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EXPERIMENTS ON THE INFLUENCE OF FATNESS ON SUSCEPTIBILITY TO CAISSON DISEASE.

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THE probability that fatness increases the susceptibility to compressed-air illness has been pointed out in a previous paper (this *Journal*, vol. VIII. p. 410). Vernon (1907) found that fat dissolves at body temperature rather more than five times the volume of nitrogen which is taken up by water. It follows that fat has an effective bulk some five times greater than its actual bulk. Hence the volume of blood circulating through fat or fatty organs is, relatively to the effective bulk of the tissues, much reduced. The assumption and discharge of nitrogen by the tissues while under pressure and after decompression vary with the activity of the circulation. Hence fat animals would probably take longer to become saturated with nitrogen while under pressure than similar thin animals, and would get rid of the excess gas more slowly on and after decompression. It was therefore presumed that fatness would either leave unaltered or somewhat diminish the susceptibility to caisson disease with very short exposures, and increase it with moderate and long exposures. The only experimental evidence which we were then able to bring forward was the observation that pregnant goats seemed to be particularly liable to death from compressed-air illness and appeared at the same time to be definitely fatter than non-pregnant animals on naked-eye inspection. A series of experiments were therefore instituted to examine the question directly and quantitatively. Very short exposures have not been dealt with, and the experiments have been confined to the effects of decompression

on animals nearly or completely saturated with nitrogen at the given pressure.

Considerations of convenience in the estimation of the total fat in the body made the use of small animals desirable. The objections to transferring the results of experiments on rats or guinea-pigs to human experience have been already dealt with. The general scheme of the experiments has been to sort up a series of animals by one or more decompression experiments into susceptible and non-susceptible groups, and then to estimate the total fat in both groups by Leathes' modification of Liebermann's method (Hartley, 1907). Shortly, the whole animal is dissolved in strong potash and the saponification of the fat completed with the aid of alcohol: the soap solution, or commonly a small fraction of it, is then acidified with sulphuric acid, the fatty acids and "fluff" collected in a filter, dried and extracted with petroleum ether boiling below 60° C. in a Soxhlet apparatus. After removal of the solvent, at the end under diminished pressure, the residue consists of hardly anything else but the higher fatty acids. The method has proved entirely satisfactory, skin, bones, etc. giving no trouble, and with appropriate apparatus could be applied satisfactorily to much larger animals. The great advantage is that the whole animal is reduced to a homogeneous soap solution which can be properly sampled; we much doubt whether any method of mincing would allow a fair average sample to be obtained with certainty for the actual estimation. The disadvantage of the method is that the final product contains not only the fatty acids derived from fats existing as such in the animal but also those set free from the combinations in which they do not appear as free fat either microscopically or, we may assume, as solvents of excess nitrogen. This latter portion is however quite small in proportion to the total fat. It is also probably pretty constant in absolute amount for similar animals, and, since our analyses show that the total fatty acids may amount to no more than 1 per cent. of the body weight in some rats, may for the present purpose be neglected.

The animals were not selected in any way before being subjected to experiment, and were kept on the ordinary laboratory diet. Most of them were used immediately after purchase; as will be seen the general fatness of the different series varied a good deal. The results are expressed as fatty acids per cent. of the total fresh weight of the whole animal. The figures for fat would be about 4 per cent. higher. The weights are given in grammes and the sex of each animal is also indicated. Animals marked p were pregnant.

A. *Experiments with rats.*

Series I. Rats. Pressure + 100 lbs., exposure 1 hour, decompression 5 seconds.

No symptoms			Doubtfully ill			Ill			Died		
Sex	Weight gms.	Fatty acids, %	Sex	Weight gms.	Fatty acids, %	Sex	Weight gms.	Fatty acids, %	Sex	Weight gms.	Fatty acids, %
M	135	0·8	F	95	1·0	*M	185	1·3	M	107	1·4
M	108	1·5	F	112	1·8	M	224	1·3	M	54	3·4
F	114	1·7	F	108	2·2	F	160	2·7	M	177	3·6
F	157	2·2	M	103	3·2	*M	120	2·8	M	209	3·7
M	88	2·3	M	142	5·7	F	97	3·2	M	247	4·5
F	157	2·4	F	127	5·9	*Fp	200	6·7	F	155	5·1
F	136	3·1	F	138	6·0	F	143	7·5	F	154	5·2
M	138	4·1	F	122	6·6	F	177	7·6	M	44	5·8
M	220	4·6	F	107	7·3				M	49	6·0
F	120	4·8	F	189	9·5				F	37	6·5
F	83	5·1							F	114	6·8
F	105	5·1							F	41	6·9
F	135	5·7							Fp	129	7·1
M	101	5·8							Fp	195	7·4
M	97	6·1							F	147	7·9
M	200	7·7							M	102	8·1
M	125	7·9							M	137	8·9
M	125	8·1							F	219	9·7
Av	130	4·4		124	4·9		163	4·1		129	6·0

* These animals had paraplegia: the rest of the "ill" group were clearly unwell but showed no definite local symptoms.

The general result was that the animals which did not die had about three quarters of the fat of those which died. The series was by no means homogeneous in respect of size, though the average weight of each group is much the same: if the four rats under 50 gms. are deducted the average weight of the "died" group becomes 153 gms. Dividing them up into weight groups[1] the results are as follows:

	37—49 gms.	50—99 gms.	100—149 gms.	150—199 gms.	200—247 gms.
Number of rats	4	6	27	10	7
No. which died and % fatty acid	4 : 6·3	1 : 3·4	6 : 6·7	4 : 5·3	3 : 5·5
No. which were ill and % fatty acid	0	2 : 2·1	10 : 4·9	4 : 5·3	2 : 4·0
No. which showed nothing and % fatty acid	0	3 : 4·5	11 : 4·4	2 : 2·3	2 : 6·1
Average % fatty acid	6·3	3·5	5·1	4·7	5·5

As far as these indefinite results go, they would indicate that mortality runs parallel with fatness rather than with size. The four

[1] For the correlation between weight and age in tame rats see Donaldson (1906), and on the relation between weight, age and susceptibility to caisson disease Hill and Greenwood (1908).

small rats used, all of which died, had lived with their mother since birth and were a good deal fatter than most rats of similar size which had led a more competitive existence (see Series II).

Analysed by sex we find no marked difference in susceptibility.

	No symptoms	Ill	Died	Total
Males	10	5	9	24
Females	8	13	9	30

There is however a fairly regular excess of fatness in the females.

	37—49 gms.	50—99 gms.	100—149 gms.	150—199 gms.	200—247 gms.	Total
Males	5·9 %	3·9	4·8	2·4	4·4	4·5
Females	6·7 %	3·1	5·3	5·3	8·2	5·4

The three pregnant females averaged 7·1 per cent.

Series II. Rats. Exposure 1 hour, decompression 5 seconds: in this series the animals were first tried at +80 lbs., the survivors on the following day at +90 lbs. and so on up to +120 lbs. The ultimate survivors had therefore been through five experiments.

Died at +80 lbs.:—								
M	26 gms.	0·85 %	M	25·5	1·0	M	210	8·2) Average
M	32·5	2·3	F	51	5·75	M	242	5·8) 4·0 %
Died at +90 lbs.:—								
F	130	8·3						
Died at +100 lbs.:—								
M	52	5·2	M	47	4·1	F	101	8·9) Average
F	31	9·2	M	80	1·2			) 5·0 %
Died at +110 lbs.:—								
F	52	4·6	F	42	7·0	M	127	11·3) Average
F	26	4·2	M	115	6·0	F	193	9·1) 8·8 %
Died at +120 lbs.:—								
F	52	2·8	M	39	1·6	F	164	7·5 Average 4·0 %
Survived:—								
F	55	3·3	M	49	6·7	M	151	5·9)
F	49	2·6	M	44	3·1	M	102	4·45) Average
M	38	3·2	M	65	4·1			) 4·2 %

On analysing these results according to size and sex we find:

Weight	Number	Died	Survived	Average fatty acids per cent. Died	Survived	Total
<50	12	8	4	3·8	3·9	3·8
50—99	7	5	2	3·9	3·7	3·8
100—149	5	4	1	8·6	4·4	7·8
150—199	3	2	1	8·3	5·9	7·5
>200	2	2	0	7·0	—	7·0
Total	29	21	8	5·5	4·2	5·1
Males	17	11	6	4·3	4·4	4 35
Females	12	10	2	6·7	2·95	6·1

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Here again we find that mortality corresponds more with fatness than with weight or sex. The difference in the fatness of those which died and those which survived (5·5 % against 4·2 %) is entirely due to the great difference between dying (6·7 %) and surviving (2·95 %) females.

Series III. Rats. Pressure + 110 lbs., exposure 1 hour, decompression 35 seconds uniformly. All the animals were killed after the experiment, and, to somewhat reduce the labour of the fat determinations, were dissolved in potash in groups.

No symptoms			Ill			Died		
	gms.	%		gms.	%		gms.	%
F	147	11·8 %	*M	110	7·2 %	M	159	14·6 %
M	136		*F	170	3·85 %	F	190	
F	106		*F	182		M	161	
F	106		F	128	1·6 %	Fp	161	
M	163	7·6 %	F	150		M	157	
F	160					F	133	16·1 %
M	165					F	98	
F	185					M	178	10·8 %
F	193					F	115	5·8 %
M	184					F	81	
M	182					Fp	142	13·2 %
M	72	7·1 %				M	125	
M	45	4·3 %				M	101	
M	46					M	86	5·3 %
F	46					M	46	3·1 %
M	55					F	55	
						M	58	
						F	41	
						F	47	
Average	124	8·3 %		148	3·5 %		112	11·7 %

In this series again the rats which died have more fat than those which lived, the whole batch being fatter than those of Series I and II. The method of pooling adopted for the estimation does not allow any further analysis, but in the quite small rats, as in Series II, fatality and fatness do not go together. Females are not more susceptible than males, 9 males dying out of 19 and 10 females out of 21.

Summary of experiments with rats.

The results of Series I, II and III may be shortly summarised as follows:

(1) The rats which died had on the whole more fat than those which survived, roughly in the proportion of 100 : 70.

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(2) Middle sized and large rats tend to be fatter than small rats, and female rats than male rats: the small rats and male rats used in these experiments were not definitely less susceptible[1].

B. *Experiments with guinea-pigs.*

The results of these observations are clearly unsatisfactory. It was obvious that a better selection of the animals into susceptible and non-susceptible groups would be obtained if slower decompressions could be used. This could not be done with rats, since a decompression as short as 5 minutes never (?) produces a fatal result or definite symptoms of illness. After some preliminary experiments we used large guinea-pigs. These proved necessary, decompressions of 23 and 34 minutes by stages after 1 hour[2] at + 100 lbs. producing the result of killing about half the animals.

Large (400—700 grammes) guinea-pigs appear to be more susceptible to caisson disease than their size would lead one to suppose. This is correlated with their relatively low rate of respiratory exchange. We made four respiration experiments to verify the commonly accepted figure of about 1·5 grammes of CO_2 per kilo per hour.

Sex and weight in grms.	CO_2 produced per kilo per hour
M 617, M 498, M 490, M 592, M 585	1·755 grms.
M 606, F 582	1·417 ,,
F 597, M 610	1·794 ,,
M 587, F 452	1·988 ,,
Average	1·739 ,,

On this figure, which appears to be if anything rather high, a guinea-pig of 550 grammes would only produce about 1·5 grammes of CO_2 per 1000 sq. cm. of surface per hour as against rather more than 2 grammes given off by goats, dogs, etc.

In view of the method of expressing the results as percentages of fatty acid on the crude body weight, we determined the proportion which the contents of the alimentary canal bear to the total weight in a series of 11 animals:

[1] We are sceptical about the general truth of this result.

[2] It is not quite certain that large guinea-pigs would be saturated in one hour. It is perhaps necessary to point out that the "stage" decompressions were not supposed to be safe: this method was used because it is less tiresome to carry out than decompression at a uniform rate.

Sex and crude weight of animal Grammes		Weight of contents of alimentary canal Grammes	= Per cent.
M	412	55	13
F	415	53	13
F	515	57	11
M	518	54	10
F	634	81	13
F	642	75	12
M	662	100	15
F	698	109	16
F	700	101	14
F	730	111	15
M	765	81	11
		Average	13

The weight of the contents of the alimentary canal has not been taken into consideration in calculating the fat content of the animals dealt with below. We found that the contents yielded no appreciable fat when treated by the method used; in most cases therefore the alimentary canal was not emptied before the animals were dissolved. In all the guinea-pig experiments, the number of determinations was reduced by pooling animal in groups of "died" and "lived." In the case of pregnant animals, the figures given include both mother and foetus. In a number of cases the foetus were actually analysed separately: their percentage fat content was always less than that of the mother except in the case of one embryo nearly at full term.

Series IV. Guinea-pigs. Pressure +100 lbs., exposure 1 hour, decompression 4 minutes uniformly.

No symptoms			Died		
	gms.	%		gms.	%
M	662	3·2	F	572	4·05
F	700		F	515	6·6
M	765		Fp	642	
M	518	2·7	F	730	
			F	698	5·3
			F	634	
			M	412	5·9
			F	415	
Average	661	3·1		577	5·8

Series V. Guinea-pigs. Pressure +100 lbs., exposure 1 hour, decompression 10 minutes uniformly.

No symptoms			Died		
	gms.	%		gms.	%
M	599	2·9	F	615	9·7
M	362	1·9	M	702	
			M	662	
			F	572	
			F	588	
Average	480	2·5		628	9·7

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Series VI. Guinea-pigs. Pressure +100 lbs., exposure 1 hour, decompression in 23½ minutes in stages as follows: 100 lbs. to 40 lbs. in 1 min., then 1 min. at 40, 1 min. at 35, 1 min. at 31, 2 mins. at 26½, 3 mins. at 22½, 3 mins. at 18, 3½ mins. at 14, 4 mins. at 9, and 4 mins. at 4½. The experiment was gone through three times with each available animal, so that the ultimate survivors had lived through three decompressions. The first eight animals however in the "no symptoms" list were killed after their first decompression.

No symptoms			Ill			Died in first trial		
	gms.	%		gms	%		gms.	%
Fp	509	3·9	M	767	4·2[1]	Fp	500	9·6
F	472		M	725	4·3[2]	Fp	742	10·5
F	509		M	672	4·7[2]	F	538	12·3
M	409	3·5	M	507	4·9[2]	M	672	7·9
M	420		M	440	4·7[2]	M	675	
M	450		M	580	3·9[2]	M	617	9·1
M	517					F	577	
M	617					M	637	
M	617	2·4				F	684	
M	498					F	465	
M	490					F	584	8·8
M	592					F	522	
M	585					F	622	
M	585	3·6				Fp	455	7·1
M	545					Died in second trial		
F	555	5·9				F	537	7·4
						M	642	
						M	762	
						Died in third trial		
						Fp	580	9·2
Average	523	3·4		615	4·5		589	8·8

[1] Paralysed. [2] Paralysed temporarily.

Series VII. Guinea-pigs. Pressure +100 lbs., exposure 1 hour; the animals were first decompressed three times on successive days in 50 minutes by stages, and afterwards three times in 34 minutes by stage: the ultimate residue had therefore survived six decompressions. Spacing of decompressions as follows, in minutes:

100 lbs. to 40 lbs. in	1	1
Wait at 40 lbs. for	3	2
,, 36 ,, ...	3	2
,, 31 ,, ...	4	2
,, 27 ,, ...	4	3
,, 22 ,, ...	5	3
,, 18 ,, ...	6	4
,, 14 ,, ...	8	5
,, 9 ,, ...	8	6
,, 4 ,, ...	8	6
Total	50	34

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No symptoms			Ill			Died in first trial		
	gms.	%		gms.	%		gms.	%
*Fp	447	3·3	M	492	3·0[1]	Fp	484	5·2
F	382	4·8	*Fp	405	4·8[2]			
M	402					Died in fourth trial		
M	615	3·5				Fp	712	8·7
M	490					Fp	462	4·3
						Died in fifth trial		
						Fp	547	8·1
Average	467	3·9		448	3·9		551	6·9

[1] Menière's disease (?) twice.

[2] The same once.

* Both these animals showed numerous bubbles in the amniotic fluid (none elsewhere) when they were killed 5 hours after their sixth decompression which caused no symptoms.

Summary of experiments with guinea-pigs.

(1) The guinea-pigs which died had more fat than those which lived, roughly in the ratio of 100 : 45.

(2) There is a much greater mortality among females than males:

	No symptoms	Ill	Died	Total
Males	20	7	9	36
Females	7	1	26	34
Of which pregnant	2	0	9	11
Total	27	8	35	70

(3) The method of pooling does not allow the exact difference in fatness between all these males and females to be ascertained, but it cannot be much different from that between survivors and dead animals. Of the 50 animals available for analysis by sex, 26 males averaged 3·7 % fatty acid, 24 females 6·7 %, and 9 pregnant females 7·5 %.

C. *Experiments with dormice.*

Series VIII. Dormice. Some incomplete experiments were made with dormice in the hope of being able to compare their susceptibility just before hibernation when they were very fat and after hibernation when the fat had been used up. The experiments were made in November when the mice were beginning to be sleepy at night: owing to the high mortality, they were not carried through.

106 lbs. 1 hour, 5 seconds

M	25 gms.	24·3 %	No symptoms
F	11	8·0	,,

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120 lbs. 1 hour, 5 seconds

M	21 gms.	22·8 %	Died at once
M	20·5	22·3	,, ,,
*F	10·5	2·5	Died 20 mins.
*M	9·25	3·4	,, ,,
*M	8·0	1·9	Died 10 mins.
M	15·0	5·1	Paraplegia: dead next day.
F	13·5	10·7	No symptoms.
F	12·0	7·3	,,
M	15·0	7·1	,,
M	15·0	10·9	,,
M	12·5	3·3	,,

The animals marked * were bemused, but not fast asleep; the rest were quite lively, as were seven other small (8 to 14 gms.) dormice in the same experiment which showed no symptoms and were not killed. The two lively animals which died were much the fattest; at the same time they were the largest. The sleepy ones, all of which died, were among the smallest and least fat, and give a good illustration of the influence of a sluggish circulation. Though it is not directly germane to the subject in hand, we may mention here that we found that sleepy dormice of 10 or 12 gms. can usually be killed by 75 lbs., an exposure of 1 hour at 75 lbs. with decompression in 5 seconds, while 120 lbs. with the same exposure and decompression had hardly any effect on lively animals of the same weight. If on the other hand they were in a deep sleep, an exposure of one, and even two hours at + 75 or + 90 lbs. did not seem to be sufficient for them to take in enough excess gas to produce a fatal effect on quick decompression.

Summary and conclusions.

Reducing the results of Series I to VII to their simplest form, we find:

			Survived			Died		
Series	Animal	Number	Number	Average weight grammes	Average per cent. fatty acid	Number	Average weight grammes	Average per cent. fatty acid
I	Rats	54	36	136	4·5	18	129	6·0
II	,,	29	8	69	4·2	21	85	5·5
III	,,	40	21	130	7·0	19	112	11·7
IV	Guinea-pigs	12	4	661	3·1	8	577	5·8
V	,,	7	2	480	2·5	5	628	9·7
VI	,,	40	22	548	3·7	18	589	8·8
VII	,,	11	7	462	3·9	4	551	6·9
Total		193	100	—	—	93	—	—

All seven series give answers in the same sense, and we may conclude that we have definite experimental evidence that *fatness*

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increases the susceptibility to death from caisson disease. The regularity of the results in the guinea-pig experiments suggests that fatness is here the predominant influence in individual susceptibility. The difference in weight between the "survived" and "died" is not always in the same sense, and is in no case very large. The weight factor may therefore be relatively excluded in considering these results: indirectly it is of influence in that rats, like men, tend to become fatter as they grow older[1]. Our results show pretty clearly that females are fatter than males, and, in the guinea-pig series, much more susceptible. Femality, like age, is not a quality which can *per se* have any influence on susceptibility. The increased susceptibility of females is probably simply due to their increased fatness, which tends to further increase during pregnancy. With regard to symptoms other than death our evidence is very meagre. Some symptoms, e.g. bends, may be presumed to be independent of fatness.

We do not make any suggestion that the extra gas dissolved by fat produces fatal effects by its liberation *in situ*. As far as we could make out, the immediate cause of death in these rats and guinea-pigs was the usual pulmonary air embolism. Though the fat itself usually contains many bubbles, both intravascular and among the cells, obesity doubtless favours death after long exposures because the fat acts as a reservoir of nitrogen and so keeps up the nitrogen pressure in the venous blood after decompression for a time sufficiently long for bubbles to form (see this *Journal*, vol. VIII. p. 356). If paralysis due to embolism of the spinal cord is really more frequent in fat animals—and our results are not clear on this point—we must assume a similar explanation, though it is not altogether clear that an increase in the bubbles on the venous side necessarily involves a more abundant supply of arterial emboli (*ibid.* p. 414).

The practical conclusions are clear. Really fat men should never be allowed to work in compressed air, and plump men should be excluded from high pressure caissons (e.g. over + 25 lbs.) or in diving to more than about 10 fathoms, and at this depth the time of their exposure should be curtailed. If deep diving is to be undertaken, or caissons worked at pressures approximating to + 45 lbs., skinny men should be selected. It is unfortunate that an increase of experience and skill in technical operations should so often be associated with the increase in waist measurement which accompanies the onset of middle

[1] Probably also guinea-pigs. We only have figures for six small guinea-pigs (154—208 grammes) which averaged 2·9 % for males and 2·8 % for females.

life. Middle aged men have a lower rate of respiratory exchange than young men: if fatness is not the explanation of this, they are at a double disadvantage, and the two factors must be multiplied, rather than added, together.

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REFERENCES.

HARTLEY, P. (1907). *Journal of Physiology*, vol. XXXVI. p. 19.
VERNON, H. M. (1907). *Proc. Royal Soc.* B. vol. LXXIX. p. 366.
DONALDSON, H. H. (1906). *Boas Memorial Volume*, p. 5.
HILL, L. and GREENWOOD, M. (1908). *Proc. Royal Soc.* B. vol. LXXX. p. 12.