VOLUME III OCTOBER, 1903 No. 4

CAISSON ILLNESS AND DIVER'S PALSY. AN EXPERIMENTAL STUDY.

BY LEONARD HILL, M.B., F.R.S.,
Lecturer on Physiology, London Hospital,

AND J. J. R. MACLEOD, M.B.,
Professor of Physiology, Western Reserve University, Ohio.

A CAISSON consists of a steel cylinder which is sunk in water, and out of which the water is kept by means of compressed air. The men in the caisson are thus able to work on the bed of the river or the sea.

The top of the caisson is provided with an air-lock, a chamber fitted with air-tight doors and cocks, whereby the air can be compressed or decompressed as the men enter or leave. A large cock is utilised for rapid decompression during the passage of material, and a small cock for the slower decompression of men. The men frequently take advantage of the large cock, and by breaking the rules get out of the air-lock quickly.

Ten metres of water roughly correspond to 1 atm.: thus for every 10 metres or 33 feet a pressure of + 15 lbs. to the sq. inch or + 1 atm. is required to keep the water out of a caisson or diving-bell. At a depth of 100 feet a man would be exposed to + 3 atm., at 200 feet to + 6 atm. In the case of a diver the conditions are the same. Compressed air is delivered through a tube to his helmet and escapes by a valve, by which means the water is kept out of his dress. The pressure of the air must always be just greater than that of the water.

The numerous accounts of caissonier's and diver's sickness which have been published show that the sickness never attacks the men while under pressure, but only after decompression. The account of the symptoms given by Pol and Watelle[1] in 1854 may be taken as

[1] *Ann. d'hygiène publique et de méd. légale*, 1854. Cit. after Bert, *La Pression Barométrique*, p. 380.

typical. These authors had charge of 64 men who were employed in a caisson on the banks of the Loire at $+3\frac{1}{4}$ atm. The men were compressed in 15 minutes, worked for a 4 hr. shift, and were—according to the rules—decompressed in 30 minutes.

The physiological effects observed in compressed air were very slight—pains in the tympanic membrane (relieved by opening the Eustachian tube); slowing of respiration and diminution in thoracic expansion; slowing of the pulse; increase of urinary secretion; a feeling of resistance to movement owing to density of the atmosphere; inability to whisper, attributed to the resistance of the compressed air to the finer muscular movements of the tongue. On decompression these authors felt a lively sensation of cold and a certain degree of breathlessness; while the pulse accelerated. The cold is due to the expansion of the air.

Pathological effects. There were 47 men out of the 64 who stood the work more or less well; 25 were discharged owing to sickness; 2 died. The slighter attacks were 14, and the serious attacks 16 in number.

The accidents without exception occurred after decompression.

Types of Cases.

I. Embarrassed respiration, pains in the limbs, loss of appetite and digestive troubles, black stools, loss of flesh.

II. A dazed condition, muscular pains and cramps, feelings of numbness, vomiting of black material. One day this man lost consciousness soon after decompression. The pulse was full and frequent, the face congested, the respiration short and stertorous with mucous rales. There was complete loss of muscular power. The man was bled, purged and blistered and recovered in four hours.

III. Severe muscular pains with cramps, the skin cold, respiration embarrassed, the pulse small and slow.

IV. A comatose condition like to drunkenness, with indistinct speech, dilated pupils, accelerated respiration and rapid pulse. Diplopia, deafness and vertigo persisted.

V. Severe pain in the limbs and chest, embarrassed respiration. The man was discharged. He returned to the work without permission. On decompression he suddenly fell unconscious and died in 15 minutes.

VI. Great oppression, with dulness and bronchophony, a rapid pulse, cold skin, continual cough, and clonic contractions of the limbs. Better

after 5 hours of care. On another occasion this man became comatose, with dilated pupils, loss of muscular power and subdelirium. He was bled—the venous blood was arterial in colour. The man recovered and was discharged.

VII. Vision disturbed and double, hearing abolished, respiration frequent, pulse frequent and high tension. Bled, venous blood arterial in colour.

VIII. Pains in the head, vertigo, cramps.

IX. A powerful man, aged 40. Died immediately after decompression.

X. Muscular pains. *Cured by recompression.*

XI. Very severe muscular pains, persisting for many days.

XII. A few minutes after decompression the man appeared to be dead; unconscious, livid face, dilated pupils, embarrassed respiration, indistinct trembling of the heart, no pulse, involuntary micturition, black vomit. Given hot baths and massage. Pulse returned in 30 minutes. Very severe muscular pains, blindness and deafness, with a wretched pulse during the night.

Next day the man is better but mentally confused. He recovered, but feeble vision and dilated pupils persisted.

Pol once suffered himself from acute pain in the left shoulder or arm, with shivering and vomiting. It seemed to him that *emphysema* existed in these places. E. H. Snell likewise thought he could detect emphysema in one of the cases of joint and muscular pain ('bends' or 'la pressure') at the Blackwall tunnel; while Bucquoy records that a cupping-glass, applied by a skilled assistant, would not hold on to a painful knee-joint owing to the gas set free in the subcutaneous tissues.

Among the numerous other reports collected together by Paul Bert[1] and recently added to by E. H. Snell[2] we will quote some cases recorded by Babington and Cuthbert at Londonderry. The pressure reached 30—43 lbs.

As in all caisson works the men suffered joint and muscular pains or from 'bends.'

Cases.

I. The man suddenly fell unconscious on decompression after 4 hours at 28 lbs. He was cold and livid. There was right facial paralysis

[1] *La Pression Barométrique.* Paris, 1878.

[2] *Compressed Air Illness.* London, 1896.

and strabismus: pupils immobile. Pulse 150, small and irregular; heart sounds almost inaudible: respirations 24—44, very irregular. Bled—blood very black. Died in 24 hours.

II. Similar to I. but no facial paralysis.

III. Sharp shooting pains in legs and thighs; unable to walk, feet cold and numb; legs anaesthetic; was found with feet almost in the fire, and toes badly burnt. Recovered in two days.

IV. Very similar to III. Recovered in a few days.

V. Fell helpless and semi-comatose during decompression. Could be roused to answer questions. Coma passed off in 18 hours. Totally paralysed from 4th rib, retention of urine. Died 160 days after.

VI. Similar to V. but paralysed from 8th dorsal vertebra. Died after 30 days.

In sinking the foundations of a bridge at St Louis on the Mississippi a high pressure of + 50 lbs. was used. The number of workers was 600, of whom 14 died and 119 were more or less affected[1]. On leaving the caisson the workers are stated to have been pale and fatigued. Involuntary contractions and nose bleeding occurred in some.

As the depth increased the illnesses became more numerous and severe. The men were not taken sick while in the caissons, but a few minutes to one hour after decompression. At the greatest depth the shifts were reduced from 4 to 1 hour, and the engineer Eads states that this reduced the serious accidents to *nil.* Visitors who stayed but a few minutes, and the workers of the locks, who were quickly compressed and decompressed, never suffered. 53 cases suffered from paralysis of the legs with, usually, epigastric pain. Nearly all these recovered in from 1 day to 1 week. The sudden deaths were preceded by coma, stertorous breathing and muscular spasms.

At Brooklyn Bridge 110 similar cases of illness occurred, with 3 deaths, as reported by Dr Andrew Smith[2]. J. Hunter[3] stated that at the Forth Bridge works "the joint pain is of all symptoms the most constant, and almost invariably it attacks the knee alone, or with other joints, rendering its poor victims from its severity absolutely helpless.... Another prominent symptom met with was epigastric pain accompanied by vomiting."

The following interesting case is reported by Dr Twyman in the *Brit. Med. Journal,* Vol. I. 1888, p. 190. A man worked for 3 hours at

[1] Cit. after E. H. Snell. *Compressed Air Illness.* 1896.
[2] *Effects of Compressed Air,* Detroit, 1886.
[3] *Edinburgh thesis,* cit. after Snell.

+60 lbs. He was decompressed in 3 minutes. On the way home he was seized with severe pain in the right elbow joint, a little later his right knee gave under him and he fell and became semi-conscious. Acute pain in both elbows and knees followed and 6 hours after decompression he was found cold and almost pulseless. He recovered but spat blood for 3—4 days. Necrosis of the right femur followed and the leg had to be amputated. The cause of this was, no doubt, embolism of the medullary artery of the femur.

The following account given by one of the caissoniers in the Blackwall tunnel gives a graphic picture of the less grave form of accidents.

"What did it feel like to go in? Oh, just the same as anywhere else. You felt a wee bit giddy when you went in, and that was all.

"We stayed in for eight hours at a shift. We had half-an-hour for dinner, but some of the men would not come out for it. They took it inside with them. Coming out again it was not so bad, but just chilly—bitter chilly, cold as charity. The pains would come on afterwards, in an hour or so, or when you got into bed. Bends in the back, and the wrists, and the legs—just awful. Men would turn out in the middle of the night, and come back to the works, and get into the compressed air again, in the medical locks. They had a full dose of it for a start, and let the pressure drop gradually. Then they went back home to bed. Do them any good? Eh, mon, it's no for me to say. They said so, but I thought it was only humbug, a faith dodge. When I had bends I just jumped about and took a drap of guid whuskey—better than all your doctor's concoctions.

"I never felt happier than when I was in the compressed air. Always happy, and on the cheery side. Why, laddie, I would get up in the morning feeling very dour and queer, and just go into the workings, and then whistle and sing all day long. Not that you could hear the whistling, at least a man with my lungs, when the pressure was over twenty-five.

"The worst thing that could happen was for the electric light to fail. Then they burnt candles, and the mixture of smoke with the air gave them 'bends' of an extra special vigour." (He was in the No. 3 caisson, where the pressure was as high as 37 lbs. to the inch. The effect of that abnormally condensed atmosphere was to cause an overpowering sleepiness.) "You nodded, and didn't care if you went to sleep for ever, though it was all very nice and dreamy. When I was alone in that 'casoon' I had to rope myself up, lest I should fall

asleep and tumble to the bottom, 60 ft. below. It was better under the river than in the casoons, because under the river the air could escape into the Thames. Tobacco had no sting. Even Irish roll had lost its savour. The only stuff that had any flavour was four-ale. You weren't allowed to take it in, but you did. But you had to take the cork out first. If you didn't the bottle would burst. The finest men in the tunnel were the first to be knocked out. The men of delicate appearance stood the pressure best."

The symptoms of the men employed at Blackwall have been fully reported by E. H. Snell (*loc. cit.*). Snell especially brought into notice cases of auditory vertigo.

In none of these cases the vertigo occurred without deafness. The vertigo was increased by moving the head in one particular direction and was frequently accompanied by vomiting and mystagmus.

That very prolonged exposure to compressed air is harmless is shown by the fact that mules were kept in the Hudson caissons (at + 2·3 atm.) for many months, and were sold for a good figure at the end (E. W. Moir[1]).

Von Schrötter[2] has studied many caisson cases at Vienna where the depth of the water was 25 metres. In one case a strong, healthy man aged 36 worked at + $2\frac{1}{3}$ atm. for the first time from 10 p.m.—2 a.m. without any trouble. Half-an-hour after his ascent he was seized with intense pains in the limbs, with great difficulty in breathing. He soon could not stand and lost consciousness. There was now great dyspnoea, an intermittent pulse, cyanosis of the face, and fine rales over the lower lobes of the lungs. The face became livid, the pulse almost imperceptible. After ether injections and artificial respiration consciousness returned. The patient complained of great pain, and especially in the right arm, and of feeling cold. He could not move. Temperature 36° C. Profuse sweating. The respiration was costal, and the diaphragm fixed in the expiratory position. The man gradually recovered, but 2 months later there was still some loss of motor power, patches of hyperalgesia, increased knee jerks, pains in right elbow and left knee, loss of sexual power, and inability to hold urine more than 1 hour. There was evidently a lesion above the origin of the phrenics in this case, producing the immobility of the diaphragm and arm symptoms. Probably there was another lesion in the lower dorsal region.

[1] The Blackwall and other Subaqueous Tunnels. *Journ. Soc. Arts*, May 15, 1896.

[2] *Prager med. Wochenschrift*, XXIV. 1899, Nr. 14.

The following are some of v. Schrötter's cases.

	Initial symptoms	More or less lasting symptoms
1.	Pains in the ears; intense pains in legs.	Myalgia.
2.	Intense pains in all limbs.	Arthralgia and myalgia.
3.	Paraplegia of legs; pains in left arm.	Monoplegia of left arm.
4.	Pain in chest; vertigo; difficulty of breathing; weakness in the legs; loss of consciousness.	Paraplegia of legs.
5.	Vertigo; pains in limbs; spastic paralysis of legs.	Paraplegia of legs.
6.	Vertigo; vomiting.	Ménièr's symptoms.
7.	Loss of consciousness and convulsions; vertigo; deafness.	Ménièr's symptoms; aphasia.
8.	Vertigo; deafness; double vision; maniacal fits.	Apoplectiform; deafness; Ménièr's symptoms.
9.	Paraplegia; asphyxial phenomena; loss of consciousness.	Spastic paraplegia.

Schrötter noticed brachycardia in several cases, disappearing within at most three weeks of the accident. The pulse rate diminished by 18 to 42 beats per minute. He attributes the cause of this to air emboli causing central stimulation of the vagus, or to air bubbles in the coronary circulation interfering with the nutrition of the heart. Either cause has been proved experimentally to decrease the frequency of the heart.

In the case of diver's sickness a large number of reports have been gathered together by Bert. M. Denayreuze[1] reported on 200 men who dived to a pressure of +3 to +4 atm. During six months' work five men died and a great number were affected, most commonly with paralysis of the legs and bladder and deafness. The men who quickly returned to the surface suffered most. None of the deaths occurred while the men were under water. M. Gal recorded the following typical cases occurring among the Greek divers.

I. Submerged for 15′ at 40—45 metres (+4 to 4½ atm.). Some minutes after returning to the boat the diver complained of dizziness and fell down and died.

II. Submerged for 45′ at 40 metres; 15′ after being pulled up he was seized with pains, and almost at once lost consciousness and died.

III. 30′ after return to the boat was seized with severe pain in the epigastrium. Became paralysed in legs, bladder, and rectum. Died after 3 months.

IV. Became paraplegic shortly after return to boat. Cured in 3 months.

[1] *loc. cit.* p. 413.

V. Depth 35—45 metres; paralysis of legs: cured in 5 days.

Messrs Siebe and Gorman tell us that among the Greek divers about a score of lives are lost every year. Catsaras[1] has recorded many such cases, and among others cases of motor aphasia, sensory aphasia, hemiplegia, Jacksonian epilepsy, blindness, and vertigo.

Through the agency of Messrs Siebe and Gorman we circulated among the pearl divers of Australia questions concerning the illnesses of divers. The divers there go to 100 feet and very rarely to 125 feet. In shallow water they work for two hours, in deep water for 15′—20′.

The symptoms of illness occur directly or soon after the diver comes on deck. "There is no pain whilst on the bottom but directly the diver comes to the top." The pains occur in the hips and knees, calves of legs and arms. Paralysis of the leg and incontinence of urine are the graver symptoms. Bassett Smith of H.M.S. Penguin[2] says cases of slight paralysis are very common. The men are paid by results, and so will go to considerable depths. A local swelling of the abdomen is regarded as of evil omen, and death is supposed to follow if the swelling passes under the ribs. So the treatment is to sit on the swelling.

The following are extracts from the records of the autopsies which have been made after deaths due to caisson illness and diver's paralysis.

Autopsies of Caissoniers.

(1) General congestion of the viscera, patches of congestion on the brain.

(2) General subcutaneous emphysema. Congestion of viscera and especially of lungs. A heavy man aged 40. (Pol and Watelle.)

(3) Interlobar emphysema of lungs, numerous punctated ecchymoses on the pleura and pericardium, bubbles of gas within the blood vessels. Death from bursting of caisson. (Gallard.)

(4) Softening of some inches of the spinal cord in the dorsal region. (Bert.)

(5) Extravasation of blood upon the spinal cord opposite the two lower dorsal vertebrae. (A. Smith.)

(6) Extravasation of blood upon, and softening of spinal cord, haemorrhages in the kidneys. (Jaminet.)

(7) Death 15 days after decompression. Numerous foci of haemor-

[1] *Arch. de Neurologie*, 1890, p. 48.
[2] *Lancet*, 1897, I. 309.

rhages and signs of acute myelitis. Small irregular fissures in mid-dorsal cord, filled with round cells. From their well-defined edge probably produced by escape of gas. (v. Leyden.)

(8) Death 2½ months after decompression. Disseminated myelitis in dorsal region with fissures suggesting laceration of the tissues. (Schultze.)

(9) Congestion and oedema of the lungs (Schrötter).

Autopsies of Divers.

(10) Necrobiosis and haemorrhages in or upon spinal cord. (Gal, Catsaras, *Greek divers.*)

(11) Haemorrhages in or upon spinal cord. (Blick, *Australian pearlers.*)

Theories of compressed air illness.

The phenomena observed in *local* compression of the body and in cupping, the pallor of caissoniers, the nose-bleeding sometimes seen on decompression, the congestion of the viscera recorded in a few autopsies, have led most medical men who have observed caisson sickness to suppose that the blood is driven from the exterior and compressed within the viscera.

"Pulmonary and cerebral congestions are," say Pol and Watelle, "the chief results of compressed air. Just as a lowered atmospheric pressure brings blood to the exterior and causes haemorrhages, so does compressed air congest the viscera." The brain and spinal cord, according to Babington, shut up in their osseous cavities, are not able like other elastic parts, to quickly accommodate themselves to changes of pressure.

Bouchard put forward the extraordinary theory that as the gases of the intestine are compressed the abdominal wall becomes concave, and as the abdominal wall resists this distortion it converts the abdomen into a kind of cupping-glass. This leads to congestion of the abdomen during compression, and the reverse on decompression.

A. H. Smith may be quoted as the chief exponent of the mechanical congestion doctrine. He deduced "the law that under high atmospheric pressure the centres will be congested at the expense of the periphery ...and that firm and compact structures will be congested at the expense of those more compressible. Moxon[1] in his Croonian Lectures said "it

[1] *Lancet*, 1881, I. p. 528.

needs no experiment to show that great increase of atmospheric pressure must drive the blood away from the surface of the body."

The neglect by these writers of physical laws is the less excusable seeing that Poisseuille[1] in 1835 observed the capillary circulation in frogs, and young mice, enclosed in a glass chamber and submitted rapidly to + 2 to + 8 atm. The circulation continued unaffected. Moreover Paul Bert in 1881 clearly stated the physical error contained in such theories. The body of a workman exposed to compressed air supports according to Guérard

at + 1 atm.	an additional	15,500— 20,600	kilograms
at + 3 atm.	„	46,500— 60,800	„
at + 6 atm.	„	93,000—123,600	„

If it were not for the incompressibility of the fluids of the body, and the equal and instant distribution of the pressure to all parts, life would be impossible under *any* variation of atmospheric pressure. The fact that mere mechanical pressure is of no importance is shown not only by Guérard's figures but by the existence of abundant life in the sea at depths of 2000 metres, corresponding to a pressure of + 200 atm. The only mechanical compressions which can take place are that of the membrana tympani, which is relieved by opening the Eustachian tube, and that of the intestinal gas. The latter leads to the workmen tightening their belts and to a freer descent of the diaphragm in respiration. It has astonished us to find the most experienced practical men in diving and submarine engineering unaware of the experimental work of Paul Bert, of the conclusion which he drew as to the causation of compressed air illness, and of the precautions which he laid down for the guidance of caisson workers.

Paul Bert by his remarkable experiments, published in 1878, proved that the true cause of caisson sickness is the effervescence of gas in the blood and tissue juices. This explanation had, it is true, been advanced by several authors, such as Hoppe (1857), François, Rameau, Bucquoy, etc., but generally as a cause additional and subsidiary to mechanical congestion.

Bert found by analysis of the gases of the blood that the nitrogen increases in compressed air more or less according to Dalton's law. He found that this gas was set free on rapid decompression, and produced embolism, in the lungs, the central nervous system, etc.: and that the gravity of the result depended on the height of the pressure, the length

[1] *C. R. Acad. des Sci.* II. 554.

of exposure, and the rapidity of decompression. He also proved that the gas set free in the tissues might produce local swellings and emphysema.

The truth of Bert's explanation is borne out by the varied nature of the lesions found in caisson sickness, by the subcutaneous emphysema which has been detected in a few cases, and by the autopsies which have been recorded. One man is struck with pain in the joints and muscles, and another with respiratory embarrassment and loss of consciousness, another with deafness and vertigo, and yet another with paraplegia. All becomes clear if the cause is once accepted to be local embolism or compression by air bubbles. Thus air bubbles in the posterior roots or posterior columns of the spinal cord may cause the intense pains so often experienced. Air frothing in the heart may kill one man, air in the heart or in the vessels of the lung, or in the respiratory nervous system, produce in another difficult breathing; air embolism in the brain may cause aphasia, hemiplegia, loss of consciousness or sudden death, or in the dorsal cord paraplegia, while a bubble in a semicircular canal will explain the cases of auditory vertigo, and bubbles in the joints and muscles cause local swellings and emphysema coupled with pain.

Bert also found that high oxygen tension acts as a general protoplasmic poison arresting metabolism, depressing the body temperature, and causing the discharge of convulsions in mammals, and finally the death of all forms of life.

Since the publication of Bert's results little experimental work has been done on the subject. The most important paper is one by Lorrain Smith[1], who has found that high oxygen tension produces inflammation of the lungs. During the last few years we have been reinvestigating the effects of compressed air and oxygen, and we propose to communicate the results obtained so far, under the following headings.

1. Effects on the respiratory exchange and body temperature.
2. Effects on the nitrogen output.
3. Effects on the lungs.
4. Effects on the neuro-muscular system.
5. Effects on the central nervous system.
6. Effects on the blood gases.
7. Effects on the circulation.
8. The effects of decompression.
9. The rules of safe working for caissoniers and divers.

[1] *Journal of Physiology*, XXIV. p. 14. 1899.

Effects on the Respiratory Exchange and Body Temperature.

Bert enclosed animals in a small air-tight chamber and exposed them to increased pressures of air or oxygen. The chamber was not ventilated, and the animals were left till they died, when the air in the chamber was analysed.

In ordinary air the animals died from want of oxygen when the tension of oxygen fell to 3·4 % atm.

In super-oxygenated air or in air compressed to + 0 to 4 atm. they died from CO_2 poisoning when the tension of CO_2 rose to 25 % of an atm. But when the tension of O_2 was raised above 150 % atm. (over 7 atm. air) the animals died before the CO_2 tension reached 25 % of an atm. This was due to the *toxic effect* of oxygen. The higher the oxygen tension the more rapidly died the animals, and the less CO_2 was produced.

Bert also observed in the rat the following consumption of O_2 and output of CO_2 under varying tensions of oxygen.

O_2 tension	O_2 consumed in 24 hrs.	CO_2 output in 24 hrs.
21 % atm.	12·6 litres	7·06 litres
48·7 ,,	13·72 ,,	10·32 ,,
87·5 ,,	11·35 ,,	6·96 ,,

Thus an increase of oxygen tension corresponding to 2·3 atm. air slightly increased the respiratory change, while an increase corresponding to 4·2 atm. air slightly diminished it. In frogs Bert obtained the same results.

We have studied the respiratory exchange in animals placed in a pressure-chamber and ventilated with a current of air or oxygen. The chamber was fitted with thick glass windows and a pressure-gauge. It was connected by an inlet tube with a bottle of compressed air or oxygen (Brin's), while an outlet tube, controlled by a screw tap, was connected with a set of Haldane-Pembrey absorption tubes and a gas meter. The outputs of CO_2 and H_2O were obtained by weighing the absorption tubes. The animals were given a wool bed to prevent their losing heat directly to the metal walls of the chamber, and the chamber in some cases was heated on a sand-bath, and the temperature of the outgoing air taken.

In the *Journal of Physiology* (XXIX. p. 492, 1903) we have published examples of the results we have obtained from mice. We concluded that compressed air at a pressure of + 4 atm. and upwards diminishes the CO_2 output and lowers the body temperature of mice. This effect

generally increases as the pressure rises, but the individual power of resistance differs greatly in different animals. Paul Bert says that "the absorption of oxygen and elimination of carbonic acid diminish in proportion as the tension of oxygen rises, and that an animal breathing pure oxygen at 2, 3, 4 atm. is in the same condition as another breathing air at pressures of 10, 15 and 20 atm.[1]"

We observed like Bert that prolonged exposure to even one atmosphere of pure oxygen slightly lowered the CO_2 output and temperature of mice, both returning to the normal on replacing the oxygen with air[2]. On increasing the tension of oxygen we find a general increase in toxic effect but no constant relationship owing to differences in the individual susceptibility of mice. For with mice kept at the same tension of O_2 and the same external temperature one may be affected sooner than another.

According to Bert's conclusion we expected to find that increased *air* pressure would depress the CO_2 and H_2O output in proportion to the partial pressure of oxygen. But this has not been the case. We have found 10 atm. of air to be as a rule far more depressing than 2 atm. of oxygen, and there are other factors to be considered besides the partial pressure of oxygen. These are the cooling effects of compressed air, and the resistance which highly compressed air may establish (1) to the movement of the air in and out of the air tubes, (2) to the diffusion of CO_2 from the alveolar air into the tidal air. We have no evidence to offer as to the relative importance of these two factors.

The increased loss of body heat arises firstly because the compressed air is a better conductor of heat, and secondly because the compressed air becomes saturated with water.

If the chamber be ventilated at the rate of 1 litre of air at atmospheric pressure per minute, and the compressed air be saturated with water vapour, the amount of water carried away per litre will fall to $\frac{1}{2}$, $\frac{1}{3}$, $\frac{1}{4}$ etc. as the pressure rises to 2, 3, 4 atms. The chamber and the animal thus become wet with condensed water vapour, and it is not possible to measure the water output of the animal by analysis of the ventilation air.

Rubner observed that an arm enclosed in a calorimeter and clothed in dry flannel lost 4·5 cal. per hour, while when the flannel was wet it lost 22·7 cal., an increase of 344 %. Thus when the chamber is cold the dampness of the animal's fur may greatly increase the heat-loss,

[1] *La Pression Barométrique*, p. 612.

[2] For details cf. *Proc. Roy. Soc.*, 1902, Vol. LXX, p. 455.

for, owing to the skin temperature being much greater than that of the air, the evaporation of water from the body of the animal is not hindered by the saturation of the air with water vapour. At very high temperatures 85—90° F. the saturation of the air with moisture would so lessen the evaporation of water from the body as to render a caisson-worker in danger of heat-stroke.

Dr Haldane tells us that miners, almost stripped, can work in air saturated with water at 85° F. and, for short shifts, even at 93° F. without rise of body temperature. They pour with sweat and drink copiously. A man clothed in flannel, on the other hand, will rise to 103° F. or higher on walking in the mine under these conditions. Miners as a rule begin to be cautious of air above 85° F. and saturated with vapour. The explanation of these facts is given in the following figures. At 20° F. air takes up 1·3 grains of water per cubic foot, at 60° F. 5·77, at 85° F. 12·78, at 93° F. 16·21, and at 99° F. 19·28.

Experimenting with cold wet air we have found that mice may have their metabolism increased by a current of moist air at 20° C., and that finally by prolonged exposure their body temperature may be lowered and death result from the increased heat loss.

We have repeated the observations made on mice, on rats and young rabbits with the following results.

I. *Large rat.*

Time	Atm. O_2	CO_2 output per min.	Remarks
11.15 a.m.	+3—3½		Room temp. 15·5° C.
12.30 p.m.		·00618	Body ,, 37° C.
			Decompressed at 12.55, rat all right, body temp. 37° C.
1 ,,	+4		
2 ,,	,,	·0870	
2.45 ,,	,,	·00663	
3.20 ,,	,,	·00653	

At 3.53 the rat was decompressed in about 1 minute. Spasms and cyanosis followed owing to gas embolism. The body temp. was 35° C. The blood contained many bubbles of gas.

II. *Large rat.*

Time	Atm. O_2	CO_2 output per min.	Remarks
10.22 a.m.	+3—4		Room temp. 19·5° C.
1.55 p.m.	,,	·00894	Body ,, 37° C.
3.15 ,,	,,	·00582	
3.40 ,,	,,	·00558	
4.30 ,,	,,	·00376	

Decompressed in 10 mins. at 4.50 p.m. Rat very inert, slight spasms, body temp. 30·5° C. Some gas bubbles in the blood.

III. *Young rabbit.*

Time	Atm. O_2	CO_2 output per min.	Remarks
10.54 a.m.	1	·0074	
11.25 ,,	+2·5—3		
11.45 ,,	,,	·0057	
12.50 p.m.	,,	·00693	
1.20 ,,	,,	·00637	
2 ,,	,,	·0069	
2.40 ,,	,,	·00475	

After slow decompression the rabbit seemed all right. The body temp. was 36° C.

IV. *Large rat, weight* 225 *grms.*

Time	Atm. O_2	CO_2 output per min.	Remarks
10.55 a.m.	+5		Room temp. 22° C.
12 p.m.	,,	·0062	
12.20 ,,	,,	·0061	
1 ,,	,,	·0	

On decompression the rat was found moribund. The body temp. was 28° C. The lungs very congested.

V. *Large rat.*

Time	Atm. O_2	CO_2 output per min.	Remarks
11 a.m.	+4		Body temp. 37° C.
11.10 ,,	,,	·0072	Room ,, 19° C.
12.10 p.m.	,,	·003	
12.20 ,,	,,	·0013	

On decompression animal found moribund. Body temp. 29° C.

VI. *Large rat, weight* 165 *grms.*

Time	Atm. O_2	CO_2 output per min.	Remarks
10.50 a.m.	+2—3		Room temp. 18° C.
11.55 ,,	,,	·0087	Body ,, 37° C.
12.10 p.m.	,,	·0068	
12.45 ,,	,,	·0107	
2.5 ,,	,,	·0079	
2.45 ,,	,,	·0054	

Decompressed slowly; animal seemed all right. Body temp. 36° C.

VII. *Young rat.*

Time	Atm. O_2	CO_2 output per min.	Remarks
10.35 a.m.	+3—4		Room temp. 20° C.
10.45 ,,	,,	·0058	Body ,, 37° C.
12.10 p.m.	,,	·0035	
12.30 ,,	,,	·0042	
1.35 ,,	,,	·0033	
2 ,,	,,	·0036	
2.55 ,,	,,	·0013	

Decompressed. Rat moribund. Body temp. 29° C.

VIII. *Large rat, weight* 152 *grms.*

Time	Atm. O_2	CO_2 output per min.	Remarks
11.10 a.m.	+3½		Body temp. 37·4° C.
11.30 ,,	,,	·0056	Room ,, 18·5° C.
11.45 ,,	,,	·0055	
12.47 p.m.	,,	·0049	
1.13 ,,	,,	·0049	
1.53 ,,	,,	·0038	

On decompression the rat was inert and the rectal temp. 32·5. Blood collected in conical glass and quickly analysed. CO_2 67 %. Temp. of water bath 18·5° C.

IX. *Large rat.*

Time	Atm. O_2	CO_2 output per min.	Remarks
11.25 a.m.	+3		
1.15 p.m.	,,	·0077	
2.17 ,,	,,	·0062	
2.24 ,,	,,	·006	
3.20 ,,	,,	·0054	

Slow decompression. Rat all right. Body temp. 36·5° C. CO_2 in blood 59·3 %.

X. *Large rat, weight* 139 *grms.*

Time	Atm. O_2	CO_2 output per min.	Remarks
10.30 a.m.	+4	—	Room temp. 16·5° C.

Decompressed at 12.30. Rat all right. Body temp. 35° C. CO_2 in blood (collected under petrol) 45·8 %.

XI. *Rat, weight* 115 *grms.*

Time	Atm. O_2	CO_2 output per min.	Remarks
1.20 p.m.	+5		Body temp. 36·6° C.
1.58 ,,	,,	·0045	
2.39 ,,	,,	·005	
3.10 ,,	,,	·0052	
3.35 ,,	,,	·0047	
3·56 ,,	,,	·0038	

The rat on decompression seemed somewhat inert and dull. Body temp. 30° C.

XII. *Rat, weight* 121 *grms.*

Time	Atm. O_2	CO_2 output per min.	Remarks
10.30 a.m. to 12.30 p.m.	+4 atm. falling to +1 atm.		
12.30 ,,	+6 atm.		
1.54 ,,	,,	·0076	
2.27 ,,	,,	·0049	

Slow decompression. Rat very inert. Temp. 28° C.

https://doi.org/10.1017/S0022172400032952 Published online by Cambridge University Press

XIII. *Rat.*

Time	Atm. O_2	CO_2 output per min.	Remarks
10.30 a.m.	+6		
11.15 ,,	,,	·0061	
12.15 p.m.	,,	·0078	
1.7 ,,	,,	·0041	

Body temp. on decompression 30° C. Rat inert.

XIV. *Rat, weight* 115 *grms.*

Time	Atm. O_2	CO_2 output per min.	Remarks
10.45 a.m.	+5	—	
12.59 p.m.	,,	·0024	

Body temp. on decompression 34° C. Rat quiet, otherwise well. CO_2 in blood (petrol method of collection) 71·8 % and 71·2 %.

XV. *Young rabbit.*

Time	Atm. O_2	CO_2 output per min.	Remarks
12.15 p.m.	+6		
12.35 ,,	,,	·0088	
1.50 ,,	,,	·0023	

Moribund on decompression. CO_2 in blood (oil method of collection) 66·41 % and 65·31 %.

The above series of experiments show that:—

Some rats or rabbits can tolerate	Some rats or rabbits are rendered moribund by
Atm. O_2 +2—3 for 3—4 hrs.	Atm. O_2 +3—4 in $4\frac{1}{2}$ hrs.
,, + 3 ,, 4 ,,	,, + 4 ,, $2\frac{1}{2}$,,
,, + 4 ,, 2 ,,	,, + 5 ,, 2—$3\frac{1}{2}$,,
	,, + 6 ,, $\frac{1}{2}$—3 ,,

The CO_2 output is depressed and the body temp. falls just as in mice.

The resistance to O_2 poisoning also differs in individuals very considerably, but the larger animals seem just as susceptible as mice. As the chamber used in these experiments was not provided with a window, we were unable to observe the symptoms of oxygen poisoning.

After exposure of dogs to high tension O_2 and *rapid* decompression Bert found the animals convulsed. Analysing the blood-gases during the convulsions he found the CO_2 diminished to 14·8 % and 10·5 %. He concluded that the oxygen had arrested the tissue metabolism. The circulation must have been most imperfect in these animals owing to gas embolism.

In some of the above experiments we analysed the CO_2% in the blood at the time when the CO_2 output was diminished and the body temperature lowered. Our method was to decapitate the animal after decompression in 10′, allow the blood to drop under oil in a conical glass, take up the blood in a syringe containing oxalate solution, and analyse two samples (each of 1 c.c. vol.) by the Haldane-Barcroft apparatus. We omitted the ferricyanide process as we did not want to measure the oxygen.

It will be seen that our CO_2 results by this method have been very high, and considerably higher than controls done with the gas pump. We have recently discovered that the omission of the ferricyanide process increases the volume of gas displaced by the tartaric acid. The acid turns out some of the oxygen. Further enquiry into the causation of this we defer for the present. From normal rats we obtained CO_2 values such as the following: $-52{\cdot}41$%, $63{\cdot}27$%.

From an asphyxiated rat we obtained $68{\cdot}21$%.

From two rats exposed to, but not seriously affected by, compressed O_2 we obtained $45{\cdot}8$% and $59{\cdot}3$%, while from two others rendered moribund we obtained 66% and $71{\cdot}8$%. The results do not confirm those of Bert but show that the CO_2 content of the blood of an animal poisoned by O_2 resembles that of an asphyxiated animal. They show that the blood does not contain less CO_2, in spite of the diminished output of CO_2 from the lungs. The diminished CO_2 output might be attributed to the inflammation of the lung which is produced by compressed O_2. This inflammation might be supposed to lessen the respiratory exchange. We think, however, that the lowering of the body temperature clearly proves diminished tissue oxidation; moreover, the lessened CO_2 output occurs before the pneumonia is set up. The slow and feeble outflow of blood in the O_2 poisoned animals shows how feeble the heart, and how imperfect the circulation of the blood have become. The veins are distended, and the blood is mostly in the venous side; very little flows from the severed carotids. Hence the amount of CO_2 in the blood is great in spite of the diminished production by the tissues.

Effects on the nitrogen output.

Bert compressed himself to a little less than +1 atm. for about 3 hrs. a day, and obtained the following results.

		Urine	Urea
1st day	Normal pressure	1650	20·15
2nd ,,	Compressed	2010	24·72
3rd ,,	Compressed	1990	26·04
4th ,,	Compressed	2255	21·18
5th ,,	Normal pressure	2080	20·80
6th ,,	,, ,,	2150	22·50

A dog placed on a daily ration and catheterised gave

		Urea
1st day	Normal pressure	7·9
2nd ,,	3 atm.	10·4
3rd ,,	,,	9·0
4th ,,	Normal pressure	9·1
5th ,,	,, ,,	8·4

From these experiments Bert concludes that moderate pressures increase the nitrogenous metabolism. Snell by observation on himself at the Blackwall tunnel was unable to determine any effect on the urea output. In two dogs compressed to 8 atm., Bert determined a considerable decrease in the urea output.

The details of Bert's experiments are as follows.

Dog. 12 kilo. Fed daily at 7 a.m. on 250 grm. bread and 250 grm. meat and 500 grm. water.

July 25. Catheterised at 8 a.m. Experiment begins.

July 26. Catheterised at 8 a.m. 280 c.c. urine; 12·1 grm. urea. Compressed to 8 atm. from 9 a.m.—3 p.m. Decompressed 3—5 p.m. Rectal temp. 35·5. Animal appears well.

July 27. Only half its ration eaten. 350 c.c. urine; 3·7 grm. urea!

July 28. No food eaten. 510 c.c. urine; 10·3 grm. urea.

Dog. 16 kilo. Same diet.

Aug. 3. 8.30 a.m. catheterised.

Aug. 4. 8.30 catheterised. 475 c.c. urine; 21·6 grm. urea. Temp. 35·8. Put at 8 atm. from 9 a.m.—4.50 p.m. Decompressed 4.50—6.20 p.m. Temp. 35·5. Animal seems well.

Aug. 5. 245 c.c. urine; 16·9 grm. urea.

It will be noticed that Bert only determined the urea for one day previous to compression. This is not a sufficient control. The fall from 12·1 to 3·7 grm. in the first experiment must surely be due to some error.

We have observed the urine of three dogs exposed to eight atmospheres of air. The dogs (females) were prepared for catheterisation by slitting the perineum. They were then placed in a metabolism cage and put on a weighed and constant diet of dog biscuit and milk—more

than sufficient to supply their energy. The bladder was emptied each morning with a catheter and syringe, and the urine analysed. After several days the animals were placed in the pressure-chamber and exposed to 8 atmospheres for 6—7 hours. Decompression was carried out in 2 hours so as to avoid all risk of air-embolism, and the animals were then returned to the metabolism cage for the night. A cage was fitted up within the pressure-chamber so that the urine, passed during compression, could be collected.

Experiment 1. The dog was kept for four days at normal atmospheric pressure. On the fifth day the pressure was raised to 100 lbs. to the sq. inch (almost +7 atm.) and kept at this pressure for 5 hours. Three hours were then taken to decompress the animal. In the urine of this day there was no definite change. During the next two days the dog was kept at normal pressure and the urine showed a slightly increased amount of nitrogen. On the eighth day the dog was exposed for seven hours to 100 lbs. pressure. The weather was very cold and we tried to warm the chamber by applying a Bunsen burner to the outside. During the fourth hour the dog became restless and tore away some of the wire netting at the door of the cage. It also defaecated in the cage and fouled its fur so that some of the urine may have been lost.

On the next day the animal was again put under 100 lbs. pressure. In about the third hour it became very restless and tore down the wire netting of the cage and escaped into the chamber. Shortly after this the dog began to profusely salivate, while the respirations became jerky in character. The pupils dilated and the eyelids twitched. At the end of six hours decompression was begun. It was completed in $2\frac{1}{4}$ hours. The dog was cold on removal, wet with saliva, and with moisture taken up from the water-saturated air of the chamber. Its respirations were jerky and somewhat embarrassed with a frequency of 62. The animal would not eat.

During the next few days the dog was kept in the metabolism cage and recovered completely.

The nitrogen content of the urine was distinctly increased on the ninth day when the above described symptoms occurred. The increase persisted on the following day. The rise in nitrogen output is quite remarkable considering that the animal took no food on the 10th day, and only milk on the 11th day. The experiment is contrary to those of Bert.

We consider that the increased N output was due to the restless efforts of the dog to open the cage, i.e. to excessive muscular work.

Experiment 2. The dog died on the second day under pressure and so rendered this experiment incomplete.

After five days' preliminary observation of the nitrogen output, the dog was submitted to 6—7 atm. of air from 11 a.m. to 7 p.m. The weather was cold (February). At 4 p.m. the dog commenced to salivate—there were no other symptoms. On the next day it was again placed under the same pressure. It salivated profusely and was very restless. Two hours before its removal from the cage the dog lay quiet. On removal, after slow decompression, it manifested

EXPERIMENT I.

Day	Food: Milk	Food: Biscuit	Quantity of urine	Reaction	Sp. gr.	Total N	Urea N	SO_3	P_2O_5	Sugar	Albumin	Weight of dog	Atm. pressure of air
1*	284 c.c.	one	350 c.c.	acid	—	—	1·480	1·0013	·343	nil	nil	4803	+ 0
2	,,	,,	325 ,,	,,	1011	1·82	1·437	—	·2925	,,	,,	—	,,
3	,,	,,	500 ,,	neutr.	1005	1·372	1·1620	·1080	·270	,,	,,	4830	,,
4	,,	,,	400 ,,	faint alk.	1010	1·872	1·624	·1388	·280	,,	,,	—	,,
5	,,	,,	460 ,,	,,	1010	1·584	—	·1500	·212	,,	,,	4950	+6—7 atm. for 6 hrs.‡
6 & 7	568 c.c.	two	550 ,,	,,	1017	2·31†	1·990†	·2453†	·253†	,,	present	—	+0 ,,
8	284 c.c.	one	505 ,,	,,	1010	1·960	1·960	—	·200	,,	,,	—	+6—7 atm. for 7½ hrs.‡
9	,,	,,	only catheter specimen obtained	acid	—	2·44 %	2·15 %	—	—	,,	,,	4760	,, 7 hrs.‡
10	none	none	168 c.c.	,,	1020	2·63	2·217	—	·218	,,	nil	4803	+ 0
11	284 c.c.	one	210 ,,	,,	1017	2·247	2·003	—	·170	,,	,,	4860	,,
12	,,	,,	173 ,,	,,	—	1·951	—	—	·242	,,	trace	—	,,

* The analysis for each day is that of the urine passed the *previous* day.
† For 24 hrs. ‡ In addition 2 hrs. were spent in slow decompression.

EXPERIMENT II.

Day	Food: Milk	Food: Biscuit	Amount of urine	Sp. grav.	Total N	P_2O_5	Atm.
1	284 c.c.	one & a half	334 c.c.	1010	2·1	0·398	+ 0
2	,,	,,	370 ,,	1009	1·92	0·490	,,
3	,,	,,	336 ,,	1018	2·114	0·393	,,
4	,,	two	300 ,,	1015	2·268	—	,,
5	,,	,,	312 ,,	1015	2·0	0·3062	,,
6	,,	,,	275 ,,	1012	2·41	0·2674	+6—7 for 8 hrs.*
7	,,	,,	375 ,,	—	1·942	0·1787	+6—7 for 6 hrs.
8	—	—	100 ,, †	—	0·658 %†	—	(died after decompression)

* Decompression was carried out in 2 hrs. † In 8 hrs. before death (×3=1·974).

EXPERIMENT III. *Metabolism.*

Day	Food: Milk	Food: Biscuit	Amount of urine	Sp. gr.	Reaction	Total N	Urea N	SO_3	P_2O_5	Atm.
1	284 c.c.	one & a half	330 c.c.	1013	faintly acid	2·821	—	0·336	—	+ 0
2	,,	,,	330 ,,	1013	,,	2·402	1·742	0·208	—	,,
3	,,	,,	320 ,,	1014	,,	—	1·869	0·292	0·512	,,
4										
5	,,	,,	265 ,,	1018	faintly alk.	2·114	1·860	0·252	0·450	,,
6	,,	,,	250 ,,	1023	,,	3·272*	2·829	0·212	0·750	6 hrs. in +6—7
7	,,	,,	253 ,,	—	,,	3·080	2·535	0·253	0·483	+ 0
8	,,	,,	215 ,,	1018	acid	2·660	2·073	0·239	0·430	,,
9										
10	,,	,,	163 ,,	1024	faintly acid	2·647	2·565	0·294	0·465	,,
11										
12	,,	,,	200 ,,	1020	faintly alk.	2·816	2·236	0·226	0·584	6 hrs. in +6—7
13	,,	,,	153 ,,	1022	,,	2·270	1·958	0·185	0·283	,,
14	,,	,,	208 ,,	1018	faintly acid	2·780	—	—	—	+ 0
15	,,	,,	225 ,,	1017	faintly alk.	2·475	2·137	0·266	0·448	,,
16										
17	not done	—	—	—	—	—	—	—	—	,,
18										
19	284 c.c.	one & a half	246 ,,	1020	faintly alk.	2·917	2·460	0·299	0·492	,,

* Urine was cloudy and contaminated with food.

symptoms of dyspnoea and died 20 minutes later. Death resulted from gas embolism in spite of slow decompression, owing, we believe, to the oxygen poisoning and pneumonia which had developed in this dog. Only 100 c.c. of urine could be obtained during the eight hours' observation of this day. This contained 0·658 % N.

No change in the nitrogen output is to be detected in this animal.

Experiment 3. The dog was exposed to +6—7 atm. for six hours on the 6th day and again on the 12th and 13th days of observation. On the 13th day the dog seemed restless towards the end of the period of compression.

No noteworthy change in the urine occurred.

The three experiments here recorded show that there is no marked and constant variation in the urinary constituents of dogs submitted to +6—7 atm. for several hours. In the case of the first dog, there was, it is true, a definite increase in the output of nitrogen. This we are inclined to attribute to the continuous and violent efforts of the dog to escape from its cage. A similar increased output of nitrogen would probably follow the convulsions due to oxygen poisoning. It is evident from Experiment III. that a dog can be exposed to +6—7 atm. for six hours without alteration of its urinary constituents, and we cannot confirm Bert's two experiments conducted on dogs at the same pressure.

Effects on the lungs.

While studying the oxygen tension of the blood by the CO method of Haldane and Lorrain Smith, the latter[1] found "that exposure of animals to a tension of 170—180 % atm. O_2 causes in a short time diminution in the power of the lungs to *actively* absorb oxygen, and that with a continuance of this exposure the arterial oxygen fell till it reached the level for which mere diffusion of oxygen from the alveolar air might account." He subsequently[2] determined that exposure of mice to high partial pressures of oxygen produces pneumonia. "The tissue of the lungs showed intense congestion in the large and small blood vessels. The alveoli were to a large extent filled with an exudate, which was granular and fibrillated in appearance, but did not give the fibrin stain by Weigert's method, nor with eosin." He found that a pressure of 40 % atm. O_2 for 8 days had no effect: 80 % atm. killed two mice in 4 days with congestion of the lungs, while two other mice survived unharmed.

An average pressure of 125·3 % atm. O_2 killed mice in an average time of 64 hours. 180 % atm. killed in about 24 hours, while 300 % atm. produced inflammation of the lungs in 5 hours.

[1] *Journ. of Physiol.*, vol. XXII. p. 315, 1898.
[2] *Journ. of Physiol.*, vol. XXIV. p. 19.

Our results confirm those of Lorrain Smith.

High partial pressure of oxygen exercises a marked irritant effect on the lungs, producing at first congestion of the alveolar capillaries, and afterwards haemorrhagic exudation and consolidation. To the naked eye the lungs present in the early stages a suffused redness. Patches of more intense exudation occur in the apices and edges of the lungs. At a later stage the congestion passes into typical hepatization, the lungs sink in water and are of a dark purple colour. The pneumonia is patchy if quickly, and universal if slowly developed.

The following tables (p. 425) illustrate the onset of pneumonia at different pressures of oxygen and air.

Lorrain Smith found that 180 % atm. O_2 killed in about 24 hours, while 300 % O_2 produced inflammation in 5 hours. Our results show somewhat higher powers of resistance. Thus in Experiment 2 the mouse showed no symptoms after 6 hours in 300 % atm. O_2, while in Experiment 4 the mouse survived 9 hours' exposure to + 400 % atm. O_2.

Lorrain Smith suggests that inflammation of the lungs may be a cause of caisson disease as well as decompression gas embolism. We do not find much in our experiments to confirm this view. The highest pressure hitherto used in caissons is + 3·45 atm. and the men never work for shifts longer than a few hours. It seems to require about 24 hours at + 7 atm. (= 168 % atm. O_2) to produce marked symptoms of pulmonary congestion.

We observed no sign of lung trouble in a monkey which was exposed on many days to + 7 atm. for 4—5 hours at a time.

To test whether the pneumonia produced by long exposure to + 7 atm. air was due to the high partial pressure of oxygen, we subjected a group of animals to air containing only 10 % of oxygen. The partial pressure of oxygen was thus 84 % atm. in place of 168 %. The gas was supplied by Brins, and being limited in quantity we were not able to freely ventilate the chamber. Soda-lime was placed within to absorb the CO_2, but in spite of this the CO_2 content of the chamber rose to over 1 %, so that we were unable to measure the amount in the sample of air which we drew off into Haldane's small CO_2 apparatus for air analysis. The two cats died after 30 hours' exposure, while two out of three mice which were enclosed in a nest of cotton-wool survived. There was no trace of pneumonia in the lungs of the dead animals and we are inclined to attribute the deaths chiefly to increased loss of heat, and partly to CO_2 poisoning.

Increased oxygen pressures.

Animal	Atm. of pure O_2	Time under pressure	Symptoms of pneumonia	State of lungs
1. Mouse	1	6 hours	none	Animal lived
2. ,,	3 (chamber at 30° C.)	,,	,,	,,
3. ,,	3 (chamber at 15° C.)	3 hours	Gasping respirations	,,
4. ,,	4 (chamber at room temp.)	9 hours	,,	,,
5. ,,	5 (chamber at 30° C.)	Died in night, probably after about 12 hrs.	,,	Very congested
6. Mouse	6·2 (room temp.)	Died in 2½ hrs.	,,	Intensely pneumonic
Rabbit		,, 1½ ,,	,,	Pneumonic
Rat		,, 1½ ,,	,,	Patchy pneumonic
Cat		,, 5½ ,,	Gasping respirations and salivation	Congested all over, pneumonic patches at roots of bronchi
7. Two rats	6 (room temp.)	2 hours	—	Both lungs markedly congested and upper lobe pneumonic

Increased air pressures.

Animal	Atm. air	Time under pressure	Symptoms of pneumonia	State of lungs
Mouse	+4 to +5	Up to 24 hrs.	None	Survived
,,	+7	Died in 24 to 30 hrs.	Gasping respiration	Pneumonic
,,	+9	6 hours	,,	Survived
,,	+10	Died in 1½ hrs.	,,	Congestion
Dog	+7	Exposure for 6—7 hrs. on 3 successive days	Salivation, jerky respiration	Survived
,,	+7	Two days' exposure for 6—7 hrs.	,,	Pneumonic
,,	+7 (chamber warmed)	24 hrs.	Panting respiration	Survived
Cat and kittens	+7 Pressure fell to +5 during night. Chamber not ventilated during night	48 hrs. Two kittens survived but died after decompression	Difficult breathing after 24 hrs.	Intense pneumonia

https://doi.org/10.1017/S0022172400032952 Published online by Cambridge University Press

Effect on the neuro-muscular system.

One of us (L. H.) exposed nerve-muscle preparations—the frog's gastrocnemius and sartorius—in a small chamber to 50—60 atm. O_2. After 1 hour the preparations were decompressed and contraction curves recorded, and compared with curves of control preparations. In the case of the gastrocnemius the curves showed remarkably little difference. The muscle was both directly and indirectly excitable; the rate of conduction in the nerve, the latent period and the form and period of the contraction curve were scarcely altered. The thin sartorius, on the other hand, showed a greatly diminished height of contraction and a prolonged latent period. The frog's heart exposed to the same enormous pressure continued to rhythmically beat for one and even two hours. The size of the contraction only gradually became lessened. After exposure for about an hour and decompression the cardio-inhibitory mechanism was tested. Inhibition by excitation of the sino-auricular junction was readily obtained. Excitation of the vagus, on the contrary, remained without effect. The action of the vagus was proved effective before the period of compression. It is probable then that call-stations are paralysed, while nerve, nerve-endings, skeletal, and cardiac muscle are but slowly affected by high tension oxygen. Paul Bert exposed frogs to 335 % atm. O_2. The animals appeared to be dead in about 40 hours. The heart continued to beat and the muscles were perfectly contractile. The central nervous system was alone paralysed and no reflexes could be excited.

We also constructed a chamber in which a small muscle lever was placed so that a disc, attached to the end of the lever, rested between the glass windows of the chamber. The disc was placed in the path of the arc light, and its shadow was photographed on a sensitive plate. The plate moved on a traveller at a fast rate. Electrodes were introduced into the chamber by means of an ebonite plug, and the muscle was excited and the curve recorded while the muscle was under pressure. As the curves showed no noteworthy change during the early period of compression, we postponed the further investigation of this matter. One of us (L. H.) has also studied with Dr Waller the effect of compressed oxygen on the action current of nerve. This research is still incomplete.

Exposure to 50—60 atm. O_2 immediately convulsed and then paralysed all the forms of life which were placed in our chamber, such as mice, frogs, worms, insects, centipedes, etc. Oxygen appears

then to be a specific poison for the central nervous system and the lungs.

Effects on the Central Nervous System.

Paul Bert observed that exposure to high tension O_2 produces convulsions in *birds*. The following are some of his results.

Atm.	Tension of O_2	Atm. of air corresponding to O_2 tension	Rect. temp.	Convulsions
1·75	150	7	—	None
3	260	13	—	None
4	300	15	—	Convulsions
20	420	20	—	,,
5	420	20	32	Convulsions, decompressed & survived
5	420	20	37	,,
5	420	20	33	Died in 30 mins.

Lorrain Smith has confirmed these results. Two larks at 300% atm. O_2 had violent convulsions in 13 min. The convulsions continued at short intervals and subsided in about 1 hr.

A tension below 270% atm. O_2 produced no convulsions. The slow and gradual increase of O_2 tension caused congestion of the lungs, and did not excite convulsions. Lorrain Smith found that after prolonged exposure to 140% atm. O_2, no convulsions followed the subsequent exposure to 300% atm. O_2. According to Haldane and Lorrain Smith the normal oxygen tension of the arterial blood of birds is 35—40% atm., while in the air breathed the O_2 tension is 21% atm.

In higher partial pressures of oxygen they found that the oxygen tension of the blood continued to be higher than that of the atmosphere and in about the same ratio. Twelve hours exposure to 140% O_2, on the other hand, lowered the oxygen tension of the arterial blood by 50%. This result Lorrain Smith attributes to the congestion of the lungs set up by the high pressure O_2. The congestion prevents the quick rise of oxygen tension in the blood, and so the convulsions fail to appear.

Bert observed that dogs exposed to high pressure O_2 go into violent convulsions *after rapid decompression.*

For example:

I. Dog. O_2 528% atm. for 45 min. Decompression in 3·5 min. Rectal temp. 30° C. Convulsions and death in 24 hrs.

II. Dog. O_2 385% atm. for 30 min. Decompression in 1·5 min. Rectal temp. 36·5° C. Convulsions—crises lasted about 20 min. Succeeded by muscular tremor. Recovered.

The tetanic convulsions were so intense that the dog could be held up by the foot like a piece of wood.

In only one dog out of many experiments did Bert record 's'agitant demi-convulsivement' while *under compression.* In all other cases the convulsions only came on after rapid decompression. Rapid decompression from *air* on the other hand did not produce convulsions but embarrassed respiration, paralysis, or death.

Bert analysed the blood gases and found the convulsions became marked when the O_2 tension of the air equalled 400% atm. and the blood contained 30% O_2. As his animals breathed in and out of a sac of oxygen enclosed in the chamber, and the respired air contained a large excess of CO_2 (8·1% was found in one case; at 5 atm. this = 40·5% atm. In another case the tension of CO_2 was 86·2!), it is impossible to draw conclusions from his analyses of the CO_2 in the blood. The animals must have been rendered comatose with CO_2. He found that blood super-saturated with O_2 up to 30—35 vols.% had no effect when injected into dogs, and concluded that the symptoms are due not to the amount of oxygen in the blood, but to the saturation of the tissues with free oxygen. Lorrain Smith finds that the blood can be 38% saturated with CO and yet the bird be thrown into convulsions by exposure to 300% atm. O_2. It is therefore not the total quantity of O_2 in the blood but *the tension of O_2 in solution* which is the cause of the intoxication. Lorrain Smith found that convulsions were produced in mice by much higher tensions of O_2 than in birds. A tension of 450% atm. O_2 convulsed 2 mice in about 20 min., another mouse became dyspnoeic and died without convulsions.

A rat at 268% atm. O_2 showed marked dyspnoea in 5 hrs. and died overnight.

Two mice at 357% O_2 died in 5 hrs. with congested lungs.

Two mice at 230% O_2 showed great dyspnoea in $9\frac{3}{4}$ hrs.; they recovered after decompression.

Two mice at 285% O_2 became dyspnoeic in $3\frac{3}{4}$ hrs. and one died after $8\frac{3}{4}$ hrs. The other recovered on decompression. In none of these animals were there convulsions.

Our numerous experiments on rats and mice confirm those of Lorrain Smith. The animals become as a rule dyspnoeic and gradually pass into coma as their CO_2 output and body temperature fall. Convulsions sometimes occur when the intoxication of the nervous system is sufficiently rapid and intense.

With 3—3·5 atm. O_2 we have not observed convulsions; with

+4—5 atm. O_2 they occur, and not infrequently we have observed them in mice, rats, rabbits and cats.

With exposure to +6—25 atm. O_2 mice and birds quickly become intensely dyspnoeic and comatose and are not convulsed.

On the other hand exposure to 50—70 atm. O_2 instantly throws mice into convulsions resembling those of acute asphyxia, and death rapidly follows.

Our experiments on the effect of rapid decompression from high pressures of oxygen confirm the results of Paul Bert.

The animals show a very striking tendency to strychnine-like convulsions. Sometimes there results marked reflex hyperexcitability: in other cases violent tetanic spasms occur which may be reinvoked by handling the animals.

Experiments on oxygen convulsions.

Animal	Atm. O_2	Onset of convulsions	Onset of coma	Remarks
Mouse	+3—3·5	none	none	Survived 6 hrs. compression.
Mouse	+4·2	12 mins.	—	Died in 2 hrs. 45 mins.
Mouse	+4—5	32 ,,	53 mins.	Died soon after onset of coma.
3 mice	+4—5	none	about 30 mins.	Decompressed rapidly, spasms followed.
Mouse	+5·5	5 mins.	25 mins.	Died in 35 mins.
2 mice	+5·5	20 ,,	—	Survived, comatose for 2 hrs.
Mouse	+10	none	10 mins.	Died in 45 mins.
Mouse	+25	none	a few mins.	Died in about 10 mins.
Linnet	+6	none	about 20 mins.	Rapidly decompressed. Haemorrhages from diploe and beak.
Linnet	+9	none	about 20 mins.	Rapidly decompressed. Haemorrhage from beak and in diploe.
Rat	+5·2	32 mins.	soon after convulsions	Died in 57 mins.
Rat	+5	none	none	Survived 2 hrs. exposure. Hyperexcitable after decompression.
Rabbit	+5·2	17 mins.	45 mins.	Died in about 60 mins.
Cat	+5·2	3 hrs. 30 m. one fit only	soon after fit	Salivation began in 3 hrs. 12 mins. Died in 5 hrs. 20 mins.

With air-pressures up to +12 atm. we have not observed convulsions during compression, the process of intoxication is too gradual.

After rapid decompression animals are often thrown into convulsions owing to the frothing of gas in the heart and consequent asphyxia, or to bubbles of gas set free in the nervous system. The convulsions soon terminate in paralysis. After rapid decompression from oxygen, on the other hand, convulsions continue to be excited, for the oxygen gas set free maintains the life of the tissues.

In the case of compressed air, the chief gas set free is nitrogen, and as this produces anoxaemia the convulsions quickly terminate in paralysis. The convulsions which Bert details as occurring in dogs are clearly decompression results, and due to the effervescence of oxygen gas in the central nervous system. The convulsions which occur during compression are due to the high tension of the oxygen in solution in the tissue lymph. They occur by no means constantly, but only in certain individuals and under certain conditions. Often dyspnoea, coma, and paralysis come on without any marked stage of exaltation. There is one sign of excitement which is almost always present in mice, and that is rapid cleaning movements of the face. The convulsions seem never to occur when the O_2 tension is below 300 % atm. or above 600 % atm., excepting the instantaneous convulsions which precede the death of animals exposed to enormous pressures such as + 60—70 atm. We may assume that with tensions below 300 % atm. O_2, the amount of gas in solution is not sufficient to excite; that with tensions above 600 % atm. O_2 the nervous system is rapidly paralysed by the large dose.

Effect on the blood gases.

Paul Bert analysed the blood gases of a few dogs exposed to compressed air by drawing off samples from the carotid artery as the pressure rose to 2—3—6 etc. atm. He found that the amount of nitrogen became increased, and, if we accept the recent determination of the coefficient of absorption of N_2, the increase is about as required by Dalton's law. The following table shows types of his results. We have

Examples of Paul Bert's blood-gas analyses.

Atm.	O_2	CO_2	N_2	Atm.	O_2	CO_2	N_2	N_2 calculated from pressure, taking coefficient of absorption of N_2 at 37° as 1·23 (Winkler)
1	18·3	37·1	2·2	2	19·1	37·7	3·0	2·46
				5	20·6	40·5	6·4	6·15
1	18·4	47·7	2·5	3	20·0	42·2	4·4	3·69
				6·75	21·0	41·3	7·1	8·3
1	19·4	35·3	2·2	3	20·9	35·1	4·7	3·69
				6	23·7	35·6	8·1	7·38
1	22·8	50·1	2·3	5	23·9	35·2	6·0	6·15
				8	25·4	37·6	9·5	9·84

carried out similar analyses. The animals (anaesthetised) were placed in our large chamber and the carotid artery connected to one of the exit

tubes. On opening the tap a sample of blood could be collected in one of the weighed blood-bulbs of the Hill gas-pump. The air-pressure expelled the blood so forcibly that no precautions to prevent clotting were required. A normal sample was obtained and then other samples at varying times of exposure to compressed air or oxygen. The samples were evacuated by the Hill pump, analysed by the potash pyro method, and the results reduced to 0° C. and 760 mm. The percentage of haemoglobin was also determined in the samples by the Gowers-Haldane instrument. Our results are published in full in the *Journal of Physiology*, Vol. XXIX. 1903, p. 382. The following table gives some typical results.

Examples of blood gas analyses.

Atm.	O_2	CO_2	N_2	Atm.	Duration of exposure	O_2	CO_2	N_2	N_2 calculated from pressure, taking 1·23 as the coefficient of absorption of N_2
1	22·5	32·79	2·03	+6⅔	30 m.	22·10	37·28	8·41	9·42
				+6⅔	2 h. 45 m.	25·81	40·66	11·61	9·42
1	14·2	43·40	2	+6⅔	1 hr.	14·3	45·7	10·14	9·42
				+6⅔	1 h. 30 m.	10·56	39·41	12·9	9·42
				+5⅓	45 m.	14·74	37·7	7·48	7·78
					1 hr.	16·55	39·24	9·27	7·78
1	13·7	47	1·53	+6⅓	1 h. 5 m.	17·4	40·9	11·17	9·42
									O_2 calculated from Hb % and from pressure
				+6⅓ O_2	40 m.	24·2	32	2·16	28·96
				+6 O_2	1 h. 35 m.	30·3	37·12	3·13	28·55

In our paper in the *Journal of Physiology* we calculated the nitrogen not according to its coefficient of absorption in water but according to the result of normal blood-gas analyses, and multiplied the atmospheres by 1·8 in place of 1·23. This made the nitrogen found less than that calculated, and we concluded that time was required to fully saturate the arterial blood according to Dalton's law. Regnard and Portier[1] make the same error in regard to Bert's analyses and conclude that his results do not come up to the requirements of Dalton's law. There is always some leakage in blood-gas analyses, and the N_2 given as 1·8 (Pembrey) or 1·5 % (Tissot) is too high. Taking 1·23 as the coefficient of absorption at 37° the figures of Bert and ourselves agree fairly well with Dalton's law. The tissues must obviously take far longer than the blood to become saturated. This explains why short shifts are far less

[1] *Traité de Physique Biologique*, vol. I. 1901.

dangerous for divers and caissoniers. The shorter the shift the less becomes the saturation and the less gas is set free on decompression.

Effect on the Circulation.

Paul Bert recorded the blood pressure in a dog submitted to less than +1 atm. The blood pressure became higher, the respiratory oscillations augmented, and the respiration less frequent.

We have recorded the blood pressure in dogs, cats, rabbits, while under compressed air and oxygen. One of us (L. H.) at first experimented in the following way. He placed an anaesthetised and morphinised dog at the bottom of a large autoclave, connected the carotid artery with a manometer, and placed the manometer to write on a small drum *enclosed in* the autoclave. Having set the blood-pressure record going, the lid was screwed on and the pressure sent up to two atmospheres by means of an oxygen bottle. Decompression was then brought about, the autoclave opened and the tracing examined. Tracings taken in this way showed that no noteworthy effect on the circulation resulted either from rapid compression or decompression.

We recently repeated this experiment on a chloralised rabbit placed in our large observation chamber. The pressure was raised to 75 lbs., and the effect of oxygen and air were tried in turn. We could detect no change in the mean blood pressure or pulse rate during compression. On sudden decompression there occurred a temporary rise in pressure—probably a reflex effect due to the noise of the escaping air.

We have also observed, with the microscope, the capillary circulation in the frog's web and bat's wing, the animals being placed in a chamber fitted at either end with glass windows. The web or wing was spread over one window and illuminated with the arc light. We could detect no change either in the calibre of the blood vessels, or the rate of flow, when the pressure was quickly raised to +20—30 atm. Neither did any change occur on rapid decompression, that is, until gas bubbles frothed off from the blood.

These experiments prove then once and for all that the pressure has no mechanical effect on the circulation, and they overthrow all the mechanical congestion theories of caisson-illness.

Effects of decompression.

Out of 24 dogs exposed by Bert to 7—9½ atm. and then rapidly decompressed in 1—4 minutes 21 died from the setting free of gas in the blood and tissues and only 1 escaped without symptoms.

Out of 3 cats exposed to 8—10 atm. and decompressed in 2—3 minutes, 1 died in 15 minutes, and the other 2 became paralysed with softening of the spinal cord.

Three rats exposed to $5\frac{1}{2}$—$6\frac{1}{2}$ atm. survived rapid decompression, while 2 at 8 atm. died.

Bert's experiments on slow decompression.

Animal	Atm.	Duration of full compression	Duration of decompression	Result
Rabbit	10 in 1 h. 30′	5 hrs.	2 hrs.	Temp. fell from 39·6 to 36·7, wet and trembling, survived.
Cat				Temp. fell from 39·5 to 34·3, wet and trembling, survived.
Rabbit	10 in 1 h. 5′	30′	20′	$1\frac{1}{4}$ hr. after decompression became paraplegic, died.
Cat				Convulsions & died, gas in right heart, 15·9 % CO_2, 84·1 N_2.
Cat				Convulsions and died.
Guinea pig	10 in 1 h. 5′	15′	10—5 atm. in 1′ 5—1 atm. in 25′	Paralysis, died, gas in venous system.
Cat				Survived, no symptoms.
Large dog (19 kilos)	$7\frac{1}{2}$ in 1 hr.	$4\frac{3}{4}$ hrs. in $7\frac{1}{2}$—$4\frac{1}{2}$	1 hr.	Wet and cold, dying on extraction, gas everywhere & pulmonary ecchymoses.
Puppy				All survived, no symptoms.
,,				
,,				
Dog	9	not stated	1 hr.	Body temp. 20° C. on decompression, gas in heart, dies.
Dog	10	not stated	30′	Paralysed, dies.
Dog	10	not stated	50′	Paralysed, gas in heart, dies.
Dog	10 in $1\frac{1}{2}$ hr.	10′	Rapid decomp. for each 2 atm. then pause for 15′. In all 70′	Slight symptoms in legs, recovers.
Dog	10 in 1 h. 12′	not stated	1 hr. 30′	Slight paralysis of hind limbs, recovers.
Dog	10 in 1 hr.	30′	10—6 atm. in 1′ 6—1 ,, in 1 hr.	Temporary paralysis of hind limbs, recovers.
Dog	10	not stated	10—$4\frac{1}{2}$ atm. in 56′ $4\frac{1}{2}$—1 ,, in 3′	Paralysed, gas in heart, dies.
Dog	10	7′	10—6 atm. in 2′ then 30′ pause, 6—3 atm. in 2′ then 45′ pause, 3—1 atm. in 15′. In all 1 hr. 30′	Survives. No symptoms.

Summary. 11 recovered with no symptoms.
2 died when decompression lasted 1 hr. (in both these the temp. had fallen owing to oxygen poisoning).
1 died when decompression lasted 50′.
5 died when decompression lasted less than 30′.

Seven rabbits at 6½—8 atm. survived rapid decompression.

The most striking of Bert's results is the following: A dog was put at 9½ atm. The apparatus burst. The dog instantly died. Enormous subcutaneous emphysema was found, with gas in stomach, omentum, anterior chamber of eye, cerebro-spinal fluid and spinal cord. The right heart was full of gas which on analysis yielded 15·2 % CO_2, 82·8 % N_2, and 2·0 % O_2.

Having observed the effect of rapid decompression, Bert found that dogs may be safely exposed to + 10 atm. if 1—1½ hours be taken for decompression. The animals must of course not be exposed too long, or oxygen poisoning will result.

G. Thompson[1] compressed monkeys, cats, dogs, and pigeons to + 4—4½ atm. of oxygen or air for 1½ hours: there were no symptoms unless the decompression were too rapid. A dog stood a presssure of + 8 atm. for some time without discomfort. He then had a slight convulsion, but was all right after decompression. Catsaras[2] decompressed a dog in 30 seconds after exposure to 5 atm. for 30 minutes. The dog became paralysed in the left leg. Necrobiosis in the left lateral column of the cord in the mid-dorsal region and descending degeneration were found 2½ months later.

Hersent exposed 7 dogs to + 5 atm. for a few hours and decompressed them in 1 hour to 1 hour 15 minutes.

No symptoms resulted eighteen times. Slight paralysis of the legs occurred 4 times. Paraplegia, cured in 5 days, occurred once. Death with gas in the heart resulted once. One dog decompressed in 50 seconds died. Two dogs decompressed in 15 minutes had paraplegia, and 1 died.

Hersent also exposed dogs to + 3—3·8 atm. for times varying from 11 minutes to 4 hours 11 minutes. The decompression lasted only 30 seconds to 50 seconds.

Out of 9 exposures, there occurred 2 cases of severe paralysis and death with bubbles in the spinal vessels, and 2 cases of temporary paralysis of the legs. All these experiments show the frightful risks of rapid decompression and that even 1 hour for decompression is not quite sufficient for a 4 hours shift at + 5 atm.

Hersent[3] exposed a man to + 5·4 atm. for 1 hour and decompressed him in 3 hours. Itching and 'bends' were not prevented, but no serious illness resulted.

[1] *New York Med. Record*, 1889.

[2] *Arch. de Neurologie*, 1890, p. 48.

[3] Cit. after Snell, p. 149.

The following preliminary experiments were carried out by one of us (L. H.).

(1) Two large toads compressed for 1 hour in 20 atm. O_2 and rapidly decompressed. The animals went into tetanic spasms, and swelled to double their size with the gas set free in their tissues. The heart was enormously distended, tense and scarlet in colour. On letting out the froth it began to beat vigorously.

(2) Toad in 20 atm. O_2 for 5 minutes. Decompressed in 1 minute. There was some temporary paralysis of the legs and inertness. The animal soon recovered and hopped away into a corner. The same toad was placed in 20 atm. O_2 for 35 minutes. After rapid decompression it was found alive, breathing and trying to escape. In about 1 minute there followed tetanic spasms and rigidity of the legs. The heart was enormously distended, immobile, scarlet and tense. On letting out the froth it began to beat. Gas bubbles were seen in the walls of the intestine, in the lymph spaces, in the anterior chamber of the eye, in the pial vessels etc. The lungs were enormously distended. The nerves and muscles were excitable, and the muscles contracted vigorously.

(3) Rat raised to 15 atm. O_2 in 4 minutes, then rapidly decompressed. The rat violently cleaned its face, there was tremor and tendency to spasm. The animal remained dull and inert but recovered next day.

(4) Rat in 20 atm. O_2 for 6 minutes. Rapid decompression. Respiration almost failed, tendency to tetanic spasms, paralysis of hind legs, contracted pupils, died in 80 minutes. Air bubbles were found in the liver, mesenteric vessels, numberless small ones in the mesenteric fat in the uterus and foetal membranes (the rat was pregnant). The spleen and intestines were greatly congested. There was almost no blood in the heart. No naked eye haemorrhages in the central nervous system.

(5) Rat to 20 atm. O_2 in 5 minutes. Decompression to 7 atm. in 10 minutes and to O rapidly. Immediate convulsions, eyeball projecting, retinal haemorrhages seen with ophthalmoscope, died in 10 minutes. Froth in the heart, and bubbles in the intestinal vessels and walls. No naked eye haemorrhages in central nervous system.

(6) Rat in 20 atm. O_2 for 2 minutes. Decompression in 1 minute. Rapidly cleaned face, dazed condition, a touch caused a violent jump like in first stage of strychnine poisoning. Recovered.

(7) Rat in 20 atm. O_2 for 5 minutes. Rapid decompression. Lay on its side partly paralysed. Soon recovered and moved into cage. On pulling it out it struggled, and this caused a violent epileptic fit (due to displacement of gas bubbles by the struggling ?). It quickly recovered and ran into the cage.

(8) Rat in 20 atm. O_2 for 9 minutes. Rapid decompression. Collapse paralysis, gasping respiration and death. Air bubbles everywhere in the right heart, liver, stomach and mesenteric vessels. General emphysema of the fat and connective tissues.

(9) Guinea-pig in 10 atm. O_2 for 2 minutes. Rapid decompression. The animal at first appeared dazed but soon recovered.

(10) Guinea-pig to 22 atm. O_2 in 4 minutes. Rapid decompression. Convulsions, rolling over to right, death. Froth in the heart and lungs. Some air bubbles in wall of intestine. Small pin point haemorrhages over base of brain. A few bubbles in the larger pial vessels.

The microscopical examination of the organs of these animals was carried out by Dr Finlayson. In the central nervous system the gas-bubbles formed small cyst-like cavities surrounded by compressed and flattened nerve-cells. The same kind of cavities formed in the liver. The bubbles set free in the vessels run together at less resistant points and the vessels become alternately occupied with columns of corpuscles and long bubbles of gas. Bubbles are also set free in all the connective tissue (lymph) spaces throughout the body and especially in adipose tissue. We have never seen bubbles actually within a muscle-fibre, nerve or other cell. The cells are not torn but compressed and rendered anaemic. It is easy to conceive how the escape of gas-bubbles into resistant structures such as bone, aponeurosis nerve-roots and nerve-sheaths may give rise to the 'bends' or pains so commonly suffered by caissoniers. Von Schrötter has published a figure exhibiting the air-bubbles in the coronary artery of a dog decompressed rapidly from 4 atm. He also gives a figure of the lesions produced in the spinal cord by the air-bubbles[1].

We have actually observed the production of air embolism in the vessels of the frog's web and bat's wing. The animals were exposed to 20 atm. for about 10 minutes. For about a minute after rapid decompression the circulation continued unaltered, then small dark bubbles were seen, first one, and then another, and then numbers scurrying through the vessels, and driving the corpuscles before them. In a moment or two the vessels became entirely occupied with columns of air bubbles, and the circulation was at an end. By means of rapid recompression we have driven the gas again into solution, and have seen the corpuscles reappear in the capillaries and the circulation become reestablished. On very *slowly* decompressing the animals we have seen no gas bubbles appear.

Our large pressure chamber, pump and other facilities kindly provided by Messrs Siebe and Gorman, the well known marine engineers, has enabled us to thoroughly study the effects of rapid and slow decompression. The chamber was provided with a large tap, by means of which the pressure could be lowered from + 7 atm. to + 0 in about 10 seconds to 1 minute.

It was also provided with a pin point opening through which the period of decompression could be made to occupy 1, 2 or more hours.

Experiment I. A large cat, two half-grown rabbits, two large rats, and two white mice were placed in the chamber and the pressure raised to 105 lbs. (+7 atm.).

[1] *Prager med. Wochenschrift*, XXIV. 1899, Nr. 14.

A ventilation current was maintained. All the animals appeared to be perfectly normal. At the end of an hour rapid decompression was brought about. The chamber filled with mist owing to the cooling of the expanded air. When the mist cleared we saw that the cat and one rabbit were dead, while the other rabbit was in violent tetanic convulsions.

On opening the chamber the rats were found to be dead.

The second rabbit died also and the mice alone survived.

There was emphysema of all the tissues and frothing of the blood in the right heart and lung. In the albino rats we could see extensive retinal haemorrhages.

II. A cat was placed in the chamber and the pressure raised to +7 atm. in 50 minutes, and then rapidly lowered to +0. The cat survived, for the tissue fluids had not become sufficiently saturated with air.

III. A large cat, a rabbit, two white rats and two mice were compressed to +7 atm. in 50 minutes, and kept at this pressure for 1 hour. Decompression occupied 1 hour. None of the animals showed any discomfort.

IV. A Rhesus monkey, a rat and 2 mice were compressed to +7 atm. for 4 hours. The animals seemed untroubled by the pressure. Decompression was started at 4·30 p.m. by opening the small tap; the last part of the decompression was hastened and when at 5·25 the pressure registered 10 lbs. to the sq. inch, the large valve was opened and the pressure quickly brought to zero. On opening the chamber the monkey and the other animals seemed perfectly normal. On removing the monkey from the chamber he struggled to escape but in the course of a minute or two suddenly became quiet and lay on his side gasping, and with a peculiar cry. He gradually got more and more dyspnoeic, and his lips, tongue and face became markedly cyanotic. Despite energetic artificial respiration he died in about 10 minutes after removal from the chamber.

Post mortem. *Heart*: not markedly distended, ventricles in 'delirium cordis,' auricles beating feebly. On opening the right heart a little deep purple frothy blood exuded followed soon however by non-frothy blood. *Mesenteric veins*: small air columns in several of these. *Lungs* perfectly healthy.

The other animals in this experiment did not show any decompression symptoms. The cause of the trouble was no doubt the acceleration of the last part of the decompression.

V. The experiment was repeated with another monkey (Rhesus). After being subjected to +7 atm. air for 4 hours, 2½ hours were taken to decompress. There was not the slightest sign of decompression symptoms.

This experiment was repeated on this monkey three or four times a week for a month, the time for decompression being in each case 2 hours. There was never the slightest sign of decompression symptoms and the monkey remained in perfect health and maintained its weight. Towards the end of the period of compression it sometimes seemed to become sleepy. The body temperature remained normal.

The treatment of the decompression symptoms.

As we have seen in the experiments on the frog and bat the bubbles of air, which develop in the capillaries, pass back into solution on a rapid reapplication of the pressure.

We have tried this in the case of larger animals.

Experiment VI.

A large hutch rabbit was kept under a pressure of +7 atmospheres of air for 4 hours and was then quickly decompressed. In a minute or so the rabbit developed typical decompression symptoms (i.e. fell on side and limbs showed tetanic convulsions). The pressure was now quickly re-applied up to about +5 atm. by emptying a large cylinder of compressed air into the chamber. The symptoms however remained unabated and the rabbit soon died. It was evident, therefore, that for the re-application of pressure to be of any avail, the pressure must be very quickly re-established and no time be given for the air bubbles to tear up and damage permanently the nervous tissues, or to produce stasis of the circulation for too long a period.

We, therefore, repeated the experiment with the modification that the pressure was more quickly re-applied.

VII. A cat and a hutch rabbit were subjected to an air pressure of +7 atm. for 4 hours. Decompression was effected to zero in about five seconds, and as quickly as the taps could be opened (about five seconds) a large cylinder of compressed air was delivered into the chamber, thus raising the pressure to 95 lbs. in about 2 minutes.

At the moment of decompression the cat sprang to the window, excited and with widely dilated pupils. In a few seconds it became entirely paralysed in the limbs so that it fell helpless on to its side, its head meanwhile showed continuous side to side pendulum-like movements. There was no mystagmus. On recompression, these symptoms gradually disappeared, the head movement being the first to go, then the pupils contracted to their normal size. Some two or three minutes after recompression to 95 lbs. the cat tried to move about but fell. The pressure was maintained for 45 minutes and then slowly lowered. The cat recovered and on removal seemed *perfectly normal*, and on being placed in his basket leapt over its side and escaped into the room. Next morning it was quite normal in every respect.

The rabbit was recompressed before it showed any symptoms of decompression and was quite normal on removal from the chamber.

All our other experiments on metabolism, oxygen poisoning etc. show that for +7 atm. 2—3 hours is a safe period for decompression. The only case in which it fails is when the animals have developed symptoms of oxygen poisoning and have become comatose, their body temperature lowered and lungs congested by too long a stay in the compressed air. The circulatory and respiratory organs then fail to rid the body of the gas with which it is saturated.

Our experiments confirm those of Bert.

The blood and tissue juices effervesce on rapid decompression like an opened bottle of soda water. The longer the shift the greater becomes the saturation of the body fluids, and the greater the risk of rapid decompression.

A 5 minutes exposure to +20 atm. O_2 is sufficient to saturate rats and guinea-pigs so far that they die on rapid decompression.

Animals can be exposed to +7 atm. air with perfect safety for four hours, and be brought out quite well when the period of decompression is made to last 2 hours.

Recompression, after rapid decompression, causes solution of the gas, and may, if quickly applied, save the life of the animal. Recompression has been found to alleviate the bends in most caisson works, and Mr Moir introduced a boiler at the Hudson tunnel wherein recompression was applied with excellent results. At the Blackwall tunnel a 'medical lock' was likewise employed and the cases of bends frequently derived benefit from recompression followed by slow decompression. Von Schrötter, from his experience at Vienna caissons, considers recompression to be the sovereign remedy for caisson sickness if it can only be applied in time.

We will now contrast the experimental results with the periods of decompression employed at some of the chief caisson works, and then discuss the influence of age and habit of body on caisson illness.

Periods of shift and decompression at Caisson works.

Atm. (maximal)	Length of shift	Period of decompression	Place
$4\frac{1}{4}$	4 hrs.	30′	Chalonnes
2	—	10″	Lorient
$3\frac{1}{2}$	4 hrs.	12—15′ (rule often broken by men)	Kehl
$3\frac{1}{2}$	—	20′	Trazegnies
3	8 hrs.	4—5′	St Louis
$3\frac{1}{2}$	4 hrs.	10′	,,
4	3 hrs.	18′	,,
2—3	8 hrs.	4′ (often shortened to 30″ by men breaking the rules)	Blackwall

Triger recommended 7 minutes.

Barella recommended 10 minutes per atm.

Foley recommended 3 minutes, and considered slow decompression dangerous.

The Greek divers are usually pulled up rapidly.

Denayreuze for divers recommended 1 minute per metre.

Siebe and Gorman recommend deep divers to take 20 minutes in ascending.

Paul Bert recommended short shifts and 30 minutes decompression for 2—3 atm. and 60 minutes decompression for 3—4 atm. The decompression chamber must, he says, be warmed.

For deep divers he recommends a half-way resting stage.

Catsaras recommends a rest of 1 minute at every two fathoms of ascent. He also advises sponge divers not to stay longer than 5 minutes at 25 fathoms, and only 1 minute at 30 fathoms.

Influence of Age. Pol and Watelle state that young men of 18—26 years stand the work best; out of 25 men discharged on account of symptoms 19 were over 40 years old.

E. H. Snell found that at the Blackwall tunnel men below 20 were immune to accidents of decompression. This agrees with the general tenour of experiments on animals. The young bear rapid decompression best. He publishes the following table.

Age	No. of men passed	No. of cases taken ill whose ages are recorded	% illness
15—20	55	0	0
20—25	145	15	10·3
25—30	152	37	24·3
30—35	91	19	20·9
35—40	61	14	22·9
41—45	38	10	26·3
45—50	3	5	166

Habit of body. In stout men or men of heavy build the liability to illness is greatly increased. A. Smith compiled the following table from the records, at Brooklyn bridge, of men under 45 years.

	Spare	Medium	Heavy
Lost little or no time from sickness	25	14	3
Taken sick	28	22	36
Paralysed	2	3	8
Died	—	—	3

Considering that under 45 years heavy men are greatly in the minority, this report is most striking. Snell excluded old and heavy men from the Blackwall tunnel caissons, and lost no cases. Men prematurely grey and with commencing arterial degeneration should also be excluded.

There is no proof that long continuance at the work renders a man immune. Cases frequently occur among old hands. The men among the new hands who are liable to attack are discharged. Divers who have when young done deep jobs become paralysed at less depths in advanced years.

A. Smith says that severe exertion after decompression predisposes to attack. This is to be expected, for the exertion may force the air bubbles in the blood vessels out of harmless into harmful places. We have brought on attacks of convulsion by massaging the abdomen of rapidly decompressed animals. The monkey in experiment IV. died after struggling.

Ventilation. E. H. Snell lays great stress on the good results which follow free ventilation of caissons. He says, "An increase of CO_2 from ·04 % to ·1 % at 30 lbs. pressure is the forerunner of much illness."

In one of the Blackwall caissons where the pressure was 25—35 lbs. illnesses were occurring at the rate of seven a day. The men were working at the bottom of the caisson; the air supply pipe opened near the roof and the air escaped again through the roof. The supply pipe being lengthened, the illnesses at once dropped to an average of 1 in 2 days.

The following table has been compiled by Snell to illustrate the effect of increased ventilation.

Caisson I. Pressure +25—35 lbs.

Cubic feet of air per man per hour	No. of days	Cases of illness	Illnesses per 100 days
Below 4000	13	41	315·5
4000—8000	26	78	300
8000—12000	10	8	80
Above 12000	12	4*	33·3

* Only 2 or 3 men were in the caisson on the days when these illnesses occurred, and so the total volume of air supplied to the caisson was reduced, i.e. the air supplied per man was high, but low per caisson.

In other tables Snell seeks to prove that a ventilation of over 12,000 c. ft. per man abolishes illness. He points out that candles smoke in compressed air, but cease to do so if put within a lamp chimney so as to increase the draught. As the velocity of diffusion of a gas varies inversely as the sq. root of the density he attributes the smokiness of the candle to the slow diffusion of the products of combustion. He thinks the same may hold good for man.

Snell suggests that an increase of CO_2 from ·04 to ·1 % may actually be the cause of caisson illness and that CO_2 may be the gas which in particular is set free in the blood on decompression. There is no evidence that this amount has the slightest toxic effect.

At Brooklyn caisson with ·33 % CO_2 was found on analysis, which at 3 atm. gives ·99 % atm. CO_2. At Blackwall with ·1 % CO_2 and at Brooklyn with ·33 % CO_2 the extra CO_2 would cause a slightly increased

depth of breathing and thus practically no effect on the composition of the alveolar air in contact with the blood. This, at least, would seem to follow from experiments recently communicated to the Physiological Society by Haldane and Priestley. One of us (L. H.) recently measured the CO_2 in the chamber when a cat was exposed to 8 atm. of air. There was finally as much as 1 %, i.e. 8 % atm. The cat breathed more deeply but otherwise did not show any ill effect.

We cannot suppose that a small percentage of CO_2 in the air would contribute in any way to the setting free of CO_2 bubbles on decompression. It is true that Paul Bert found 15 % CO_2 and 85 % N in the air obtained from the heart of animals killed by rapid decompression. When blood is exposed to air it gives off CO_2 owing to the very low partial pressure of this gas in the atmosphere. Similarly when nitrogen gas is set free in the heart, some CO_2 will diffuse out, and Bert found some traces of oxygen. Bert's analyses of blood gases show that the CO_2 in the arterial blood is if anything lessened under the influence of compressed air, and our results confirm Bert.

Hunter notes that the most dangerous times in the Forth Bridge caisson were (1) when soft wet silt was being removed, (2) when concreting was going on. It must be borne in mind that the presence of traces of a toxic gas such as H_2S is dangerous in compressed air, owing to the increase in the partial pressure of such impurities. In the case of CO the increase in partial pressure will be balanced by that of oxygen. But the CO might produce its effect on decompression. The caissons become fouled with the excretions of the workmen, and it is very needful that proper earth-pails should be provided.

As matters stand at present it is not easy to explain Snell's ventilation results, and it is urgently required that they should be confirmed.

Increased rate of ventilation has not seemed to affect our animals in regard to the dangers of decompression.

From the records of caisson sickness and from our experimental results we conclude that the men selected for high pressure work should be small men, of spare and wiry habit, not older than 20—25. The men should be total abstainers and abstemious in all their habits.

The men should all be tested at low pressures first, and those who suffer from symptoms should be discharged.

The following we consider to be safe rules for working.

The longer the shift, the greater is the saturation of the body fluids with gas, and the slower therefore should be the decompression.

The higher the pressure, the shorter should be the shift, and the longer the decompression.

We suggest the following times as safe:

Atm.	lbs.	Shift	Decompression period
+2	30	4 hrs.	30′—1 hr.
+3—4	45—60	4 hrs.	1—2 hrs.
+5	75	1 hr.	1—2 hrs.
+6—7	90—105	30′—1 hr.	2 hrs.

To prevent men breaking the rules the decompression chamber should be provided with one cock only, which will allow decompression to take place in the given time. A separate lock should be provided for the rapid passage of material. The decompression chamber must be artificially warmed so that the temperature does not fall below 60° F., and it must be thoroughly ventilated during decompression.

The ventilation of the caisson or diving apparatus should be very free, and the temperature of the air should be about 60° F. The men should remain quiet for an hour or so after decompression and be recompressed on any sign of sickness. Paul Bert recommends that oxygen be supplied to the decompression chamber in order to hasten the diffusion of nitrogen. This is no doubt a means by which the period of decompression might be shortened, but it introduces the danger of oxygen poisoning.

We are of opinion that by proper choice of men and regulation of the shift and decompression period, work could be carried out without loss of life at a depth of even 200 *ft., i.e. about* 7 *atm. or* +100 *lbs. pressure.*

Summary.

1. Compressed air above 5 atm. lessens the CO_2 output, and lowers the body temperature in mice, rats, and young rabbits.

2. Oxygen at and above 1 atm. has the same effect. It is a sign of oxygen poisoning.

3. Compressed air at 10 atm. is more damaging—at least to small animals—than oxygen at 2 atm.

4. Compressed air increases the loss of body heat both because it is a better conductor, and because it is saturated with moisture.

5. The saturation of the air with moisture in caissons does not prevent evaporation from the body because the skin temperature is above that of the air. The wet air by damping fur or clothes increases loss of heat.

6. Highly compressed air may possibly interfere with the diffusion

of CO_2 from the alveolar air, and may, owing to increased friction, hinder the passage of air in and out of the air-tubes.

7. The nitrogen output in dogs is not altered in any noteworthy degree by exposure for six hours to 8 atm. air.

8. Inflammation and consolidation of the lungs is produced by exposure to 8 atm. air for over 24 hours. $1\frac{1}{2}$ atm. of pure oxygen has a similar effect. The higher the oxygen tension the more rapidly does the inflammation ensue, e.g. 6 atm. O_2 produces marked congestion in 2 hours.

9. It does not seem likely that inflammation of the lungs should be produced in the pressures and times of exposure usual in caissons.

10. Excised frog's hearts, muscles, and nerves are not rapidly poisoned by even 50 atm. O_2. A heart will beat more than an hour exposed to this pressure. The vagus nerve endings appear to be paralysed by such exposure, while inhibition can be obtained by stimulating the crescent. The thin sartorius muscle is much more easily affected than the gastrocnemius, and soon gives a curve like a fatigue curve.

11. All animals investigated, vertebrates and invertebrates, are instantly convulsed and killed by exposure to 50 atm. O_2.

12. Convulsions are frequently produced in vertebrates by exposure to 4—5 atm. O_2, while exposure to 6—25 atm. O_2 produces dyspnoea and coma, and the convulsive stage does not usually appear. Cleaning movements, salivation, gaping, jerky deep respiration, are symptoms which precede the convulsions, and coma soon follows them.

13. We have not observed convulsions with air pressures up to 12 atm. Salivation, dyspnoea, and coma are the symptoms.

14. The blood-gases increase in compressed air or oxygen according to Dalton's law, but the process of complete saturation of blood and tissues takes some time.

15. The circulation is unaffected mechanically by compressed air.

16. The cause of caisson-sickness is the escape of gas bubbles in the blood vessels and tissue fluids on decompression. An animal exposed for 4 hours to 8 atm. air and quickly decompressed is like an opened bottle of soda-water. The fluids of the body generally effervesce.

17. The effervescence can be studied in the circulation of the frog's web or bat's wing, the animals being enclosed in a suitable chamber. It takes a little time for the bubbles to grow to an appreciable size.

18. Recompression causes the bubbles to go into solution, and if applied quickly enough the circulation recommences.

19. The bubbles after rapid decompression can be seen post-mortem in the blood vessels, in the heart, retinae, aqueous humour, connective tissue spaces, etc. The alimentary canal is blown out with gas. The bubbles produce cyst-like cavities in solid organs, e.g. in the central nervous system, the liver. The cells are compressed round these cysts.

20. In the case of oxygen an animal may recover after an extraordinary amount of this gas has been set free by rapid decompression. The nerve cells are not killed by the oxygen bubbles, and the animals are convulsed and exhibit hyper-reflex-excitability.

21. The varying symptoms of caisson-sickness are due to the varying seat of the air emboli.

22. Young men escape caisson-sickness owing to the elasticity of their tissues, and greater facility for collateral pathways of circulation.

23. Animals can be safely exposed to 8 atm. of air for 4 hours if 2 hours be spent in gradual decompression. Such exposure can be safely repeated three times a week.

24. By the choice of suitable men, and proper regulation of the period of compression and decompression, caisson and diver's sickness can be avoided.

We are greatly indebted to Messrs Siebe and Gorman who placed their unequalled experience in diving at our disposal, and provided us with air-pumps, chambers and a skilled assistant. We are also indebted to Dr Haldane for several valuable criticisms.

The work has been carried out with the help of grants from the Royal Society Government Grant.