the „**k**" mnemonic / command you invoke the K-Value Plan dialogue, using the already calculated CNS- & P-OT K-values to project into the K_{max} values (pl. cf. slide # 6) for the next required / planned hyperoxic exposure, the default being 1.6 atm:

```
 was jetzt?k
 K-Value Plan: CNS-OT & P-OT
 Target pO2, default = 1.6:
 in [atm] !!!
 topical K CNS-OT:    92229.6         topical K P-OT:      5.6
****  K max values  ****************** CNS-OT:
 1% risk:   26108.  2% risk:   58571.  4% risk:  196811.  6% risk:  432700.
 percent of K max dose:
 1% risk: ****  2% risk: ****  4% risk: .469  6% risk: .213
 max. time [min] for 4% CNS risk:   28.3
 max. time [min] for 6% CNS risk:   71.6
****  K max values P-OT:  244      1220 ****
 percent of K max dose:
 -2% delta VC: .023 -10% delta VC: .005
 max. time [h] for - 2 % delta VC:   4.527
 max. time [h] for - 10 % delta VC:  11.124
 was jetzt?
```

The 1% & 2% risk values are already exceeded, so there is no time left („ **** ")

Handling of DIVE Version 3_10 (4)

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Once again: „**k**“ , and the new pO_2 set to „**3.**“ atm:

```
was jetzt?k
K-Value Plan: CNS-OT & P-OT
Target pO2, default = 1.6:
in [atm] !!!  3.
topical K CNS-OT:    92229.6        topical K P-OT:      5.6
****  K max values  ******************** CNS-OT:
1% risk:   26108.  2% risk:   58571.  4% risk:  196811.  6% risk:  432700.
percent of K max dose:
1% risk: ****  2% risk: ****  4% risk: .469  6% risk: .213
max. time [min] for 4% CNS risk:    3.3
max. time [min] for 6% CNS risk:    8.5
****  K max values P-OT:  244      1220 ****
percent of K max dose:
-2% delta VC: .023 -10% delta VC: .005
max. time [h] for - 2 % delta VC:   1.077
max. time [h] for - 10 % delta VC:   2.645
was jetzt?
```

Et voilà ! There results a ca. 8 min @ 3 atm time frame for an approx. 6 % risk of an CNS-OT episode to appear and ca. 1 h for a decrement of 2 % vital capacity or 2½ h for an approx. 10 % decrement in VC.

Handling of DIVE Version 3_10 (5)

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Once you let her breathe a normoxic mixture („**m**“ „**.21**“ „**0**“ „**0**“)
during surface interval, say 30 min („**d**“ „**0.**“ „**30.**“),
you follow the recovery function (from [1] to [5]),
again via „**z**“ or in black-&-white in the log file, for later documentation / evaluation:

```
 was jetzt?z
Luftdruck:  1.013   PO2:  0.213 AMV: 25.0 RQ:  1.000
 O2:   0.210 He:   0.000 N2:   0.790
 CNS:    95.2 OTU:    74.7 AR =   9.00 VO2 =  0.250 Latency: N
 K Values   CNS-OT:    8630.       P-OT :      0.
 NUM FLAG: OFF   Wassertemp.:   20.00  Wasserdichte:  998.203   PRT=  16.5
Korrektur: N GFHI=   1.00 GFLO=   1.00 LAST STOP=  3.0 m First Stop =  3.0 m
Tiefe:   0.00    Zeit:     30.0 max. Tiefe=  10.10 ges. Tauchzeit=     60.0
  berechnete Kompartimentwerte mit N2 Matrix: ZH-L      He Matrix: ZH-L
 Nr.:  1 0.7464 P N2 0.0000 P HE Sum.=  0.7464 Ceil. m=  0.00 Putol:  0.000
 Nr.:  2 0.6991 P N2 0.0000 P HE Sum.=  0.6991 Ceil. m=  0.00 Putol:  0.000
 Nr.:  3 0.6370 P N2 0.0000 P HE Sum.=  0.6370 Ceil. m=  0.00 Putol:  0.000
```

Et voilà ! The ASCII log-file from: C:\DIVE\PROT\PROTOCOL.TXT (*):

PROTOCOL.TXT - Editor

Datei Bearbeiten Format Ansicht ?

```
 Yr: 2021 Mon: 05 D: 20 Hr: 11 Min: 11  Version: 3_10     , 06/2021

   TIEFE   ZEIT   GES.ZEIT  N    O    HE    CNS   OTU    K CNS     K POT    GAS
X    0.0     0.0      0.0  0.79 0.21 0.00    0.    0.       0.       0.     0.0
D   10.1    30.0     30.0  0.00 1.00 0.00  120.   75.   92230.       6.  1501.3
D    0.0    30.0     60.0  0.79 0.21 0.00   95.   75.    8630.       0.     0.0
X    0.0     0.0      0.0  0.79 0.21 0.00   95.   75.    8630.       0.     0.0
```

(*): proper installation on hard disk C: required

Handling of DIVE Version 3_10 (6)

We hard-coded these K-values, the exponents c (pls. cf. slides # 2 & 6) and the connected risk numbers into the DIVE FORTRAN source code and thus took them for granted. But they are not!

If you look at the data scatter ([2], tables 1 & 2; [3], Fig. 3; and [4]) and that multi-collinearity is not adressed properly, it is obvious, that a couple of thousands CNS episodes are needed to get the proper statistics.

This both translates to approx. 100,000 additional dives to be analyzed. But the data is already out there: for e.g. the USN has collected more than 145,000 dives on MK-25 and 29,000 on MK-16 systems during a ca. 7 year period [10] with 14 rebreather related „mishaps" (not specified) in the 0 to 30 feet depth bins.

The first derivative of a dose-reaction function is an underlying normal distribution. But this idea from the central limit theorem holds only for large, very large numbers. Which underlines the above. I.e.: there is leeway in the risk predictions and thus in the such derived c and K-values.

So, please, consider all of the above & the refs. as a start of a cooperation, run as an iterative process!

Handling of DIVE Version 3_10 (7)

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An agile implementation of the "K-value": a severity index for CNS- and pulmonary oxygen-toxicity

As already pointed out in the „Preamble“ section:
DIVE Version 3_10 is a **BETA Test version**,
in an early deployment stage. Chances are, there are errors!
Pls. notify them to us: we will appreciate it.
As well if you have feature requests.

Et voilà !
Basically, the DIVE software is for free, i.e.:
the software is provided on an „as-is“ basis. A full-blown english version 3_11 and a new english handbook will need some months, so take the german 3_10 in conjunction with the old english manual. But anyway we promise to give „friendly support“:

We want you to help get your job done!
If we could assist or if you have any questions:
do not hesitate to contact us per e-mail.

We would even set up on short notice an on-line session,
usually via CISCO Webex ®, free of charge!
Promise!

Fine tuning of DIVE:

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For **hyperbaric exposures with or without immersion**
a fine tuning could be done via the commands:

- → ascent rate („**AR**“)
- → ambient atmospheric pressure („**L**“)
- → the respiratory coefficient („**R**“)
- → physical workload / oxygen consumption („**W**“)
- → the ambient (water)-temperature („**te**“)
- → the water density („**di**“)
- → Buehlmann Safety Factor („**B**“)
- → last stop depth („**LS**“)
- → Gradient Factors High- & -Low („**gf**“)
- → a host of 9 alternative perfusion models („**nc**“)

- → And, as well, features like:
- → in-depth **P(DCS)** analysis with various models
- → pulmonary **R-/L** (right-to-left) shunting according to A. A. Buehlmann
- → oxygen-effects during decompression with pO_2 > 1.6 atm, like:
- → **bradycardia** and **vasoconstriction**
- → **latency** during change of breathing mix
- → **reduced perfusion** rates through low ambient temperature

And with: „**K**“ we recieve the K-Value Plan subroutine (slides # 7 & 8; 13 & 14)