Metabolic rate and animal size correlated with decompression sickness

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Kindwall, Eric P. Metabolic rate and animal size correlated with decompression sickness. Am. J. Physiol. 203(2): 385-388. 1962.—A number of small animals, rats, guinea pigs, rabbits, and cats were exposed to high ambient pressure for long periods of time and rapidly decompressed. They were found not to suffer from clinical "bends" except when decompressed almost explosively. Usually they did not suffer joint symptoms, delayed shock, or other disabling or permanent sequelae. Nitrogen saturation-desaturation curves based on the small animals' metabolic rate per kilogram weight were derived. A number of small animal dives were analyzed, and the calculated surfacing nitrogen tensions were depicted graphically for six tissues in each animal. It was found that small animals can surface with extremely high nitrogen tensions, particularly in the slower tissues, without serious ill effect. This appeared to be true even in the presence of bubble formation. A clinical description is given of a cat, surfaced from a saturation exposure at 350 ft (106.5 m) with 47 min decompression. It appears that the shorter circulation time of small animals did not by itself explain their immunity to bends.

The classical explanation of decompression sickness, or "bends," is that gaseous nitrogen from the air pumped down to the diver at a pressure equal to the depth at which he is working is gradually absorbed into his tissues. This causes him no difficulty (aside from perhaps a certain narcotizing effect) so long as he remains at depth. Should he, however, rise too rapidly to the surface, the nitrogen quickly bubbles out of solution, tearing tissues, plugging small vessels with gas emboli, and embarrassing circulation and even cardiac function itself (1, 2, 2a). Onset of the disease may occur from 5 min to 24 hr postdecompression. Symptoms range from a mild pruritis to arthralgia, paralysis, convulsions, shock, and death.

As reaction to bubble formation appears to vary widely from species to species, and indeed within the same individual on different days, it seems that theoretically something more than the simple mechanics of Boyle's law must play a part. Thus it was initially decided to investigate the bends syndrome from the biochemical point of view and to conduct these studies with small animals, for convenience as well as economy.

However, it was soon found that small animals react differently to decompression from large animals. Therefore, an attempt was made to analyze in greater detail the mechanism of bends in these small animals.

Other workers (3) have noted that small animals are more resistant to bends. An explanation that has been given is that their more rapid metabolism, and corresponding faster circulation, is able to remove the excess of nitrogen from the tissues before symptoms can appear (3). Despite the fact that short circulation time is a "double-edged sword" (the animal is also saturated more quickly in shorter exposures), even a relatively fast decompression should theoretically still allow enough nitrogen to be flushed out to remove the small animal from danger.

A specific attempt was made in this study to determine how closely the circulatory rate was related to the appearance of bends symptoms in small animals. A goat and a dog were used for comparison.

Methods

Forty animals, rats, guinea pigs, rabbits, and cats, were exposed to greatly increased ambient pressures for varying periods of time in a large recompression chamber and then decompressed. The animals breathed air at all times, and exposures ranged between 15 min and 9 hr. Decompression was accomplished either in stages or directly to atmospheric pressure in from 1 to 98 min. The shallowest equivalent pressure used was 74 ft (22.5 m sea water), and the greatest was 350 ft (106.5 m sea water). Only one animal was exposed to the 350-ft depth; a female cat later found to be gravid. This animal's postdecompression course will be described in detail.

Decompression tables were worked out in accordance with the animals' different body weights, metabolic rates, and resultant calculated circulation times. Cardiac

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output and circulation times were calculated indirectly from metabolic need. Kleiber’s formula for metabolic rate in relation to body size was used (4). The formula is as follows:

\[
\log_{10} M = 1.83 + 0.756 (\log_{10} W) \pm 0.05
\]

where \( M \) — metabolic rate of animal in kilocalories per day and \( W \) = body weight in kilograms.

It was decided to consider small animals as having six tissues equivalent to the 5-min through the 120-min half-time tissues of man, but of shorter duration in proportion to the metabolism per kilogram body weight. The small animal tissue half-times were determined by dividing the human tissue half-times by the small animal-to-human metabolic ratio. Saturation-desaturation curves were plotted for small animals with tissue half-times modified as described above. Using the new half time curves, a number of small animal dives were analyzed and the surfacing tissue nitrogen tensions were calculated. The animal surfacing tensions were compared with what have been considered by Van der Aue and co-workers (5) and Workman (6) to be the safe human surfacing ratios. The safe human surfacing ratios are as follows:

<table>
<thead>
<tr>
<th>Half-Time Tissue, min</th>
<th>( T ) atm</th>
<th>( T ) atm</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>3.211</td>
<td>3.211</td>
</tr>
<tr>
<td>10</td>
<td>2.721</td>
<td>2.721</td>
</tr>
<tr>
<td>20</td>
<td>2.241</td>
<td>2.241</td>
</tr>
<tr>
<td>40</td>
<td>1.781</td>
<td>1.781</td>
</tr>
<tr>
<td>80</td>
<td>1.611</td>
<td>1.611</td>
</tr>
<tr>
<td>120</td>
<td>1.571</td>
<td>1.571</td>
</tr>
</tbody>
</table>

After decompression the animals were observed grossly for signs of bends, such as pruritis, leg raising, limp, paralysis, or shock. In addition, hematocrits were taken from some of the animals before the dive and in the postdecompression period. Paper electrophoretic studies were carried out on plasma proteins in the rabbits and guinea pigs. The animals were observed for various time periods after decompression for the purpose of detecting residual or permanent disabilities. One rabbit, decompressed in 17 min from saturation at 200 ft (61 m) was followed in this manner for 6 months postdecompression.

RESULTS

All of the small animals used in this series, with one exception (the gravid cat), failed to show signs or symptoms truly comparable to the bends syndrome as seen in larger animals and man. It was, of course, possible to produce rapid asphyxial death by extremely fast decompression, but limping or favoring of an extremity, paralysis, delayed shock hemococoncentration, or other signs ofclassic bends were striking by their absence. Symptoms noted in the animals that did not die of immediate asphyxia were relative inactivity in the immediate postdecompression period and, in more severe cases, transient cyanosis. With the one exception described below, there were no permanent disabilities or detectable sequelae secondary to decompression.

The accompanying bar graphs (Figs. 1–8) show the safe human surfacing tensions (6) of the six different half-time tissues (A–F) and the calculated tissue nitrogen tension to 1 atm (total gas pressure) at surface.
tensions on surfacing of some of the animals in this series. The tissues shown at extreme left are the fast tissues, while those to the right are the slowest. The full extent of each white bar indicates the maximum safe nitrogen surfacing tension (human standard) for the tissue in question. Horizontal lines within the white portion of the bars show the calculated nitrogen tensions of the animal tissues in this series surfacing within “safe” limits. The shaded areas, denoted by cross-hatching, diagonal lines, or black shading, show the calculated pressure of nitrogen in each animal tissue in excess of the permissible tensions which are found to be asymptomatic in humans. The graphs shaded in black (Figs. 2 and 3) indicate animals which died within a few minutes of surfacing, from what appeared to be asphyxia. Graphs shaded with hatching (Figs. 1, 4, and 5) show animals which experienced no serious symptoms and survived without apparent sequelae. The two crosshatched graphs (Figs. 7 and 8) represent a dog and a goat who manifested severe shock with hemoconcentration and paraplegia, respectively. It is interesting to note that none of the animals surfacing with tissues A and B within safe limits died from immediate asphyxia.

The small animal hematocrits taken before and after decompression did not differ significantly, and the pre- and postdecompression electrophoretic patterns showed no measurable changes.

Since the exposure up to 9 hr at 200 ft followed by rapid decompression had failed to produce symptoms (7), it was decided to try the extreme depth of 350 ft.

A female cat (later found to be gravid), was exposed for 5 hr at 350 ft and decompressed in three stages over a 47-min period. It appeared to be conscious at depth but was groggy. On surfacing, with the fastest two tissues calculated to be within safe limits but with the slowest four grossly overloaded with nitrogen, the cat showed no immediate symptoms. It crouched quietly showing little movement for a period of 15 min. As all the previous animals dying of rapid decompression had done so within 10 min of surfacing, the cat was thought to be out of immediate danger. It was given a saucer of milk, as it had taken no nourishment for over 8 hr. After lapping up some of the milk, it got up and tried to walk, then suddenly became very unsteady, stumbled, and fell on its right side. Its breathing, which up to that time had been slow and regular, now became rapid, labored and stertorous. It seemed to choke, breathing ceased; and it extended its legs and assumed a position of extreme opisthotonos. Then it became quiet and limp, and it was thought that the animal had expired. Its apparent modus exodus seemed similar to the other animals which had died. Within a minute, however, it moved one of its forelegs and breathing started again, continuing rapidly, although its hind legs were paralyzed and it was insensitive to superficial or deep pain in the legs and tail. The respiratory rate slowly decreased and the animal appeared more alert. However, when its hind legs were moved by the experimenter or when it moved its forelegs or upper body, breathing immediately became more labored and rapid and its condition appeared to deteriorate. When the animal remained quiet, its condition improved. It appeared that movement and exacerbation of symptoms were related.

Forty minutes postdecompression, the first movement returned in the hind legs, and 50 min postdecompression it was able to sit up, though unsteadily. Two hours postdecompression the animal was able to walk, but there still appeared to be weakness in the hind legs. It was then noticed that the animal had started to bleed per vagina, and in the following 2 days it aborted four young embryos with placentae. Its condition improved over the next few days but it exhibited a very slight generalized weakness. As this barely detectable weakness was present in both the front and hind legs, it is difficult to say what was due to decompression and what were the effects of the abortion. This case was the most severe decompression to which an animal was exposed in this series. The stippled graph (Fig. 6) shows the state of the calculated tissue saturation on surfacing. This animal is described as a separate case because of its exceptional immediate symptoms and also because of the possibility that it experienced aftereffects from decompression.

**DISCUSSION**

Haldane (3) in addition to deriving the first workable decompression tables, was the first to conduct systematic studies on the relationship of the circulatory rate to the appearance of bends. He found that in goats there is a definite relationship, and he related goats' susceptibility to that of man. It seemed logical that small animals would show even less susceptibility to bends, but still in proportion to their metabolism.

Haldane in his original calculations conceived the idea of dividing the body arbitrarily into tissues of different half-times, i.e., tissues that saturate or desaturate to 50% of their nitrogen capacity at a given pressure differential within the specified half-time. This is convenient, of course, as saturation follows a logarithmic curve. This somewhat arbitrary but proven method has been followed by subsequent workers in deriving improved decompression schedules. The original Haldane tables proved to be too safe and therefore too time consuming for short, shallow exposures, and inadequate for deep, prolonged dives. The original tables, therefore, have been revised over the years as experience dictated. Van der Aue et al. (5) and later Workman (6), from their own studies as well as by reviewing records of dives made at the United States Navy Experimental Diving Unit, derived a series of safe surfacing tissue tension ratios designed to cover even the most extreme exposures. Workman found that for deep prolonged dives it was necessary to consider even the 160- and 240-min tissues as controlling at the shallowest stops, if...
symptoms were to be avoided. In exceptional individuals even slower tissues had to be considered.

Although it may be arbitrary to assume that small animal tissues correspond directly to human tissues in regard to producing bends symptoms, it seemed logical that if the presence or absence of bends was related to metabolic rate and circulation such an assumption was justified.

Kleiber's formula (4) for interspecies metabolic relationship was selected because of its accuracy over an extreme range. He found that metabolic rate was most closely related to the $\frac{3}{4}$ power of body weight in 26 groups of mammals ranging from dwarf mice to the elephant.

Part of Haldane's theory (3) concerning small animals' immunity to bends was that "this (circulation) time is so short in small animals that no bubbles at all are formed, in spite of the temporary existence of very great supersaturation in the blood and tissues." However, in many of the small animals observed in this series, distinct transitory cyanosis appeared from 28 min to $1\frac{1}{2}$ hr postdecompression indicating the presence of bubbles even in the animals that survived the decompression without other serious symptoms (7). Bubble formation does appear to occur with sufficiently great surfacing tissue tensions, even though the animal may have an extremely short circulation time compared to that of man. These bubbles in the usual case do not, as opposed to larger animals and man, scum to cause joint symptoms or other signs of serious bends except in the case of overwhelming embolization with resultant asphyxial death. It is of interest to note that the goat (Fig. 8) theoretically required less time to rid itself of its nitrogen excess on surfacing than did the rabbit (Fig. 4) after exposure for 9 hr at 200 ft. The goat became paralyzed; the rabbit, however, showed no symptoms.

The reason for small animals' resistance to the bends syndrome is not completely explained, but these experiments would appear to cast some doubt on the theory that the shorter circulation time in small animals, per se, provides them with immunity to bends. It is evident from the graphs that extreme overloading of the tissues with nitrogen, even with ensuing subasphyxial bubble formation, does not, in small animals, provoke the unfortunate sequence of events that is seen in the larger species. In view of this observation the author would caution against drawing direct conclusions regarding the efficacy of decompression schedules for larger species tested on small animals. It is possible that small animal histopathologic studies may not indicate the actual postdecompression tissue status in larger animals.

It would be most useful to look further into the factors concerning animals' biologic reaction to bubble formation as this might have direct application to understanding the great variation in susceptibility to bends seen in humans.

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REFERENCES