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TESTING JS HALDANE'S DECOMPRESSION MODEL

Chris Acott

Key Words

Diving theory, history, physiology, research, tables.

Last year I presented a paper on J S Haldane summarising his work.[1] As the majority of dive computers are based on the decompression algorithm that J S Haldane designed, I present here the testing procedures, for goats and humans, used to support his conclusions. Quotations from Haldane's report[2] are printed in *italics* in this paper.

Haldane's assumptions

1 That for bubble formation, the tissue pressure must be greater than the environmental pressure.

2 That tissues can hold gas in supersaturation, and only if the decompression rate is correct this supersaturation can be tolerated without risk.

3 That there were no symptoms of decompression sickness (DCI) without bubbles. We now know that is not correct.

4 From Sir Leonard Hill's work Haldane assumed that carbon dioxide had no influence on decompression risk. We now know this is probably incorrect.

5 That tissue perfusion is the limiting factor in gas uptake. Haldane adopted a mathematical simplification, in the form of an exponential, to describe uptake of inert gas. Hill considered that the limiting factor was gas diffusion.

6 That gas elimination is the mirror image of gas uptake. We now know that is incorrect.

Half times

Using these assumptions and the published work of other people Haldane divided the body into arbitrary half time tissues. A half time is half the time it takes to saturate a tissue with a specified gas. A short half time denotes a tissue with a good blood supply and rapid saturation. A long, or slow, half time is a tissue which takes up the gas slower because of a lesser blood supply. Haldane calculated these half lives to represent what happened in the body. Moir's data gave him his 20 minute half time. Haldane used Hill and Greenwood's[3] data of nitrogen excretion to provide his 5 minute half time. That is based on the nitrogen content of urine. Hill and Greenwood considered that as the kidneys are very well perfused in life they represented what we now call a fast tissue. They experimented on themselves in a chamber under pressure where they passed urine every 5 minutes or so. The urine was passed out of the chamber and the nitrogen content measured. JS Haldane's experiments on goats gave a 75 minute half life. From his mathematical calculations he showed that, if the body had an equal perfusion, then this would represent a 10 minute half time. I have not been able to find the origin of his 40 minute half time.

Funding for Haldane's research was both private and from the Admiralty. At first Haldane started by using small animals. Later he used a large chamber, donated by Ludwig Mond, based at the Lister Institute in London. Haldane worked with Boycott, who was Professor of Physiology at Oxford University, and Damant, who was a Lieutenant in the Royal Navy (RN) and Inspector of Diving. When the tables were developed, Damant and Mr Catto, Gunner, RN, were the divers who tested the tables in London and in the water in Scotland. Damant was also involved with the second RN Deep Diving Unit in the 1930s. In the 1930s Damant modified the Haldane tables so that RN divers could dive to 300 feet on air.

The experiments

Haldane's team used goats because they were the largest animals which could be conveniently dealt with. They were also relatively cheap. Experience had shown that in smaller animals symptoms of were not easily detected. Haldane used 5 to 8 goats for each experimental dive. He realised that the goats had to be fit. The pressures that the goats, and humans, were exposed to were recorded in pounds per square inch of gauge pressure usually referred to as *lbs*. Sometimes they were quoted as *atmospheres absolute*. Haldane used *15 lb* as the conversion for one atmosphere. In this paper pressures are given as absolute pressure in bar and as sea water depths in metres {m} and feet {ft} with the original pressures in brackets [*and in italics*].

There were four series of goat experiments. In Series 1, 24 goats were exposed to 6 bar {50 m, 165 ft} [*75 lbs (6 atmospheres absolute)*] for 12, 15 and 30 minutes and then decompressed, either in stages or at a uniform rate. Actually there were 164 experiments on 34 animals but the results were inconclusive, because of poor planning, so only those experiments which showed the difference between staged and uniform decompression were retained for use. Series 2 was 20 goats exposed to 6 bar {50 m, 165 ft} for 15, 30, 60, 120 and 240 minutes and then decompressed either in stages or at a uniform rate. Series 3 had 15 goats exposed to 4 bar [*45 lbs (4 atmospheres absolute)*] {30 m, 100 ft} for 15, 30, 45, 60, 90, 120, 240 and 480 minutes. Most of the series 4 goats had been compressed in series 3. Series 4 exposed a total of 26 goats of a range of pressures; 6 bar {50 m, 165 ft} for 0.5, 3, 6, 10, 15, 30, 30, 60, 120, and 180 minutes; 4.4 bar (*51 lbs*) {34 m, 112 ft} for 180 minutes and then decompressed to the surface (1 bar) in 4 minutes (2 goats died, six developed bends and two had no symptoms); 4 bar {30 m, 100 ft} for 120 minutes then decompressed to 1.4 bar (*6 lbs*) {4 m, 12 ft} in six minutes (one animal died, one became paraplegic and the third developed bends); 3.6 bar {26 m, 86 ft} for 120 minutes then decompressed to 1.4 bar (*6 lbs*) {4 m, 12 ft} in 6.5 minutes (one goat had no symptoms and the other 3 developed bends and dyspnoea); 3 bar (*30 lbs*) (20 m or 66 ft) for 60 minutes with uniform rate decompression in 10 minutes gave 4 bent goats and 16 without symptoms; 2.7 bar (*25 lbs*) (17 m or 56 ft) for 240 minutes with decompression in 2 minutes produced 2 bent goats and 21 undamaged; and 2.3 bar (*20 lbs*) (13 m or 44 ft) for 240 minutes with decompression in 2 minutes bent one goat out of 22.

The chamber was not ventilated until decompression was started unless the exposure was over 4 hours when CO_2 levels tended to rise above 2% of atmospheric. There was no temperature control in the chamber. At the end of the dive, the goats were allowed to run free, but were closely observed for about 30 minutes, and then observed frequently after that. They had one pressure exposure per day, and after that they were allowed to roam free for a week before being used again in another experiment. Table X of Haldane et al.'s paper (reproduced in Table 1) records 57 different experiments involving 675 goat dives. After making allowances for goats used in both series 3 and 4 of the experiments, each goat must have done about 10 dives. It was a magnificent and marathon effort.

Decompression symptoms

Haldane' list of symptoms of decompression sickness in goats are quite similar to those in human beings. The words in italics are taken directly from the published work.[2]

1 Bends. The commonest symptom which we have observed consists of the exhibition of signs indicating that the animal feels uneasy in one or more of its legs. The limb, most commonly a fore-leg, is held up prominently in the air, and the animal is evidently loth to bear weight upon it. .. "Bends in parts of the body other than the limbs are very difficult to identify in animals; we have however occasionally noted symptoms which might be bends in the trunk, though we are not prepared to definitely identify them as such.

2 Temporary paralysis may be of two kinds. ... The animal. while showing no signs of general illness, or in other instances having already had bends, exhibits foot-drop or a more extensive palsy in one or more hind- or fore-limb. The paralysis does not usually come on till about 15 minutes after decompression, rapidly becomes more marked for a few minutes after the first signs are noted, and then soon begins to mend, so that there is marked improvement in about half an hour, and by next day the animal is found quite well. showed some improvement within 30 minutes, and 24 hours later they had made a spontaneous improvement, and were found to be otherwise well. This form of paralysis chiefly involves the hind legs.

3 Pain. In some cases the animals have shown signs of acute pain by urgent bleating and continuous restlessness. .. In other instances animals showing only severe bends bleat in a most distressing manner and are evidently in acute pain; at the same time they may gnaw at some part of their body (such as the testicles) as if localising the origin of the pain. In animals which have recovered, we have not had any instance where these signs persisted for more than 10 or 15 minutes.

4 Permanent paralysis. The onset is usually immediately after decompression, the condition is complete from the first and for at leas several days there are no signs of improvement. In a few cases the first paralysis has passed off (to all appearances completely) in two or three hours and the animal has been found next morning to be again paralysed. This second paralysis is permanent. A similar *history has often been noted in human cases.....In the most severe cases the animals have been killed; others have however begun to mend and have lived for some months with a slight spastic paralysis of the hind legs. .. In some there has been retention of urine, one animal had to be killed on account of acute distension of the stomach which came on some 20 hours after the onset of the paraplegia.*

5 A fair number of cases have occurred where the animal has been obviously ill, but in which it has been impossible to identify any definite local symptoms or any definite dyspnoea. The goat may lie down, refuse to move or be tempted with corn (of which goats are inordinately fond) sometimes lying extended on the side, sometimes hurriedly rising, walking a few steps and then lying down again.

6 Dyspnoea is usually the precursor of death and only a minority of goats survived after showing clear dyspnoea. ....The delay in the onset of first symptoms is often most striking; the animal may appear quite normal for as long as 10 or 15 minutes, dyspnoea then appears, the goat falls down helpless and in another 15 minutes is dead.

Results

Table 1 (page 48) shows that these were deep diving goats. Thirty seven of the experiments were at *75 lb* {6 bar, 50 m, 165 ft}. There was one experiment at *51 lb* {4.4 bar, 34 m, 112 ft} where the exposure was 180 minutes and the decompression took 4 minutes. Not surprisingly the 10 goats provided 2 bends, one bad bend, one was obviously ill, two developed paraplegia and two died. Sixteen experiments were at *45 lb* {4 bar, 30 m, 100 ft}.

Only three experiments were at less than 30 lbs gauge pressure (3 bar), equivalent to 20 m or 66 ft. These were one at 20 m for 60 minutes with 10 minute uniform decompression which produced bends, as defined above, in 4 out of 19 goats (21%). Another, with 23 goats at 25 lb {2.7 bar, 17 m, 56 ft} for 240 minutes with a 2 minute decompression, gave 9% bends. The third, with 22 goats at 20 lb {2.3 bar, 13 m, 43 ft} for 240 minutes with a 2 minute decompression produced 5% bends. Over all these experiments on 64 goats resulted in 7 cases of bends (11%).

Haldane's conclusions about goats from his experiments included:

The variation in the individual susceptibility of different goats is very marked. ... The complete explanation of this individual variation in susceptibility probably requires a knowledge of the details of caisson disease far beyond that which we at present possess. Data exist, however, on which the influence of several factors may be discussed.

It would appear that there is no clear difference between the sexes in liability to decompression symptoms in general. The experiments suggested however that under certain circumstances there might be a marked difference in the susceptibility to death. ...in Series II are shown 1 death in 7 males and 4 deaths in 11 females. All these last four animals were to some degree advanced in pregnancy, and their mortality is very probably to be associated with this condition, which, in the goat, is accompanied by a marked increase in the subcutaneous and intra-abdominal fat.

The only conclusion to be drawn is that these figures do not indicate that either sex or weight was a determining factor in the incidence of decompression symptoms.

Conclusions. Of the four factors considered in detail, it appears therefore that age, sex and blood volume were without appreciable influence. Pregnancy and a low rate of expiratory exchange seem to favour the occurrence of symptoms.

Pathology of caisson disease

When discussing the pathology of caisson disease in goats Haldane concluded that:

There is not much doubt that some of our animals which showed no symptoms must have had bubbles present in the blood.

In our own animals attempts were made to see bubbles in the retinal vessels during life. Though an excellent view of the fundus may easily be obtained, no bubbles were ever seen in animals with severe dyspnoea, so the method cannot be taken as giving any indication of the absence of bubbles in the blood. Some of these animals died and plenty of free gas was found in the retinal vessels post-mortem.

.. goats were killed before the expiration of the appropriate period for the development of bends. The experience of similar experiments indicates that they might have shown symptoms if they had not been killed. Yet three of four had no bubbles in the blood.

Synovial fluid is almost always full of bubbles; exposure for 15 minutes at 75 lbs.[6.1 atmospheres absolute or 28 fathoms = 168 feet] (51 m) is sufficient to cause their presence, while decompression in 100 minutes uniformly is not enough to prevent their formation. In animals which have died within 3 hours of decompression, we have found them in every case.

Solid organs. Fat commonly shows bubbles, often in extreme abundance. They are more numerous in the abdominal than in the subcutaneous fat; the latter is much

TABLE 1

Pressure lbs positive	Compression minutes	Actual exposure minutes	Decompression minutes	No. of goats	No symptoms		Bends					Temporary paralysis	Various indefinite	Paraplegia	Dyspnoea	Total severe symptoms	Death
					Number	Percent	?	Slight	"Bends"	Bad	Total						
75	6	0.5	60 un	8	7	87			1		1					0	0
		1	1	6	6	100					0					0	0
		3	1	5	4	80					0		1			1	0
		3	10 un	2	2	100					0					0	0
		6	1	6	6	100					0					0	0
		10	1	7	6	86					0			1		1	0
		15	1	6	2	33	1		1		2	1				1	1
		15	10 un	7	2	29			3		3		1			1	1
		15	31 st	34	29	85		2	2	1	5				0	0	
		15	31 un	36	19	53	2	3	8		13		1	2		3	1
		15	90 un	12	9	75			3		3					*	*
		30	31 st	23	12	52			7	1	8	3				3	0
		30	31 un	6	1	17			3	1	4	1				1	0
		30	68 st	14	14	100					0					0	0
		30	68 uu	14	7	50			7		7					0	0
		60	31 st	22	15	68			3	1	4	1	1		1	3	0
		120	31 st	9	0	0				4	3	7			1	1	1
		120	70 st	14	9	64			4		4				1	1	0
		120	70 un	13	4	31		1	6		7	1		1		2	0
		120	92 st	19	15	79			3		3	1				1	0
		120	100 un	19	10	53			1	2	3	2	1		2	5	1
		180	134 st	14	12	86			2		2					0	0
		180	134 un	10	5	50	1	1	3		5					0	0
		240	31 st	8	2	25			3	1	4	1				1	1
		240	31 un	4	0	0				2	2	1				1	1
51	6	180	4	10	2	20			2	1	3		1		2	3	2
45	6	15	2	15	14	93			1		1					0	0
		30	2	15	12	80			3		3					0	0
		45	30 st	14	14	100					0					0	0
		60	1	13	10	77			4		4					0	0
		60	10 un	13	7	54			4	1	5			1		1	0
		60	30 st	13	9	69		1	3		4					0	0
		60	52 st	13	10	77		2	1		3					0	0
		60	30 st	8	5	62			1	1	2		1			1	0
		120	1	10	4	40			1	1	2	1		3		4	0
		120	10 un	12	6	50			4		4	1			1	2	0
		120	30 st	13	12	92			1		1					0	0
		120	57 st	15	13	87			2		2					0	0
		240	10 un	11	6	55			4		4	1				1	0
		240	30 st	13	11	85			2		2					0	0
		240	62 st	15	9	60			6		6					0	0
		480	10 un	11	6	55			3		3	2				2	0
30	6	60	10 un	19	15	79			4		4					0	0
25		240	2	23	21	91			2		2					0	0
20		240	2	22	21	95			1		1					0	0
75	39	1	7 un	8	7	87					0			1		1	0
		10	10 un	4	3	75					0					0	1
		12	45 st	4	1	25			3		3					0	0
		12	45 un	6	4	67			2		2					0	0
		15	45 st	6	4	67			2		2					0	0
		15	45 un	12	4	33			8		8					0	0
		30	45 st	11	7	64			3	1	4					0	0
		30	45 un	12	5	42			5	1	6				1	1	0
		30	10 un	4	0	0					0					0	4
		30	10 un#	4	4	100					0					0	0
		30	10 un##	4	0	0			2		2			1		1	1
		60	75 un	4	2	50			1		1					0	1

* These two entries were left blank in the original publication. # Recompressed at once to 15 lbs for 32 minutes. ## Recompressed to 15 lbs for 37 minutes 18 minutes after decompression. un = uniform decompression: st =decompression by stages.

more vascular. Other solid organs for the most part show no bubbles outside the blood vessels.

Among the solid organs, bubbles outside the vessels are found most frequently in the central nervous system.

Duration of bubbles. It is difficult to say how long bubbles may remain the vessels and tissues after their first formation in animals which survive. [Zografidi (Revue de Médecine, 1907, p 159) records the finding of numerous bubbles in the peripheral vessels, but not the heart, of a diver who was paralysed and died 33 days after decompression!] The question is much complicated by the fact that we have reason to believe bubbles may continue to form for a long, and quite unknown, time after decompression.

..bubbles have been found in the blood of one animal which died two days after decompression (and that in an animal which had shown no dyspnoea) and in the joints up to 26 hours. In the spinal cord bubbles may persist much longer: in two cases we have found them 15 days after the last exposure to pressure and in 27 days after the last occurrence of symptoms.

Haldane's tables

The Haldanian staged decompression tables were tested at 7 different profiles, in the chamber, with Lieutenant Damant and Mr G V Catto, Gunner RN, as the subjects. The profiles are shown in Table 2, which has been constructed from Appendix 1.[2] The pressures ranged from 26-53 m {86-175 ft}. The compression times were much longer than most of the goat dives. It is not clear whether this was a result of inadequate compressors or was deliberate. Neither man developed symptoms.

Then Damant and Catto did 20 test deep dives from HMS SPANKER off Rothsay, Isle of Bute, in Scotland. These dives are shown in Table 3, constructed from Appendix 2 (page 50).[2] These were without incidents of decompression sickness. But on one of them the diver, Mr Catto, became entangled and the planned bottom time of 12 minutes was extended to 31.5 minutes, but by extending the decompression time to one and a half hours the diver was recovered without symptoms. These dives were done using hand pumps with a crew of six for each pump. Pumps in those days usually had a handle on a wheel on each side so that two men could work at once. At depth they had to maintain 24 revolutions a minute to supply the diver with adequate air. The men had to be relieved every five minutes.

Nowadays a total of 27 bends-free dives would not be enough to establish the safety of a new dive table.

Haldane's tables, published as Tables 1 and 2 in Appendix 4 of the report, are reproduced here as Tables 4 (page 51) and 5 (page 52).[2] Haldane's Table 1, headed *Stoppages during the ascent of a diver after ordinary limits of time from surface*, was limited to 33 minutes of staged decompression. It went down to 34 fathoms (or 204 feet = 61.3 m) where it allowed 12 minutes with 32 minutes of decompression with six stops starting at *60 ft* (18 m).

Haldane's Table 2, headed *Stoppages during the ascent of a diver after delay beyond the ordinary limits of time from surface for longer times at depth*, allowed over an hour at 34 fathoms (or 204 feet = 61.3 m) with a decompression time of 238 minutes. and gave a greater risk of decompression sickness. The original published table has an arithmetical error in the last three feet-measured entries. They are two feet deeper than the fathom depths

TABLE 2

EXPERIMENTS CARRIED IN THE CHAMBER AT THE LISTER INSTITUTE 1906

Subjects Lieutenant Damant and Mr A.Y.Catto, Gunner, R.N.

Date	Start of dive	S I h.min	Pressure	Depth m	Depth feet	Compression time	Time at depth	Bottom time	Deco time	Stops
25th July	NR		39 lb	26	86	17	60	77	24	2
26th July	1037		50 lb	33	110	24	27	51	34	4
26th July	1503	3.01	55 lb	36	121	28	19	47	31	4
27th July	1029	18.08	60 lb	40	132	30.5	20	50.5	37.5	5
27th July	1537	3.40	67 lb	45	147	36	18	54	36	5
30th July	1057	18.50	74 lb	49	163	39	15	54	42	6
31st July	1100	22.27	80 lb	53	176	44	12	56	51	7

NR = Not recorded.

TABLE 3

DEEP DIVING EXPERIMENTS CARRIED OUT OFF ROTHSAY, ISLE OF BUTE, FROM HMS SPANKER, 1906

Diver	Date	Time of dive	Depth Fathoms	Depth Feet	Depth m	Bottom time	Decompression time Total	Decompression time Stops
Damant	21st August	p.m.	15	90	27	62	18.5	2
Catto	21st August	p.m.	15	90	27	61.5	17.5	2
Catto	22nd August	a.m.	23	138	42	22	35.5	5
Damant	22nd August	p.m.	23	138	42	22.5	32.5	4
Damant	23rd August		25	150	45.5	20.75	37.75	5
Catto	23rd August		25	150	45.5	21.25	37.75	5
Catto	24th August	a.m.	27	162	49	18.5	55.5	5
Damant	24th August	p.m.	27	162	49	17.75	44.5	6
Catto	25th August		29	174	53	17.5	46	6
Damant	25th August		29	174	53	15	48.5	6
Catto	27th August	1123.25	30	180	54.5	13.5	45.75	6
Damant	27th August	1415.75	30	180	54.5	13.25	44.5	6
Damant	28th August	1018.5	30	180	54.5	16	47	NR
Catto*	28th August	1417	30	180	54.5	31.5	90	9
Catto	30th August	a.m.	30	180	54.5	15.75	46.25	6
Damant	30th August	p.m.	30	180	54.5	14.3	46.25	6
Damant	31st August	1108.25	36	216	65	8	48.5	7
Catto	31st August	1412.75	35	210	63	7.75	50.25	7
Catto**	3rd September	1426		142	43	19	38	NR
Damant**	3rd September	1503.5		139	42	70#	39	NR

*1431.75 *Diver called up , but could not come up as he was foul, unti*l 1448.5
** This was a working dive raising a 56 lb. weight *by meas of an arrangement of rope and pulleys. The heavy rope and blocks used caused great friction and resistance.* The height that the weight was raised was observed on deck.
#This bottom time is improbable given the ascent time and the notation *No ill-effects*. The record shows Damant left the surface at 3.03, arrived on the bottom at 3.05 and took the first sample at 4.00. The likely explanation is that he left the surface at 3.53 arrived on the bottom at 3.55 and took the first sample after 5 minutes. This would give a bottom time of 19 minutes, the same as Mr Catto's dive.
NR = Not recorded.

The Haldane tables have now been modified so often that they now bear very little resemblance to the originals. But the assumptions and theory used to produce them have endured. At present the air tables produced by the Canadian Defence and Civil Institute of Environmental Medicine (DCIEM) are considered to be the most conservative available. They have been developed from the results of thousands of closely monitored dives undertaken in Canada, the USA and the UK. Table 6 (pages 53 and 54) compares some of the profiles in Haldane's Tables I and II with similar profiles in the DCIEM tables. In table 6 the top line of each pair of entries is taken from the Haldane Tables and printed in ***bold italics***. The lower line in from the DCIEM tables. Times that are taken from Haldane's Table II, for *the ascent of a diver after delay beyond the ordinary limits of time from surface* or below the limiting line, which should only be exceeded under unusual circumstances, in the DCIEM tables are marked*.

Why blame the diver

Why are divers blamed for developing decompression sickness? There is a widespread attitude that a diver must have done something wrong to develop decompression problems, although we know that both bubble formation and decompression illness are random events.

I think Haldane probably started it by stating "*so the compressed air illness has now practically disappeared, except in isolated cases, where from one quarter or another the regulations have not been carried out*".[4] He had so much faith in his tables which had vastly reduced the incidence of decompression problems.

In 1922 Haldane recommended recompression treatment, but had little to do with experiments in

TABLE 4

[Table 1 of Appendix IV (page 442)]

STOPPAGES DURING THE ASCENT OF A DIVER AFTER ORDINARY LIMITS OF TIME FROM SURFACE.

Depth Feet	Depth Fathoms	Pressure Pounds per square inch	Time from surface to beginning of ascent	Approximate time to first stop	Stoppages in minutes at different depths* 60 ft.	50 ft.	40 ft.	30 ft.	20 ft.	10 ft.	Total time for ascent in mins.
0-36	0-6	0-16	No limit	-	-	-	-	-	-	-	0-1
36-42	6-7	16-18.5	Over 3 hours	1	-	-	-	-	-	5	6
42-48	7-8	18.5-21	Up to 1 hour	-	-	-	-	-	-	-	1.5
			1-3 hours	1.5	-	-	-	-	-	5	6.5
			Over 3 hours	1.5	-	-	-	-	-	10	11.5
48-54	8-9	21-24	Up to 0.5 hour	-	-	-	-	-	-	-	2
			0.5-1.5 hours	2	-	-	-	-	-	5	7
			1.5-3 hours	2	-	-	-	-	-	10	12
			Over 3 hours	2	-	-	-	-	-	20	22
54-60	9-10	24-26.5	Up to 20 mins.	-	-	-	-	-	-	-	2
			20-45 mins.	2	-	-	-	-	-	5	7
			0.75-1.5 hours	2	-	-	-	-	-	10	12
			1.5-3 hours	2	-	-	-	-	5	15	22
			Over 3 hours	2	-	-	-	-	10	20	32
60-66	10-11	26.5-29.5	Up to 0.25 hour	2	-	-	-	-	-	-	2
			0.25-0.5 hour	2	-	-	-	-	-	5	7
			0.5-1 hour	2	-	-	-	-	3	10	15
			1-2 hours	2	-	-	-	-	5	15	22
			2-3 hours	2	-	-	-	-	10	20	32
66-72	11-12	29.5-32	Up to 0.25 hour	2	-	-	-	-	-	2	4
			0.25-0.5 hour	2	-	-	-	-	3	5	10
			0.5-1 hour	2	-	-	-	-	5	12	19
			1-2 hours	2	-	-	-	-	10	20	32
72-78	12-13	32-34.5	Up to 20 mins.	2	-	-	-	-	-	5	7
			20-45 mins.	2	-	-	-	-	5	10	17
			0.75-1.5 hours	2	-	-	-	-	10	20	32
78-84	13-14	34.5-37	Up to 20 mins.	2	-	-	-	-	-	5	7
			20-45 mins.	2	-	-	-	-	5	15	22
			0.75-1.25 hours	2	-	-	-	-	10	20	32
84-90	14-15	37-40	Up to 10 mins.	2	-	-	-	-	-	3	5
			10-20 mins.	2	-	-	-	-	3	5	10
			20-40 mins.	2	-	-	-	-	5	15	22
			40-60 mins.	2	-	-	-	3	10	15	30
90-96	15-16	40-42.5	Up to 10 mins.	3	-	-	-	-	-	3	6
			10-20 mins.	2	-	-	-	-	3	5	10
			20-35 mins.	2	-	-	-	-	5	15	22
			35-55 mins.	2	-	-	-	3	10	15	30
96-108	16-18	42.5-48	Up to 15 mins.	3	-	-	-	-	3	5	11
			15-30 mins.	3	-	-	-	3	7	10	23
			30-40 mins.	3	-	-	-	5	10	15	33
108-120	18-20	48-53.5	Up to 15 mins.	3	-	-	-	2	3	7	15
			15-25 mins.	3	-	-	-	5	5	10	23
			25-35 mins.	3	-	-	-	5	10	15	33
120-132	20-22	53.5-59	Up to 15 mins.	3	-	-	-	2	5	7	17
			15-30 mins.	3	-	-	-	5	10	15	33
132-144	22-24	59-64.5	Up to 12 mins.	3	-	-	-	3	5	5	16
			12-25 mins.	3			2	5	10	12	32
144-156	24-26	64.5-70	Up to 10 mins.	3	-	-	-	3	5	5	16
			10-20 mins.	3	-	-	2	5	10	12	32
156-168	26-28	70-75	Up to 10 mins.	3	-	-	2	3	5	5	18
			10-16 mins.	3	-	2	3	5	7	10	30
168-180	28-30	75-80.5	Up to 9 mins.	3	-	-	2	3	5	5	18
			9-14 mins.	3	-	2	3	5	7	10	30
180-192	30-32	80.5-86	Up to 13 mins.	3	-	2	3	5	7	10	30
192-204	32-34	86-91.5	Up to 12 mins.	3	2	2	3	5	7	10	32

* During each stoppage the diver should continue to move his arms and legs.

TABLE 5

[Table II of Appendix IV (page 443)]

STOPPAGES DURING THE ASCENT OF A DIVER AFTER DELAY BEYOND THE ORDINARY LIMITS OF TIME FROM SURFACE

Depth Feet	Depth Fathoms	Pressure Pounds per square inch	Time fom surface to beginning of ascent	Approximate time to first stop	Stoppages in minutes at different depths 80ft	70ft	60ft	50ft	40ft	30ft	20ft	10ft	Total time for ascent mins.
60-66	10-11	26.5-29.5	Over 3 hours	2	-	-	-	-	-	-	10	30	42
66-72	11-12	29.5-32	2-3 hours	2	-	-	-	-	-	-	10	30	42
			Over 3 hours	2	-	-	-	-	-	-	20	30	52
72-78	12-13	32-34.5	1.5-2.5 hours	2	-	-	-	-	-	-	20	25	47
			Over 2.5 hours	2	-	-	-	-	-	-	30	30	62
78-84	13-14	34.5-37	1.25-2 hours	2	-	-	-	-	-	-	15	30	47
			2-3 hours	2	-	-	-	-	-	5	30	30	67
			Over 3 hours	2	-	-	-	-	-	10	30	35	77
84-90	14-15	37-40	1-1.5 hours	2	-	-	-	-	-	5	15	25	47
			1.5-2.5 hours	2	-	-	-	-	-	5	30	35	72
			Over 2.5 hours	2	-	-	-	-	-	20	35	35	92
90-96	15-16	40-42.5	1-1.5 hours	2	-	-	-	-	-	5	15	30	52
			1.5-2.5 hours	2	-	-	-	-	-	10	30	35	77
			Over 2.5 hours	2	-	-	-	-	-	30	35	35	102
96-108	16-18	42.5-48	40-60 minutes	2	-	-	-	-	-	10	15	20	47
			1-2 hours	2	-	-	-	-	5	15	25	35	82
			Over 2 hours	2	-	-	-	-	15	30	35	40	122
108-120	18-20	48-53.5	35-60 minutes	2	-	-	-	-	5	10	15	25	57
			1-2 hours	2	-	-	-	-	10	20	30	35	97
			Over 2 hours	2	-	-	-	-	30	35	35	40	142
120-132	20-22	53.5-59	0.5-0.75 hours	3	-	-	-	-	5	10	15	20	53
			0.75-1.5 hours	3	-	-	-	5	10	20	30	30	98
			Over 1.5 hours	3	-	-	-	15	30	35	40	40	163
132-144	22-24	59-64.5	25-45 minutes	3	-	-	-	3	5	10	15	25	61
			0.75-1.5 hours	3	-	-	-	10	10	20	30	35	108
			Over 1.5 hours	3	-	-	-	30	30	35	40	40	178
144-156	24-26	64.5-70	20-35 minutes	3	-	-	-	3	5	10	15	20	56
			35-60 minutes	3	-	-	-	7	10	15	30	30	95
			Over 1 hour	3	-	-	20	25	30	35	40	40	193
156-168	26-28	70-75	16-30 minutes	3	-		-	3	5	10	15	20	56
			0.5-1 hour	3	-	-	3	10	10	15	30	30	101
			Over 1 hour	3	-	5	25	25	30	35	40	40	203
168-182*	28-30	75-80.5	14-20 minutes	3	-	-	-	3	3	7	10	15	41
(168-180)			20-30 minutes	3	-	-	2	2	3	10	15	25	60
			0.5-1 hour	3	-	3	3	7	10	20	30	35	111
			Over 1 hour	3	-	15	25	30	30	35	40	40	218
182-194*	30-32	80.5-86	13-20 minutes	3	-	-	-	3	3	7	15	15	46
(180-192)			20-30 minutes	3	-	-	3	3	5	10	15	25	64
			0.5-1 hour	3	-	3	5	10	12	20	30	35	118
			Over 1 hour	3	5	20	25	30	30	35	40	40	228
194-206*	32-34	86-91.5	12-20 minutes	3	-	-	3	3	5	7	10	20	51
(192-204)			20-30 minutes	3	-	3	3	3	5	10	20	20	67
			0.5-1 hour	3	3	3	5	10	15	20	30	35	124
			Over 1 hour	3	15	20	25	30	30	35	40	40	238

* These original figures are incorrect. The correct figures are bracketed below.

TABLE 6

COMPARISON OF DECOMPRESSION REQUIREMENTS *HALDANE 1908* AND DCIEM 1999

*** Depth and time taken from Haldane's Table II or time is below the limiting line in DCIEM tables**

Depth		Bottom	Time to	Stop times (minutes) at different depths (feet)								Total
feet	m	time	1st stop	80	70	60	50	40	30	20	10	time
50	***15***	***60***	***2***								***5***	***7***
50	15	60										1
50	***15***	***180***	***2***								***10***	***12***
50	15	*180									43	43
50	***15***	***280***	***2***								***20***	***22***
50	15	*280									97	97
60	***18***	***45***	***2***								***5***	***7***
60	18	45										1
60	***18***	***90***	***2***								***10***	***12***
60	18	90									19	19
60	***18***	****180***	***2***							***5***	***15***	***22***
60	18	*180								5	77	82
70	***21***	***15***	***2***								***2***	***4***
70	21	15										1
70	***21***	***30***	***2***							***3***	***5***	***10***
70	21	30										1
70	***21***	***60***	***2***							***5***	***12***	***19***
70	21	60								2	11	13
70	***21***	***120***	***2***							***10***	***20***	***32***
70	21	*120								8	56	64
80	***24***	***20***	***2***								***5***	***7***
80	24	20										2
80	***24***	***45***	***2***							***5***	***15***	***22***
80	24	45								4	12	16
80	***24***	***75***	***2***							***10***	***20***	***32***
80	24	75								9	35	44
80	***24***	***120***	***2***							***15***	***30***	***47***
80	24	*120							3	20	76	99
90	***27***	***10***	***2***								***3***	***5***
90	27	10										2
90	***27***	***20***	***2***							***3***	***5***	***10***
90	27	20										2
90	***27***	***40***	***2***							***5***	***15***	***22***
90	27	40								6	11	17
90	***27***	***60***	***2***						***3***	***10***	***15***	***30***
90	27	60							2	9	32	43
90	***27***	****90***	***2***						***5***	***15***	***25***	***47***
90	27	*90							6	15	62	83
100	***30***	***15***	***3***							***3***	***5***	***11***
100	30	15										2
100	***30***	***30***	***3***						***3***	***7***	***7***	***23***
100	30	30								6	10	16
100	***30***	***40***	***3***						***5***	***10***	***15***	***33***
100	30	40								9	18	27

TABLE 6 (Continued)

COMPARISON OF DECOMPRESSION REQUIREMENTS *HALDANE 1908* AND DCIEM 1999

*** Depth and time taken from Haldane's Table II or time is below the limiting line in DCIEM tables**

Depth feet	Depth m	Bottom time	Time to 1st stop	Stop times (minutes) at different depths (feet) 80	70	60	50	40	30	20	10	Total time
100	30	*60	2						10	15	20	47
100	30	*60							6	9	43	58
100	30	110	2					5	15	25	35	82
100	30	*110						4	9	39	112	164
110	33	35	3						5	10	15	33
110	33	35							4	7	19	30
110	33	*110	2					10	20	30	35	97
110	33	*110						8	16	50	136	210
120	36	30	3						5	10	15	33
120	36	30							5	7	17	29
120	36	*60	2					5	10	15	25	57
120	36	*60						6	8	19	61	94
130	39	30	2						5	10	15	33
130	39	30							7	8	23	38
130	39	*90	3				5	10	20	30	30	98
130	39	*90					7	7	22	54	144	234
140	42	25	3					2	5	10	12	32
140	42	25							7	8	19	34
140	42	*90	3				10	10	20	30	35	108
140	42	*90				4	6	8	30	68	157	273
150	45	20	3					2	5	10	12	32
150	45	20							6	8	11	24
150	45	*90	3				5	10	20	30	30	98
150	45	*90					7	7	22	54	144	234
160	48	15	3				2	3	5	7	10	30
160	48	15							7	7	10	23
160	48	*60	3			3	10	10	15	30	30	101
160	48	*60				6	6	7	18	45	129	211
170	51	14	3				2	3	5	7	10	30
170	51	14							6	7	10	23
170	51	*60	3		3	3	7	10	20	30	35	111
170	51	*60			4	5	6	8	23	54	144	244
180	54	13	3				2	3	5	7	10	30
180	54	13							8	7	11	26
180	54	*60	3		3	3	7	10	20	30	35	111
180	54	*60		3	3	5	7	9	29	65	155	276
190	57	13	3				2	3	5	7	10	30
190	57	*13					4	5	6	9	31	55
190	57	*55	3		3	5	10	12	20	30	35	118
190	57	*55		4	4	5	6	10	28	65	154	276
200	60	12	3			2	2	3	5	7	10	32
200	60	*12						6	5	8	18	37
200	60	*50	3	3	3	5	10	15	20	30	35	124
200	60	*50		5	4	5	6	10	27	62	153	272

recompression treatment of decompression sickness. He said "*the trouble, however, about the use of recompression chambers is that it is very often very difficult to get the patient out without the symptoms recurring, and that decompression in these sorts of situations may take up to many days*".[5] Also he recommended underwater recompression if no chamber was available, but he qualified that by saying that "*The trouble, however, is to get the man up again safely*".[6]

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ARTICLES OF INTEREST REPRINTED FROM OTHER JOURNALS

MECHANISMS OF EMBOLISM

R W (Bill) Hamilton

Key Words

Air embolism, decompression illness, medical conditions and problems, physiology, pulmonary barotrauma.

Decompression Illness: Mechanisms of Disease II is a continuation of a course on decompression diseases carried on for many years along with the UHMS Annual Meeting under the direction of **David Elliott**, whose position was ably assumed by **James Francis** last year in Seattle. James said about the first session last year that he could relieve David but not replace him, but he is well on his way to establishing a commendable course pattern of his own. Last year began with a description of decompression illness (DCI) from the point of view of how it comes about, considering the formation, growth, and behaviour of bubbles, and some of their overall consequences.

This year's course got out the magnifying glass and focused on embolism, or embolic phenomena. The subject was tackled by a strong group, including some regulars, some new faces, and a couple of old friends who had not been among us as often recently as we would like. The main target of gas embolism is the brain, and effects there were examined in detail, but the course began with a careful look at the lung, inasmuch as pulmonary barotrauma is the source of most cerebral gas embolism in divers.

The lung was elegantly characterised by **David Denison** as many "densely branching and closely intertwined tubular trees" contained in a "flimsy bag". The continuing and rather magnificent function of this organ, described at one point as an invagination, was covered with particular attention to the surface tension effects on the alveoli. Lung function is assessed by three main categories of test: blowing in a bag, breathing inside a box (a body plethysmograph), and use of a tracer (CO) to measure diffusion. This broncho-alveolar tree ruptures at a differential pressure of as little as 70 mmHg (10 kPa or about 1 msw). Most such overpressures are caused by behaviour rather than disease.

Tom Neuman looked at the clinical features of pulmonary barotrauma, beginning with the frustration that accompanies having neither a clear clinical definition nor a reliable incidence of the condition. He cites studies showing radiologically detectable gas in otherwise asymptomatic submarine-escape trainees at about a 1% level, suggesting it may be more common than we think. Gas can take many routes once it escapes the lung and, fortunately, many of these have benign consequences. When bubbles get into the blood, there can be serious or even fatal results.

Eric Kindwall asked if the lung ruptures in compression chambers, then answered "almost never". He reports a couple of cases, one in a tracheotomy patient with