TOWARDS A HYPOBARIC DECOMPRESSION SICKNESS TREATMENT MODEL

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ABSTRACT

INTRODUCTION: Treatment options for decompression sickness (DCS) during Exploration Class extravehicular activity (EVA) must follow an evidence-based approach. The approach must ultimately match the most effective treatment to the anticipated low risk of DCS. Providing standard-of-care hyperbaric oxygen (HBO) treatment at remote locations is costly. All but an optimized treatment plan impacts the mission. **METHODS**: In-house and external data are available on effective interventions to resolve pain-only, serious, and cutaneous signs and symptoms of hypobaric DCS. Data on 194 symptoms (mostly pain-only) based on 119 cases of DCS from NASA-funded tests of prebreathe protocols covering from 1982 to 2009 were assembled into an Astronaut DCS Treatment Database. The goal is to describe these data with future efforts to create multivariable linear or logistic regression models that quantify the contribution of explanatory variables toward symptom resolution. A biophysical model of bubble growth and resolution in tissue will also be applied to quantify the time required to resolve the asymptomatic gas phase, as treatment is not complete until the offending gas phase is resolved. **RESULTS**: Thirty-seven of 194 symptoms (19%) resolved at the test altitude (most often 4.3 psia or 222 mmHg), 122 symptoms (63%) resolved during repressurization, 14 symptoms (7.2%) resolved at site pressure, and 21 symptoms (10.8%) were persistent at site pressure and resolved during HBO treatment (USN Treatment Table V or VI). Given the lengthy period of denitrogenation provided to NASA subjects before depressurization to 4.3 psia, 89% of symptoms resolved with a return to 14.7 psia (760 mmHg), an applied pressure difference of 10.4 psia (538 mmHg) with 50% resolution over a pressure difference of just 3.0 psia (155 mmHg). **CONCLUSIONS**: The application of pressure, the continued use of 100% oxygen at site pressure, and the time to affect treatment are considerations for effective treatment of hypobaric DCS. Application of pressure during repressurization was effective to resolve the majority of pain-only symptoms given conservative denitrogenation protocols. Statistical and biophysical models have the potential to minimize (optimize) resources, such as time, 100% oxygen, and treatment pressure. Models can eliminate treatment options that are otherwise inefficient and wasteful of resources in astronauts with DCS at remote locations.

INTRODUCTION

- Hyperbaric (diver) and hypobaric (aviator, astronaut) decompression sickness (DCS) differ significantly, especially in the gas composition of the offending gas phase (8,9). This necessitates the need for an evidence-based approach to define effective treatment for astronauts.
- Astronauts conducting extravehicular activity (EVA) at remote locations need options for effective treatment, not simply standard of care hyperbaric oxygen (O_2, HBO) therapy for divers (1,2,4). Using USN Treatment Tables V or VI have significant mass, consumable, and volume considerations.
- We draw from our own data and from the literature (6) for guidance on effective treatment interventions for hypobaric DCS.

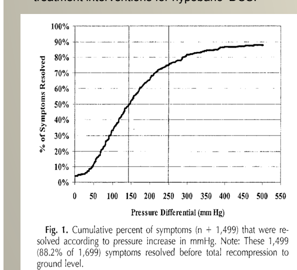

Fig. 1. Taken from USAF data (6). Shows 4.4% of symptoms resolved at the test altitude while 88.2% of all symptoms resolved before reaching site pressure. Fifty percent of symptoms resolved after the application of 138 mmHg of pressure while 75% of symptoms resolved after applying 250 mmHg of pressure.

METHODS

- Our data comes from 820 human altitude exposures, mostly at 4.3 psia (222 mmHg), during tests of 40 protocols from 1982 to 2009.
- 119 cases of DCS (25 women and 94 men) with a total of 223 symptoms are available, and 194 symptoms were associated with a resolution pressure. Symptom data are specific to conservative NASA denitrogenation [prebreathe (PB)] protocols.
- Symptom location and character, time to symptom onset, and pressure delta (repressurization pressure – symptom pressure, psia) for relief of symptom are available in our DCS treatment database.
- Explanatory variables for symptom resolution include gender, age, time to symptom onset, time delay to repressurization, ambulation as part of exercise at altitude, 0-10 pain intensity scale, and more.
- Initial efforts are to describe symptoms and pressure delta for relief of symptoms.
- We apply multivariable linear regression to identify explanatory variables that influence pressure delta for relief of symptoms.

RESULTS

TABLE 1. Summary Counts for Symptoms

symptom category	symptom resolution details	count	Records out of 220	fraction of total 223
A	resolved at altitude	37	207	16.6
B	resolved on repressurization	140	207	62.7
C	resolved at site pressure	14	211	6.2
D	resolved after HBO for a persistent symptom at site pressure	21	219	9.4
E	resolved but then reoccurred and required HBO	11	219	4.9
	Total symptoms resolved	223	----	100.0

TABLE 2. Summary Counts for Pressure Resolution

symptom category	symptom resolution details	count	pressure treatment records	fraction of total 194
A	resolved at altitude	37	37	19.0
B	resolved on repressurization	140	122	62.9
C	resolved at site pressure	14	14	7.2
D	resolved after HBO for a persistent symptom at site pressure	21	21	10.8
E	resolved but then reoccurred and required HBO	11	+	+
	Total treatment pressures	223	194	100.0

+ Since repressurization resolved 11 cases, a treatment pressure already exists even though a hyperbaric (HBO) treatment was later required.

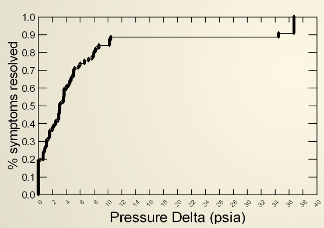

Fig. 2. The cumulative percentage of 194 symptoms that resolved at the given pressure difference defined as the pressure at symptom resolution minus the altitude test pressure, in units of psia. Thirty-seven symptoms (19%) resolved at the test altitude, before repressurization, 122 symptoms (63%) resolved during repressurization, 14 symptoms (7.2%) resolved at site pressure (14.5 – 14.7 psia), and 21 symptoms (10.8%) were persistent at site pressure and resolved during an HBO treatment (USN TT V or VI). Not represented on the figure are 11 symptoms that initially resolved prior to the subject being released from the test but reoccurred later and required HBO treatment. Given the lengthy denitrogenation provided to NASA subjects, 89% of 194 symptoms resolved over a pressure difference of 10.4 psia with 50% resolution over a pressure difference of just 3 psia.

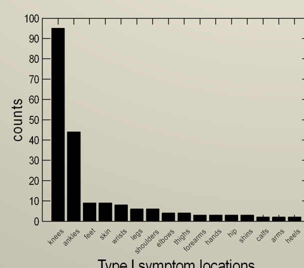

Fig. 3. The number of locations of Type I (pain-only) symptoms attributed to DCS. Knees and ankles dominate the location of symptoms. Symptoms in toes or fingers were included in feet or hands. One subject had skin symptoms (tingling) located in 7 body locations.

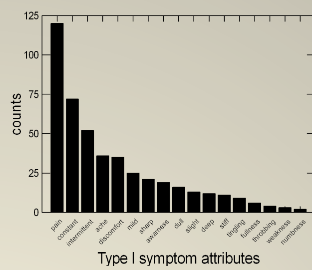

Fig. 4. The number of attributes of Type I (pain-only) symptoms attributed to DCS. Pain and ache, whether constant or intermittent, were the dominate attributes of symptoms. Seven of the 9 records for "tingling" symptom came from one subject. The 2 symptoms of numbness were attributed to impaired circulation and not neurological in origin.

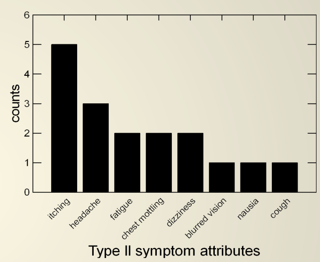

Fig. 5. The number of attributes of Type II (serious) symptoms attributed to DCS. One of 3 headaches here was classified as Type I DCS. Headache and a sensation of being hot during an otherwise unremarkable 4-hr test caused the symptom of "headache" to be classified as Type I DCS in a female. However, the subject later reported with Type I symptoms and underwent HBO treatment. Chest mottling (cutis marmorata) was initially classified as Type II DCS at the Johnson Space Center but now exists as its own category of DCS – not Type I or Type II. It is shown on this graph in its historical context.

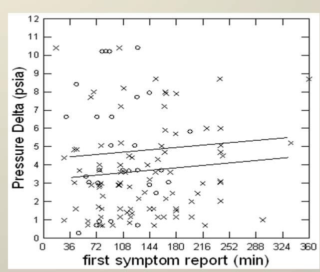

Fig. 6. The relationship between the first report of a DCS symptom and the pressure delta for relief of symptom during repressurization to site pressure. The parallel lines are from a multivariable linear regression for subjects that ambulated (n = 95 X) and subjects that did not ambulate (n = 36 O). Top line is for no ambulation while bottom line is for ambulation. The overall goodness of fit of this regression model is poor, an r^2 of only 0.04, but within this poor model the ambulation status had a significant influence (p = 0.02). The non-ambulation condition required about 1 psia of additional pressure to resolve the symptoms when compared to the ambulatory condition.

DISCUSSION

- Boyle's Law is a major factor but not the only factor to consider for effective DCS treatment (see Fig. 7).

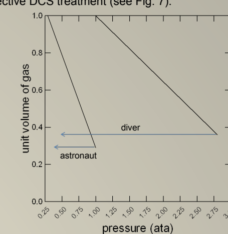

Fig. 7. Demonstration of Boyle's Law to reduce a unit volume of gas with the application of sea level pressure (1 ATA) to gas at 0.29 ATA from an astronaut and application of HBO pressure (2.8 ATA) to gas at 1.0 ATA from a diver. There is a slight advantage in the hypobaric case in that the unit volume decreases to 29% of the original volume compared to the hyperbaric case where the volume decreased to 36%.

- Due to the presence of a constant metabolic gas partial pressure the N_2 partial pressure of astronaut and diver bubbles is different (8).
- The reabsorption of the bubbles during the application of pressure while breathing 100% O_2 is dictated by the N_2 partial pressure gradient between the bubbles and mixed venous blood N_2 tension (9).
- In some situations the N_2 gradient is greater for the astronaut relative to the diver since the astronaut is breathing 100% O_2 for several hrs as DCS evolves compared to the diver who is breathing air during and after the dive (3).

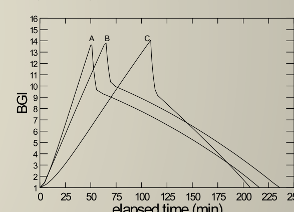

Fig. 8. Three examples to demonstrate the resolution of a Bubble Growth Index (BGI) of 14 units given a Boyle's Law decrease in bubble volume with applied treatment pressure and the bubble-to-tissue N_2 gradient as computed with the BGI model (3). Curve A is after a 60 min PB in an astronaut exposed to 4.3 psia with return to 14.7 psia, curve B is a saturation diver with return to 41.1 psia after exposure to14.7 psia, and curve C is after a 300 min PB in an astronaut exposed to 4.3 psia with return to 14.7 psia (5 min for all pressure transitions). The elapsed time from the start of decreased pressure (time 0) to bubble resolution is shorter in the astronaut cases (A and C), dependent on the PB time, compared to the saturation diver (B). The difference is due to a slight Boyle's Law advantage during the return to site pressure (14.7 psia for astronaut and 41.1 psia for saturation diver) combined with a greater bubble-to-tissue N_2 gradient for the astronaut with the longer PB compared to the saturation diver.

- Any treatment protocol necessarily influences spacecraft design and acceptable DCS risk.
- Future efforts will define the appropriate treatment pressure and the period of optimum ground level oxygen (5,7) that resolves the greatest number of DCS symptoms following conservative PB protocols.

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