ALTITUDE DECOMPRESSION SICKNESS

VARIABLE PHYSIOLOGICAL PARAMETERS IN INERT GAS EXCHANGE MODELS IMPROVE OUTCOME PREDICTIONS IN OPERATIONAL ALTITUDE EXPOSURES

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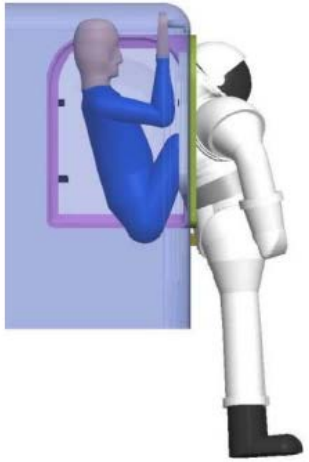
High Altitude Operations

Actual DCS occurrence is still reasonable foreseeable
(*ref. NATO standard AAMedP-1.18*)

Exploration Extravehicular Activity



Development of new prebreathe protocols
(*ref. Abercromby, Gernhardt and Conkin)*

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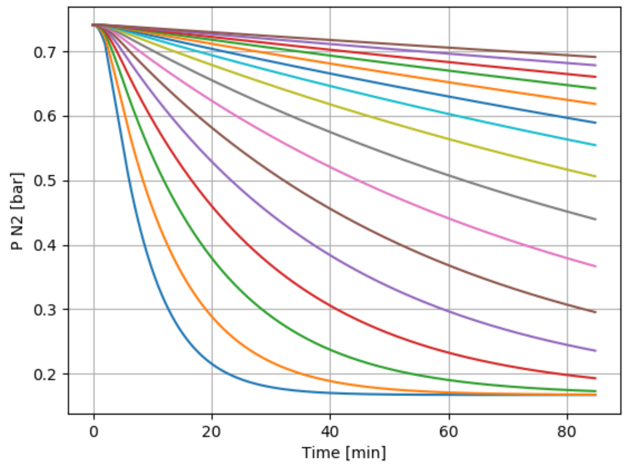
Tissue Gas Saturation

Decompression

1. Tissue Gas Supersaturation

Inert Gas Exchange Models – Inert Gas Tension

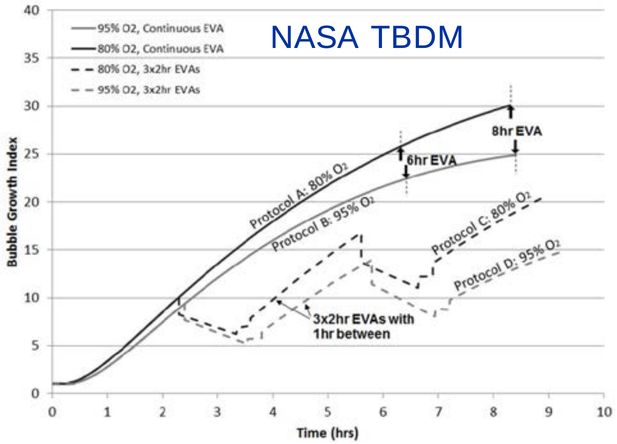


Fixed half-times

#1: no accurate view on the actual inert gas state

Venous Gas Emboli as evaluation tool

Bubble Growth Prediction



2. Bubble Formation & Growth

#2: mismatch between DCS risk predictions and experimental outcomes

3. Direct & Indirect Effects of Bubbles

e.g. embolization, tissue compression, inflammatory response…

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Experimental Data

Biophysical Gas Exchange Model

Model Predictions and Analysis

Nitrogen Washout and Venous Gas Emboli During Sustained vs. Discontinuous High-Altitude Exposures

Rickard Ånell; Mikael Grönkvist; Ola Eiken; Mikael Gennser

INTRODUCTION: The frequency of long-duration, high-altitude missions with fighter aircraft is increasing, which may increase the incidence of decompression sickness (DCS). The aim of the present study was to compare decompression stress during simulated sustained high-altitude flying vs. high-altitude flying interrupted by periods of moderate or marked cabin pressure increase.

METHODS: The level of venous gas emboli (VGE) was assessed from cardiac ultrasound images using the 5-degree Eftedal-Brubakk scale. Nitrogen washout/uptake was measured using a closed-circuit rebreather. Eight men were investigated in three conditions: one 80-min continuous exposure to a simulated cabin altitude of A) 24,000 ft, or four 20-min exposures to 24,000 ft interspersed by three 20-min intervals at B) 20,000 ft or C) 900 ft.

RESULTS: A and B induced marked and persistent VGE, with peak bubble scores of [median (range)]: A: 2.5 (1–3); B: 3.5 (2–4). Peak VGE score was less in C [1.0 (1–2), $P < 0.01$]. Condition A exhibited an initially high and exponentially decaying rate of nitrogen washout. In C the washout rate was similar in each period at 24,000 ft, and the nitrogen uptake rate was similar during each 900-ft exposure. B exhibited nitrogen washout during each period at 24,000 ft and the initial period at 20,000 ft, but on average no washout or uptake during the last period at 20,000 ft.

DISCUSSION: Intermittent reductions of cabin altitude from 24,000 to 20,000 ft do not appear to alleviate the DCS risk, presumably because the pressure increase is not sufficient to eliminate VGE. The nitrogen washout/uptake rate did not reflect DCS risk in the present exposures.

KEYWORDS: decompression sickness risk, fighter aircraft, gas bubble formation, hypobaric DCS, in-flight refueling, nitrogen elimination, repeated altitude decompression.

Ånell R, Grönkvist M, Eiken O, Gennser M. ***Nitrogen washout and venous gas emboli during sustained vs. discontinuous high-altitude exposures.*** **Aerosp Med Hum Perform. 2019; 90(6):524–530.**

This study concerns decompression stress during simulated long-duration high-altitude flying in fighter aircraft, with special reference to effects of intermittent excursions to lower altitudes. Before the introduction of pressurized aircraft cabins, altitude decompression sickness (hence- prebreathing oxygen vary between 18,000 and 25,000 ft (5486 and 7620 m) in different reports,[18,22,29] with a reported 5% DCS incidence after ≥4 h at 20,500 ft (6248 m) during oxygen breathing.[29] For tactical reasons, and since modern military aircraft commonly possess in-flight refueling capacity, demands

STUDY OVERVIEW

Conditions:

- A: continuous exposure to 24000ft for 80 min
- B: 4 x 20 min at 24000ft, with 3 x 20 min intervals at 20000ft
- C: 4 x 20 min at 24000ft, with 3 x 20 min intervals at 900ft

Breathing gas at 24000ft: 52.5% O_2 (normoxic breathing gas)

8 test subjects

1 case of DCS for condition B during last exposure to 24000ft

2 measurements:

- N_2 washout
- Venous Gas Emboli (VGE)

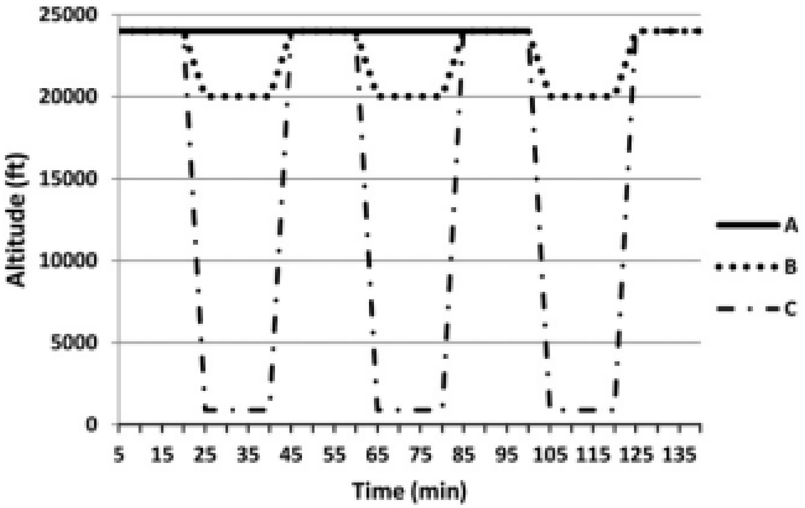

Fig. 1. Time-altitude profiles in conditions A, B, and C.

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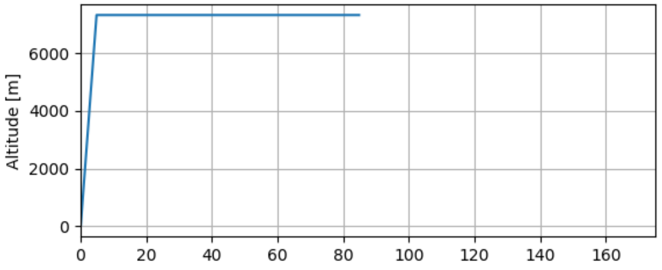
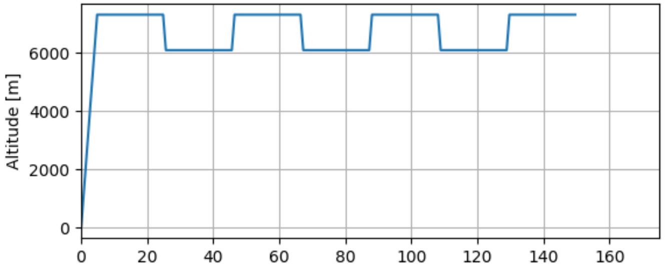
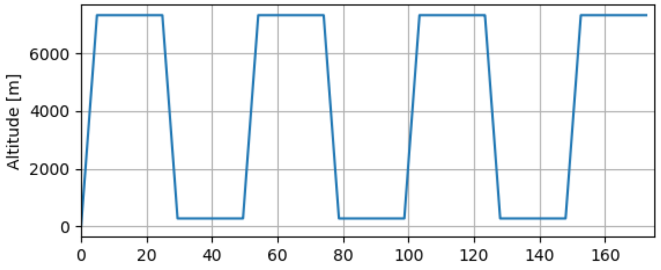
MEASURED N_2 WASHOUT







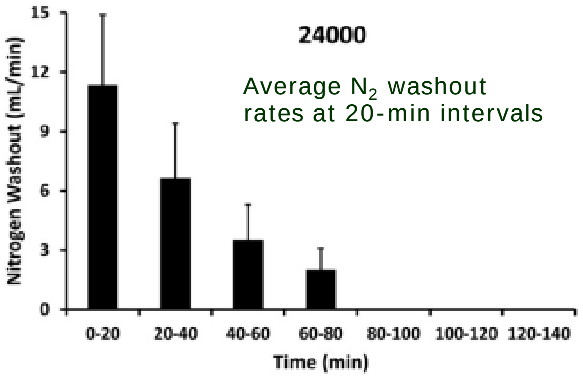


Fig. 3. Average nitrogen washout rate at 20-min intervals in condition A. Values are means (SD), *N* = 8.

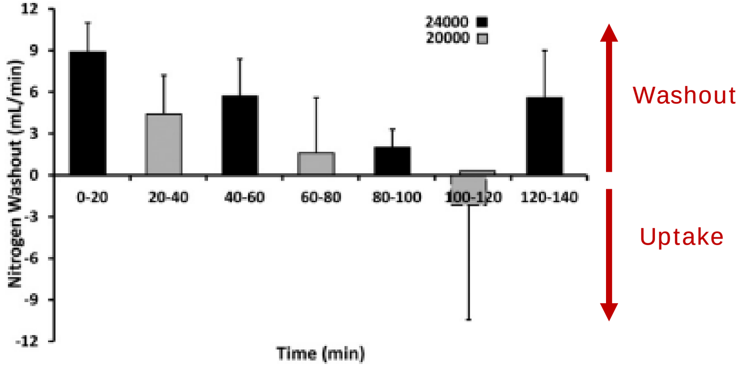


Fig. 4. Average nitrogen washout rates during the course of condition B. Hatched bar showing nitrogen uptake during the third period at 20,000 ft is without the subject who developed DCS. Values are means (SD), *N* = 8 for all time periods except for 0–20 min, where *N* = 5.

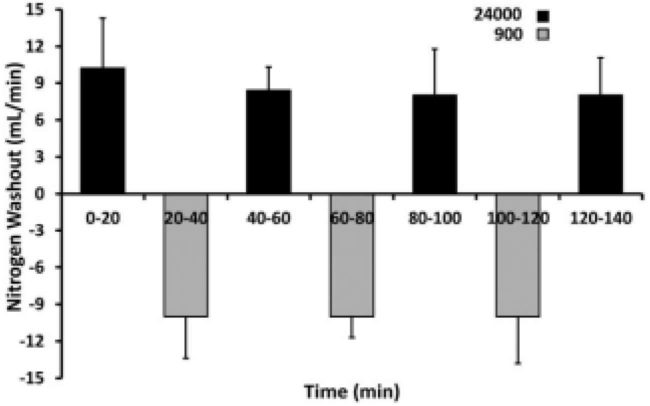


Fig. 5. Average nitrogen washout rates in condition C. Values are means (SD), *N* = 8.

gradually decreasing N_2 elimination rate

gradually decreasing N_2 elimination rate + uptake + increased outwash

alternating N_2 elimination and uptake

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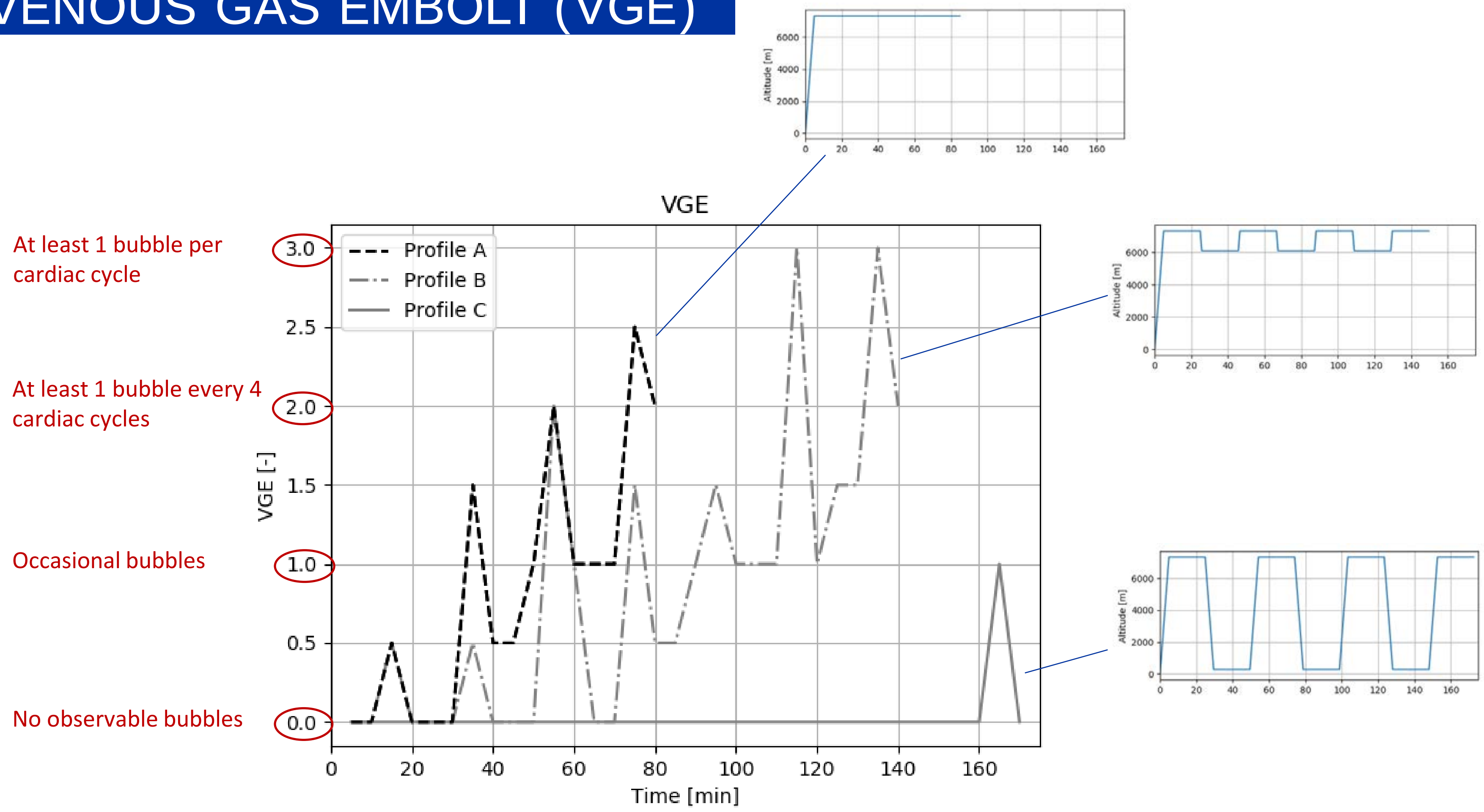
MEASURED VENOUS GAS EMBOLI (VGE)



The incidence of VGE during an 80min exposure to 24000ft is substantially reduced by intermittent 20min excursions to 900ft, but was slightly increased by 20min excursions to 20000ft.

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Experimental Data

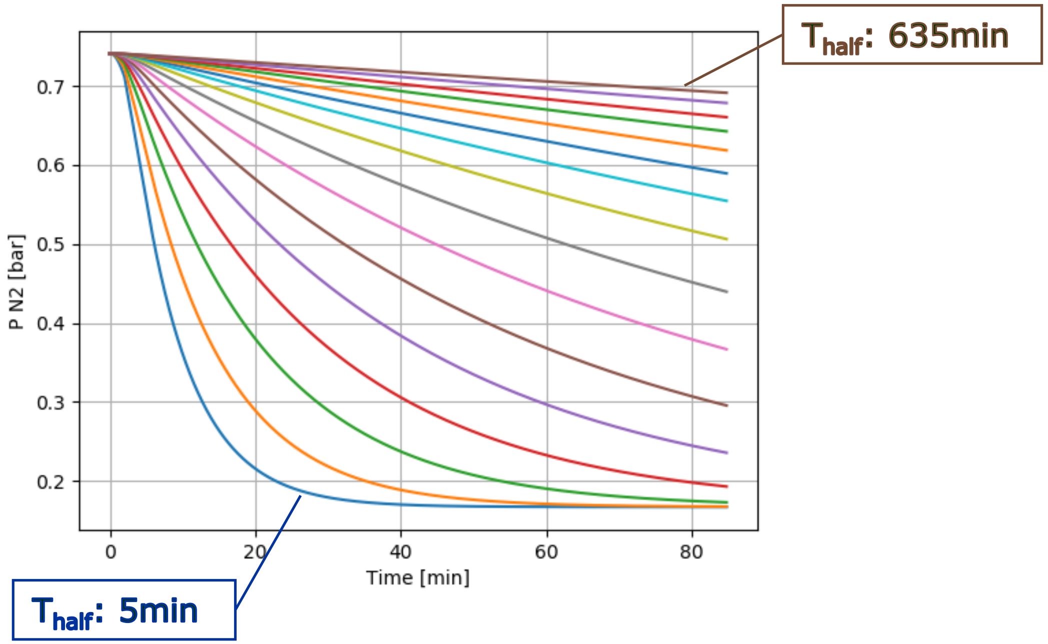
Biophysical Gas Exchange Model

Model Predictions and Analysis

INERT GAS TENSION

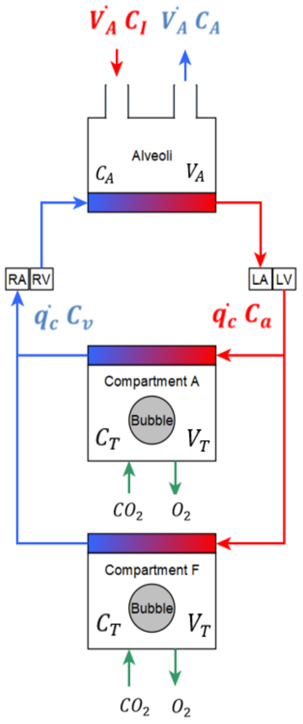
Theoretical N_2 gas tension using pre-determined fixed half-times

Bühlmann ZH-L16B model



Different approach: step away from using fixed half-times, and model instead the underlying <u>physiological parameters</u>

BIOPHYSICAL INERT GAS EXCHANGE MODEL



$\dot{q}_c$ = cardiac output

$\dot{V}_A$ = alveolar ventilation

C_I = inhaled concentration inert gas

C_A = alveolar and measured output concentration inert gas

C_a = arterial blood concentration inert gas

C_v = venous blood concentration inert gas

C_T = tissue concentration inert gas

V_A = alveoli compartment volume

V_T = tissue compartment volume

RA = right atrium

RV = right ventricle

LA = left atrium

LV = left ventricle

Only 2 out of 6 compartments are shown in the figure

Data based on ‘A.A. Bühlmann and E.B. Vollm, *Tauchmedizin*, Springer, 2002’

		Mass [kg]	Volume [L]	H_T/H_B	Perfusion [L/min]	Half-time [min]
A	brain & spinal cord	1.7	1.85	1.00	0.85	1.51
B	central circulation	2.1	2.64	1.00	2.58	0.71
C	skin	4.0	4.36	1.00	0.32	9.44
D	joints and bones	12.0	13.07	1.00	0.36	25.17
E	skeletal musculature	30.0	28.30	1.00	1.20	16.35
F	fatty tissues	12.0	13.07	5.15	0.36	129.72
	cardiac output [L/min]	5.67				
	alveolar ventilation [l/min]	6.80				

Six parallel compartments with physiological and anatomical parameters of particular tissues.

The half-times are a result of the physiological parameters. Physiological changes have a direct impact on these half-time values.

The transportation of N_2 is modelled by a set of Ordinary Differential Equations based on the ‘conservation of mass’ principle.

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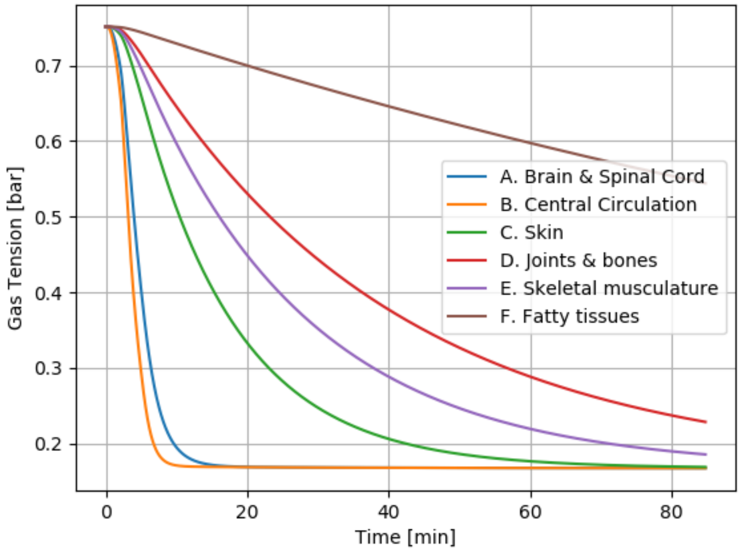
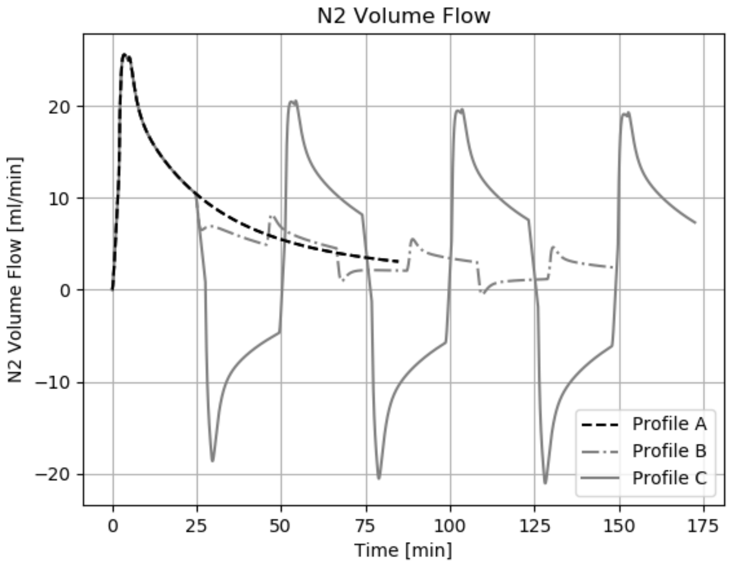
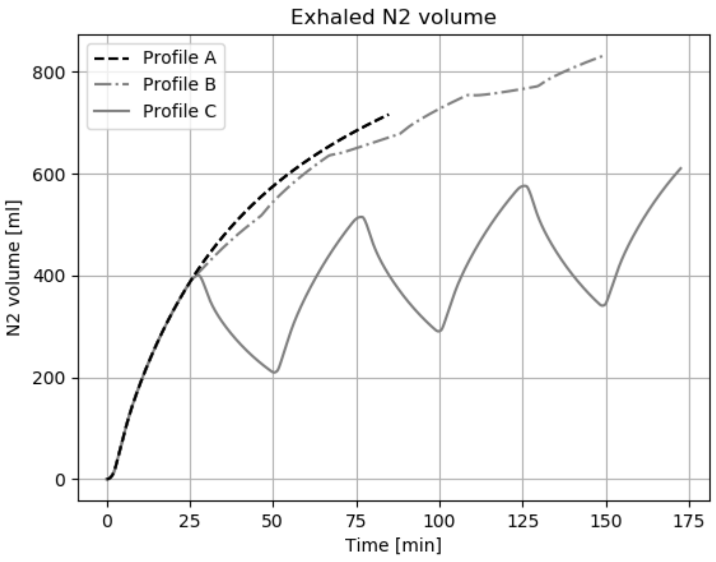
MODEL OUTPUT

N2 Gas Tension Curves







The physiological model provides additional information on the N_2 volume and N_2 volume flow.

The benefit of the physiological model is that its output can be directly compared with measurable signals.

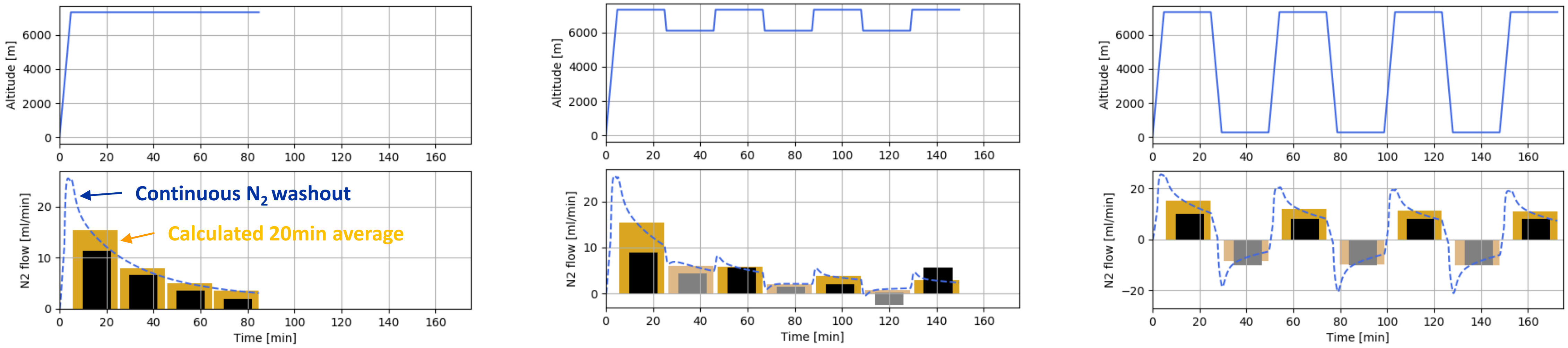
Experimental Data

Biophysical Gas Exchange Model

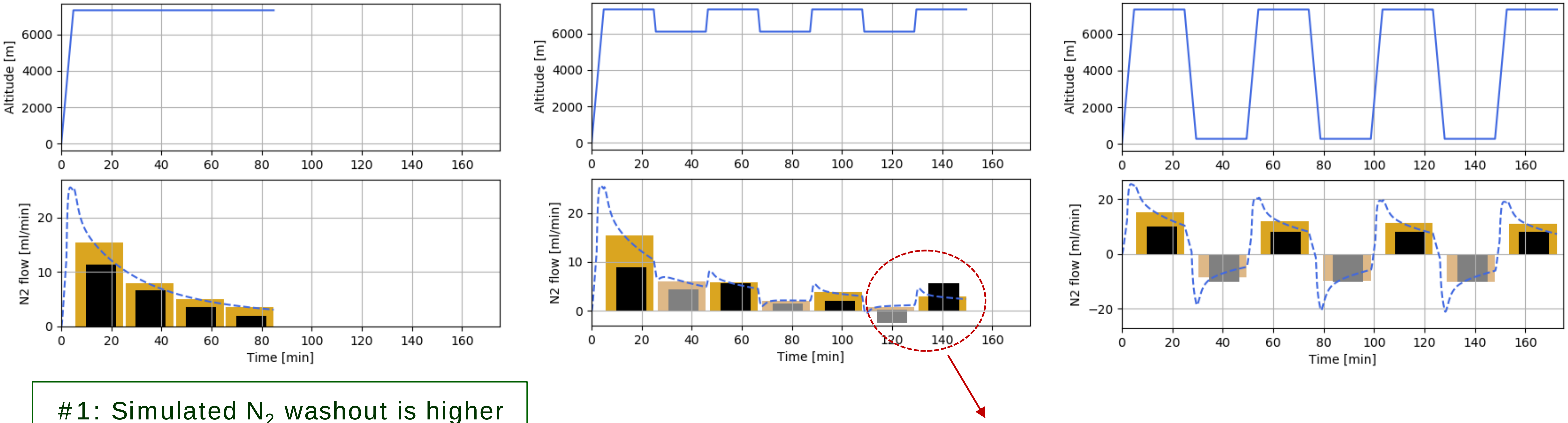
Model Predictions and Analysis

Washout Curves **Physiological Changes** **Flow Components** **Bubble Growth Predictions**

N_2 WASHOUT - SIMULATION



N_2 WASHOUT - OBSERVATIONS



#1: Simulated N_2 washout is higher than the measured N_2 washout

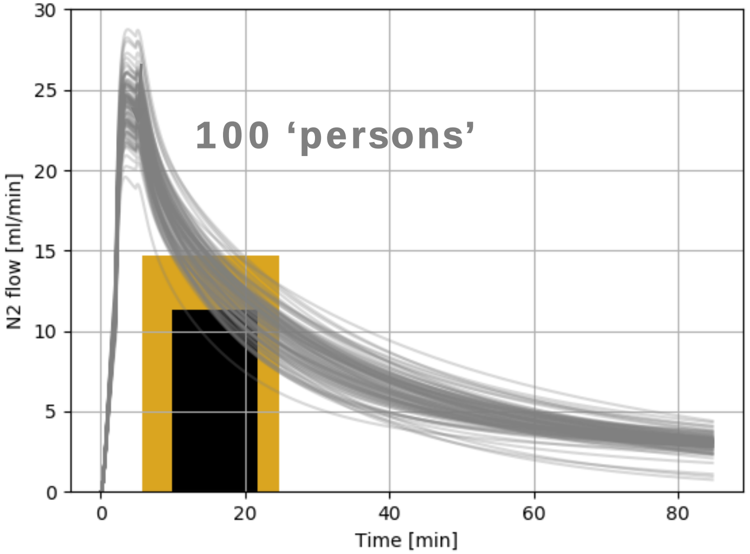
N_2 gas dynamics during last intermittent recompression at 20000ft:
- 5 subjects with <u>uptake</u>, 2 subjects with <u>slow washout</u> and 1 subject with a <u>very high washout rate</u>
- Overall: N_2 uptake when 1 subject is discarded

#2: The model does not predict an N_2 uptake, and it underestimates the N_2 outflow during the last altitude exposure

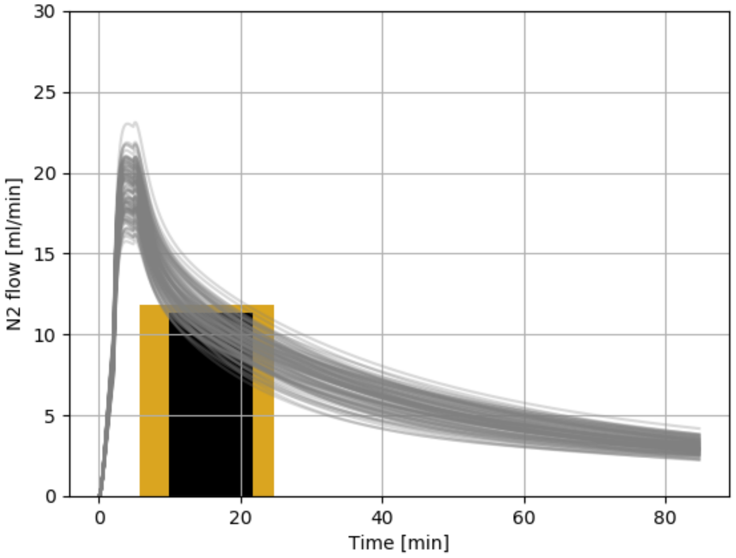
IMPACT OF PHYSIOLOGICAL CHANGES

Cardiac Output (CO) measurements during the experiment showed a significant reduction of CO during the experimental period, in rest.

Nominal Cardiac Output



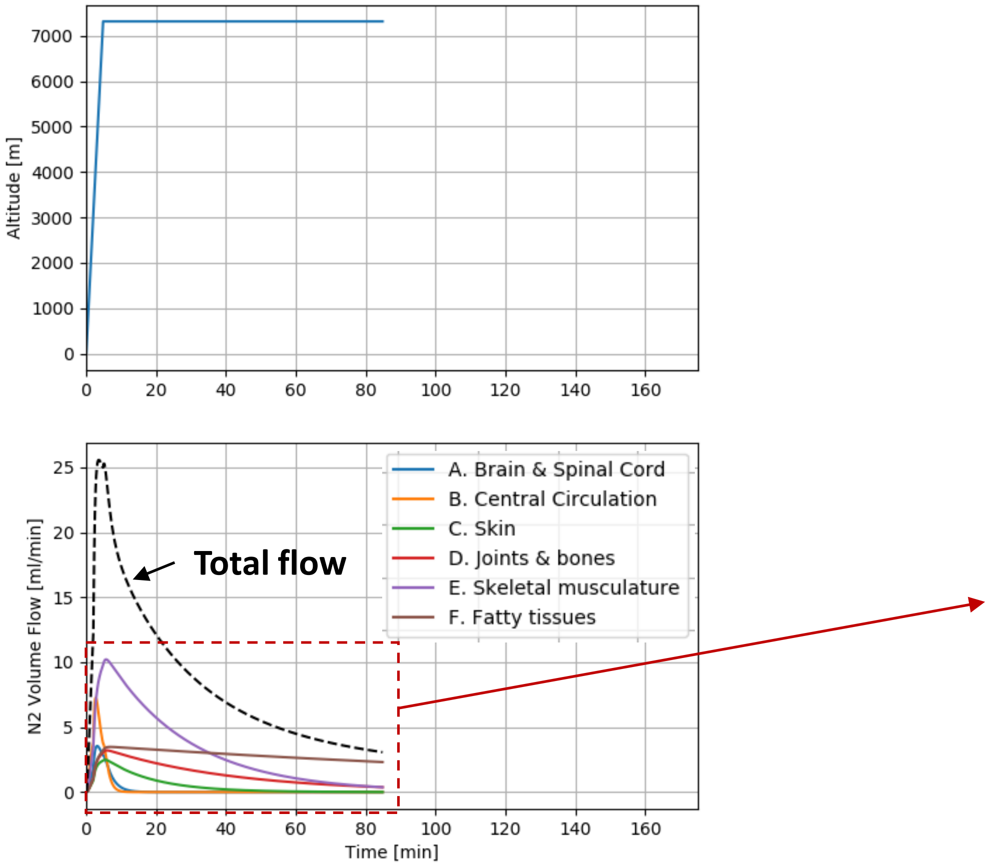
Reduced Cardiac Output (-30%)

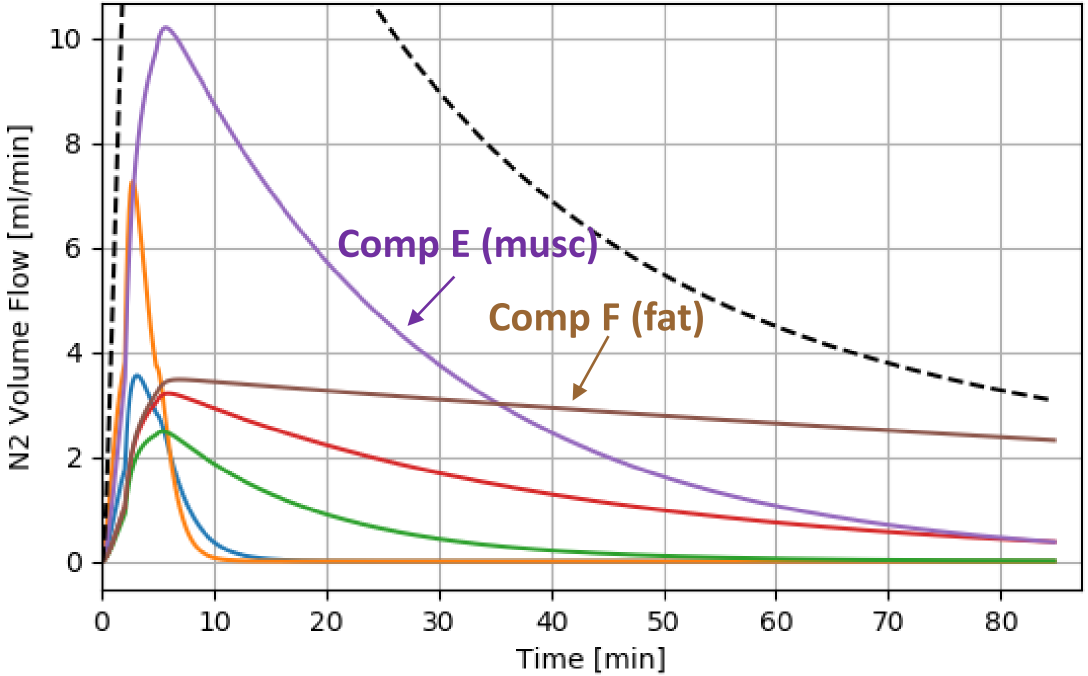


The benefit of a biophysical model is that physiological changes during decompression exposures can be accounted for.

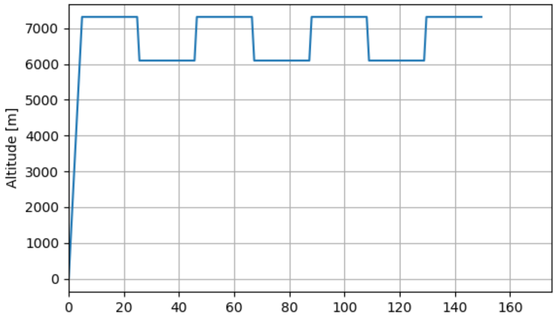
N_2 FLOW COMPONENTS – PROFILE A

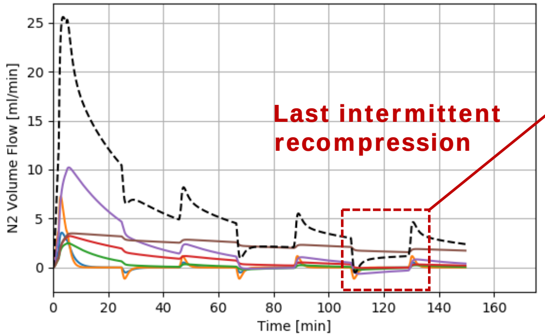
The total flow can be decomposed into the flow components of the different compartments

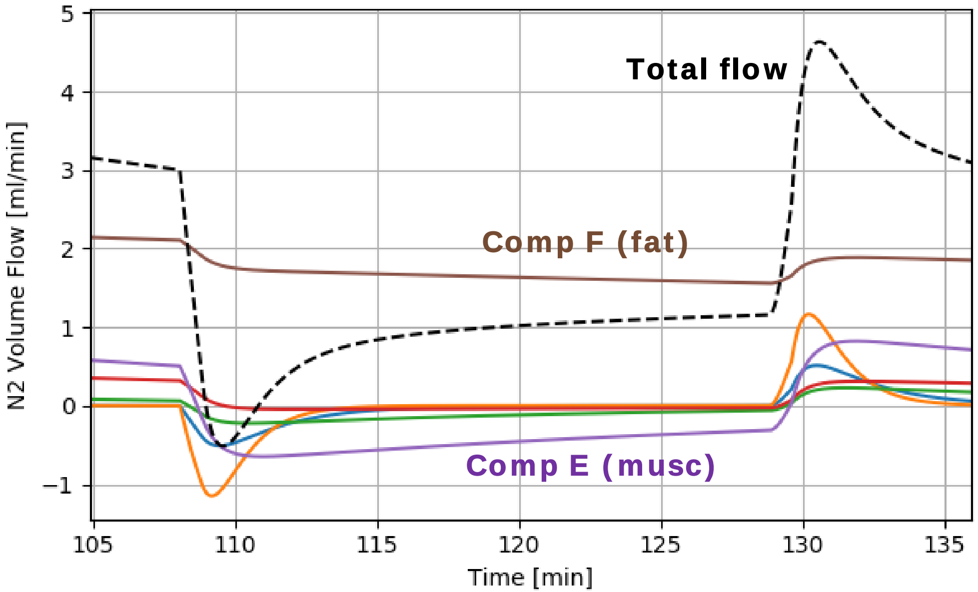




N_2 FLOW COMPONENTS – PROFILE B





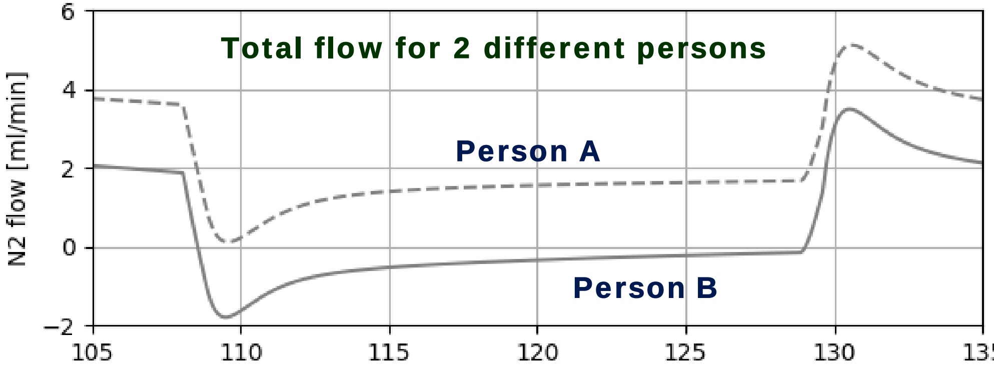


Washout

Uptake

Slow compartments: N_2 elimination

Faster compartments: N_2 uptake



Washout

Uptake

Proportion of different N_2 flow components determines total N_2 flow

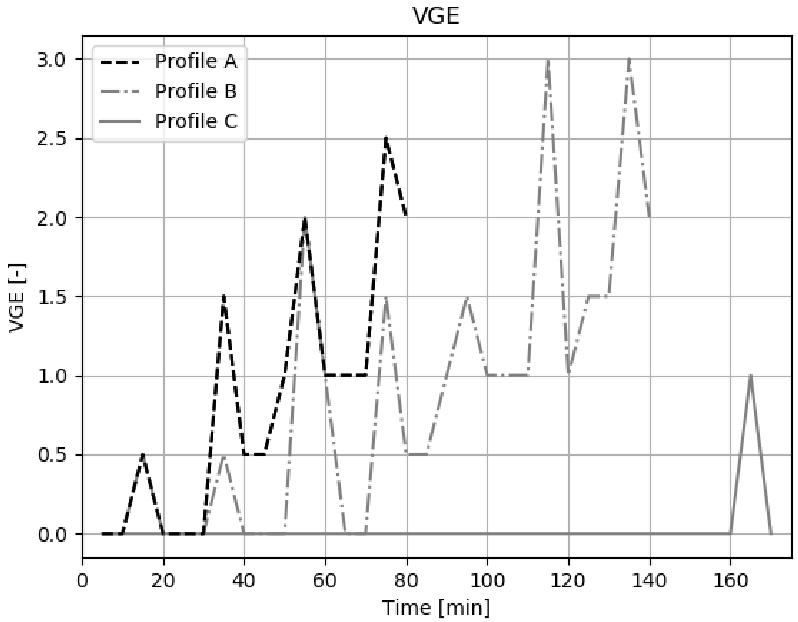
VGE – BUBBLE GROWTH

Bubble growth prediction as a <u>decompression stress predictor</u>

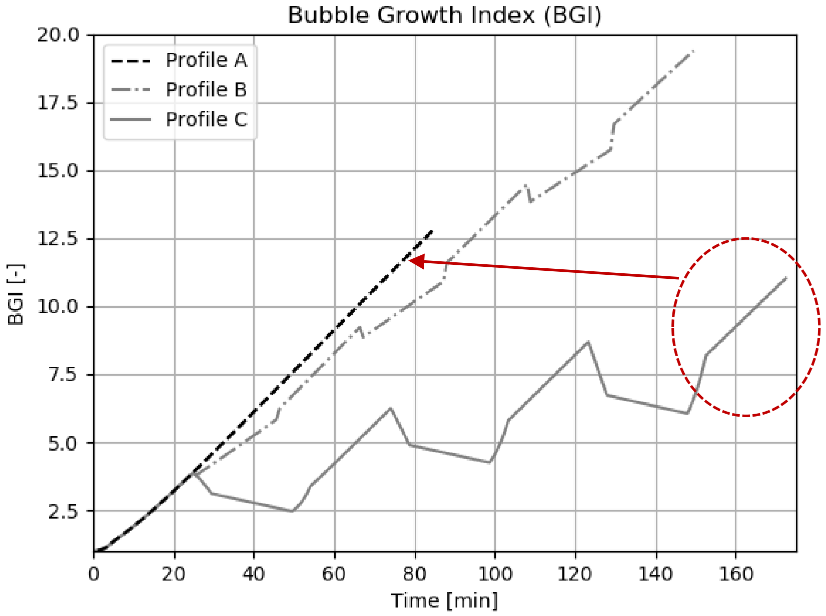
<u>Tissue Bubble Dynamics Model</u> (**TBDM**) (*ref. Gernhardt)*

- 10 compartments with fixed half-times; single bubble in each compartment
- input: inert gas tension
- Bubble Growth Index (**BGI**): maximum bubble size attained in any of the compartments, relative to an inital bubble nucleus size.

Measured



TBDM prediction

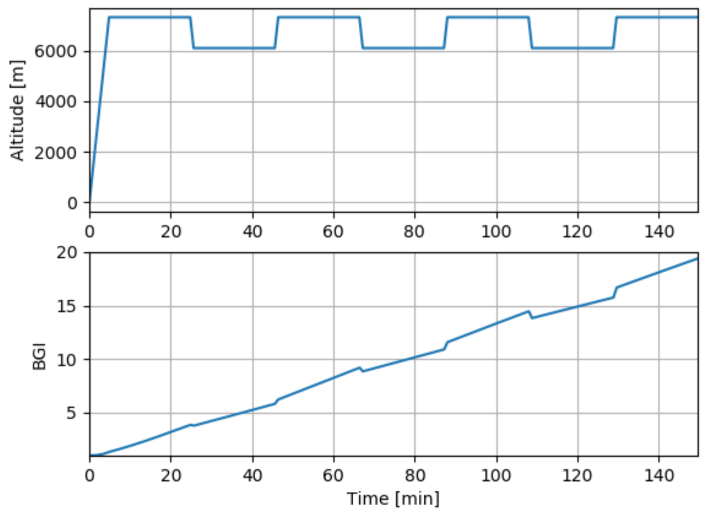


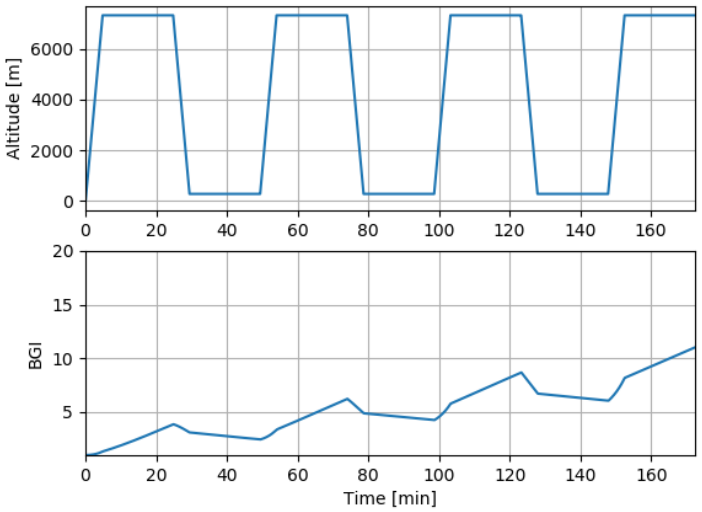
Predicted bubble growth similar to profile A

Incorrect evaluation of decompression procedures using the theoretical bubble growth (TBDM) as decompression stress predictor

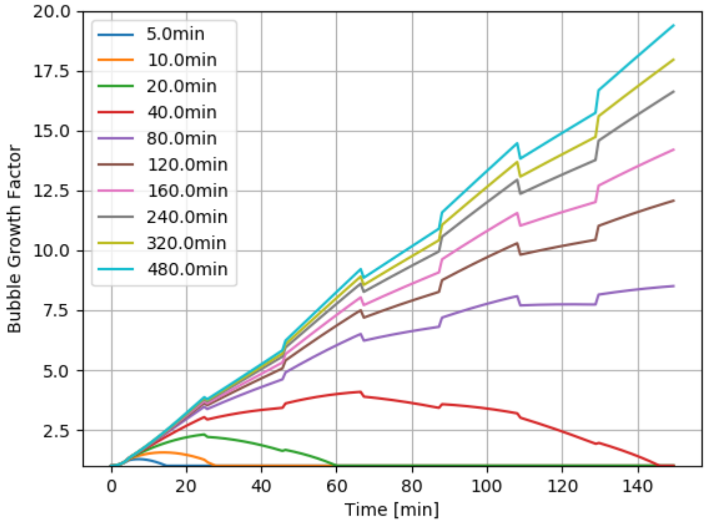
BGI: TISSUE COMPONENTS FOR EACH PROFILE

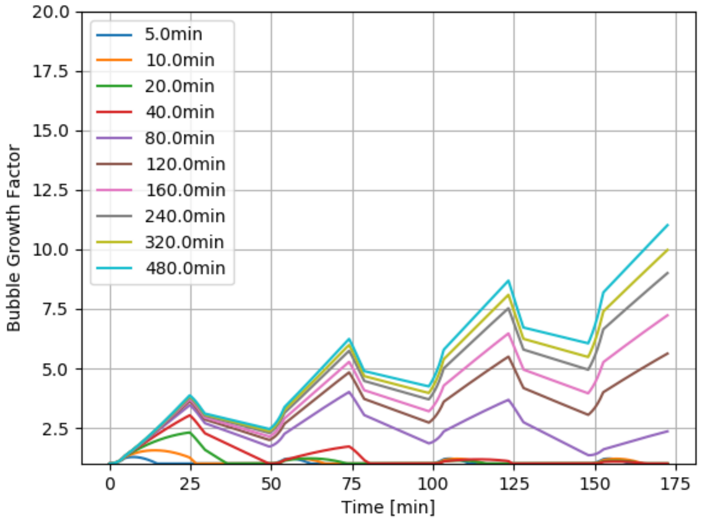
Maximum = BGI





BGI components



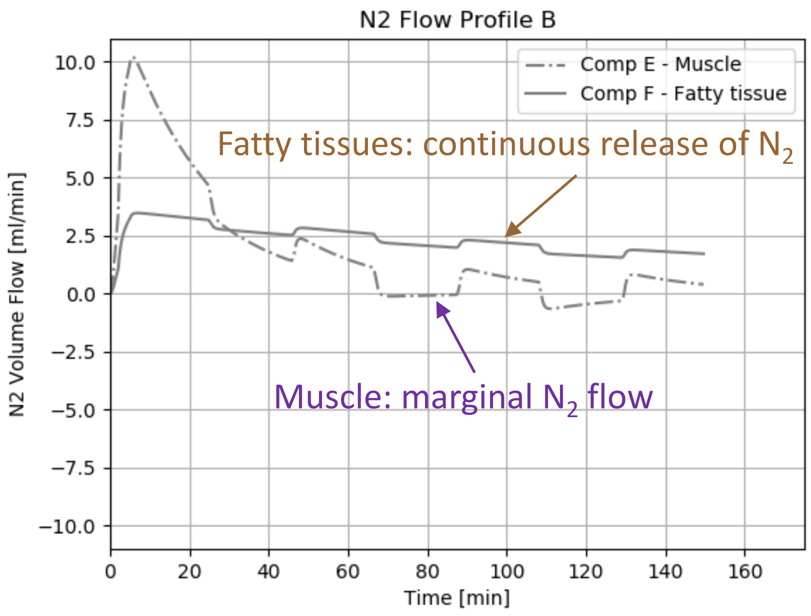


WEIGHING FACTORS – N_2 FLOW COMPONENTS

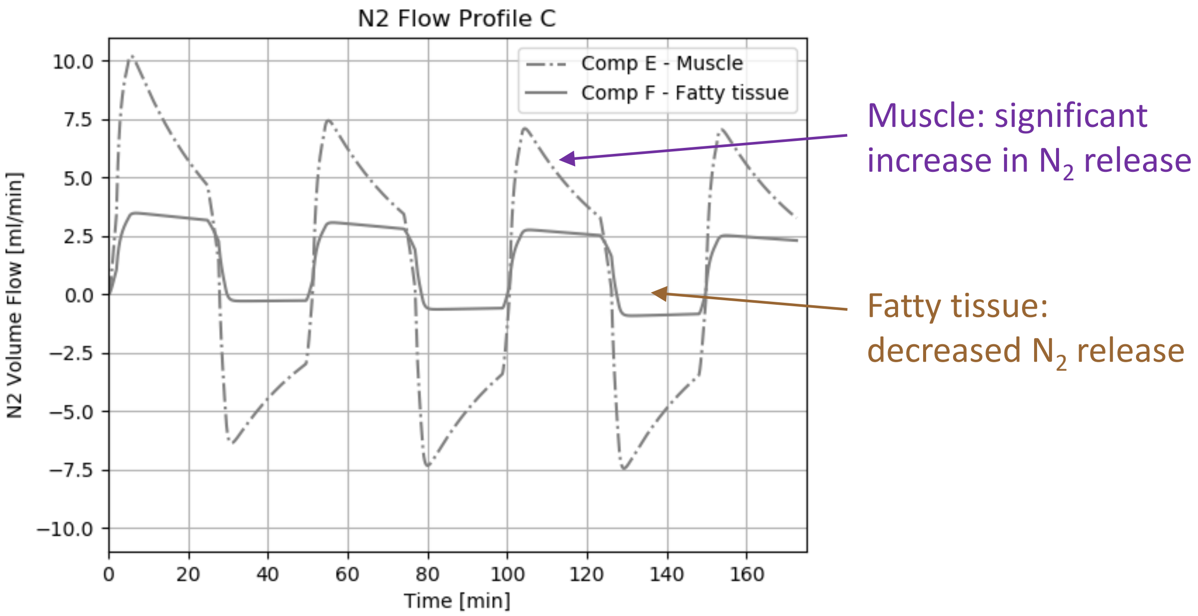
Traditionally, all compartments are assumed equally important.

However, some body compartments will have a more pronounced impact on the inert gas exchange.

N_2 flow as a weighing factor

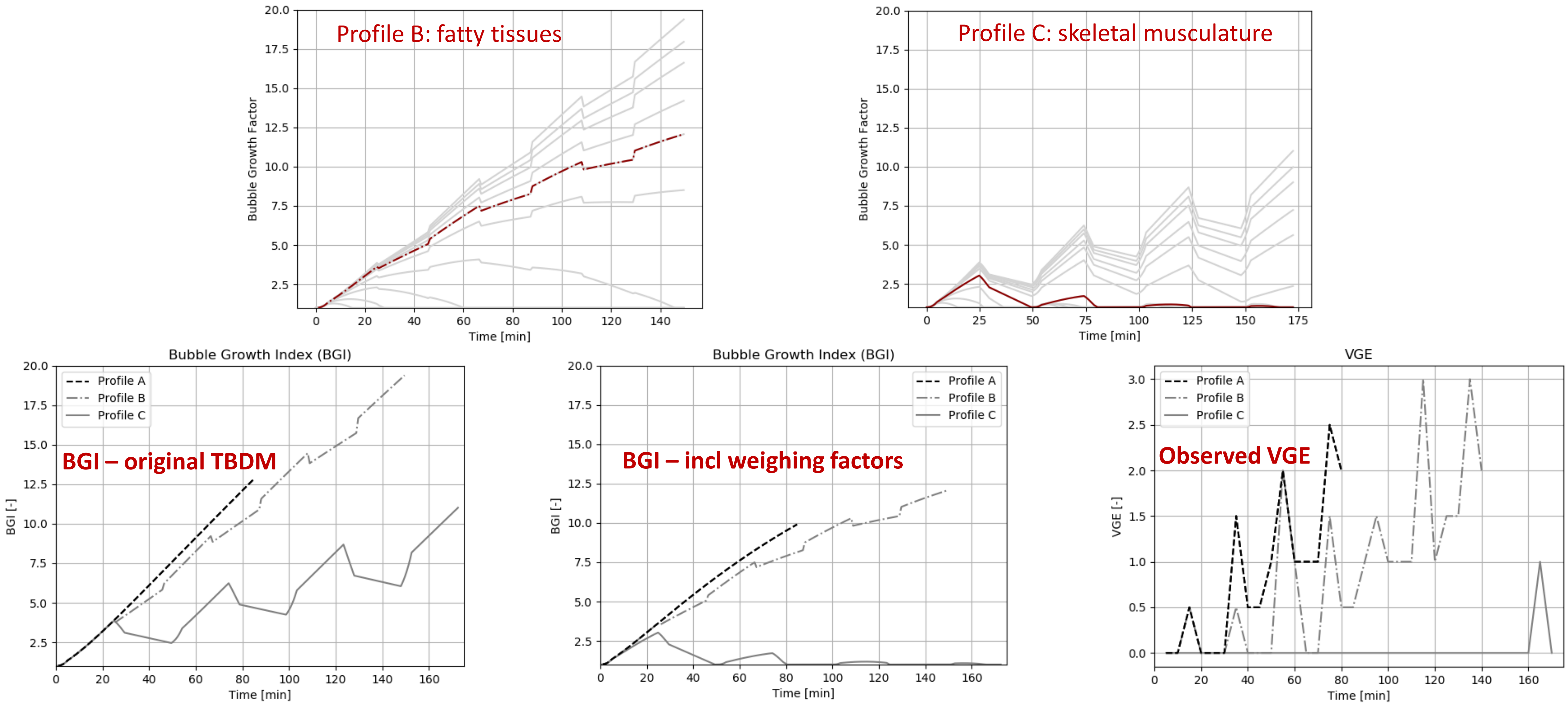


Steady N_2 gas exchange is governed by **fatty tissue**



Dynamic N_2 gas exchange is governed by **skeletal musculature**

BGI INCLUDING WEIGHING FACTORS



Evaluation using BGI incl weighing factors appears much more correct than using original TBDM.

CONCLUSIONS

1. **Fixed tissue half-times do not accurately describe the measured inert gas flow.**
2. **More accurate gas dynamic models should include variable physiological and anthropometric parameters.**
3. **Bubble growth models, with a ‘one-fits-all’ gas dynamic model as input, do not always correctly predict the decompression stress.**
4. **Different exposures yield different gas dynamics. Including N_2 flow-based weighing factors should be considered to obtain a more correct evaluation of operational altitude decompression profiles.**

This research is funded by the Royal Higher Institute for Defence via study HFM 21-06

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