Calibration of a new biophysical model dedicated to the prevention of decompression sickness

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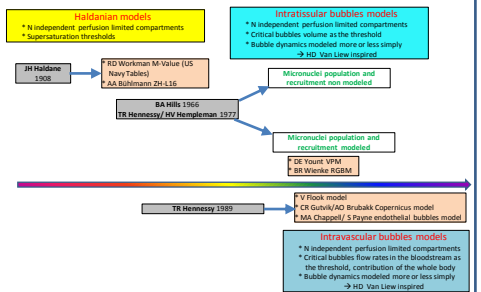
– Background of Scientific Research –

- Mathematical models of decompression allow the determination of safe decompression procedures for a limited range of exposures (pressure, duration, breathing gas)
- Most of the time, models contain parameters non related to a biophysical reality ➔ parameters tuned to fit at best tested/safe decompression profiles
- An extrapolation of these models to any type of exposition remains hazardous
- It is deemed that a biophysical approach of decompression can produce a relevant model for DCS prevention and DCS risk prediction

➔ A critical review of the biophysical foundations of existing models has been conducted by BF-SYSTEMES (micronuclei population recruitment, microbubbles dynamics, tissue saturation/desaturation asymmetry due to bubbles)

➔ A biophysical model merging the best hypothesis of existing models has been elaborated and preliminary validated by BF-SYSTEMES

- These last years there is a will to build biophysical models using Doppler detections as valuable data for parameters estimation [1][2]

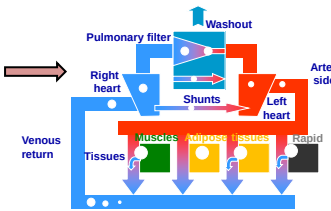


Relations between intravascular bubbles detected by Doppler and decompression sickness demonstrated in 1991 [3]

– BORA Biophysical Model –

Objective : determine and limit the global volume of microbubbles flowing through the right heart and accumulated in the pulmonary filter on a given period of time

Interest : the biophysical model can be correlated using risk database and experimental measurements through Doppler detections



$$\frac{dP_t}{dt} = k\left[f(P_{amb} - P_{H2O}) - P_t\right] - \frac{1}{RTS_t}\left[v_b \frac{dP_{amb}}{dt} + (P_{amb} - \beta)\frac{dv_b}{dt}\right]$$

- recruitment of pre-existing gas nuclei populations in tissues, transformed in microbubbles (depends on the supersaturation extent)

$$P_{ss} = P_t - P_{amb} + \beta$$

$$N_{microbubbles} = N_{max}\, e^{\frac{2\gamma A}{r_{ss\_max}}}$$

- microbubbles dynamics and their transfer in the blood

$$\frac{dR}{dt} = \frac{RTD_t S_t \frac{P_{ss}}{\beta} - \frac{R}{3}\frac{dP_{amb}}{dt}}{P_{amb}}$$

– References –

1. **Flook V.** *Predictions from a mathematical model of decompression compared to Doppler scores*, Undersea & Hyperbaric Medical Journal, 38(3) : 187-196, 2011.
2. **Gutvik C.R.** ***et al.*** *Parameter estimation of the copernicus decompression model with venous gas emboli in human divers*, Medical & Biological Engineering & Computing, 48(7) : 625-636, 2010.
3. **Sawatzky K.D.** *The relationship between intravascular Doppler-detected gas bubbles and decompression sickness after bounce diving in humans*, Thesis, York University, Toronto, 1991.
4. **Nishi R.Y.** ***et al.*** *XDC-2 digital decompression computer : assessment of decompression profiles by ultrasonic monitoring, Phase I to III*, DCIEM Reports 80-R-32, 1980, 81-R-02 ,1981,82-R-38, 1982.
5. **Lauckner G.R.** ***et al.*** *Evaluation of the DCIEM 1983 decompression model for compressed air diving, Series A to Q*, DCIEM Reports 84-R-72,1984, 84-R-73, 1984, 85-R-18,1985.

– Database & Calibration Method –

- The data set analyzed (Z) contains N=444 exposures selected amongst 48 different diving profiles [4][5]. For each exposure i we know the actual depth profile followed during the dive and we measure Doppler grade Z_i (in a discrete scale from 0 to 4, Spencer scale).
- We assume that bubble grades correspond to a quantification of the peak total gas volume produced by the body tissues :

$$Z_i = k \Leftrightarrow max_t\, V_i(t) \in]s_k, s_{k+1}],\ s_0 = 0,\ s_5 = \infty$$

- All parameters of the biophysical model are assumed known except two (α=[A ,N_{max}]). Moreover, the thresholds that define the discrete observed bubble grades are also unknown. Our goal is to infer the distribution of α, $p(\alpha)$, as well as the value of thresholds $s_1,\ldots,s_4$ based on the observations Z.
- We approximate the probability distribution of biophysical parameters A and N_{max} by a discrete measure, allocating weight $w_{i,j}$ at the point $\alpha_{i,j} = (A_i\ , N_{max,j}\ )$, i,j=1,…,$K$:

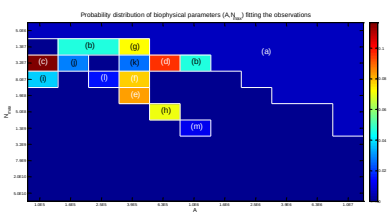
$$p(\alpha) = \sum_{i,j=1}^{K} w_{i,j}\delta(\alpha - \alpha_{i,j})$$

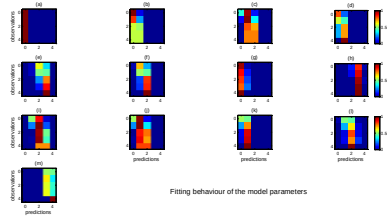
K=11 is the dimension of the (logarithmic) grid defined over the biophysical parameter space.

- Let θ denote the complete set of unknown parameters : $[A, N_{max}, s_1, \ldots, s_4]$. We estimate θ by maximum likelihood, by searching the maximum of :

$$\mathcal{L}(Z, w, \theta) = \Pr(Z|w,\theta) = \prod_{i=1}^{N} \Pr(Z_i|w,\theta).$$

– Results –





– Conclusion & Perspectives –

- Based on a data set Z of moderate size, we were able to reproduce the observed dispersion of bubble grades using the estimated discrete probability distribution of the biophysical model parameters.
- Future work : characterize accuracy of prediction; characterize the dispersion of a larger set of parameters; increase model complexity (with additional tissues); extend to non-discrete distribution of model parameters; estimate the probability of DCS for a given diving profile; use of continuous Doppler signals for parameters estimation (dynamics of bubbling and not only peaks)