indeed a martyrology. In the last few years I have operated in almost all cases that have come to me, for I have felt that it was well worth the while of any patient to face the risk of operation rather than to suffer the agony which must otherwise be his lot. In all cases I have joined the gall bladder to some part of the alimentary canal—to the duodenum if I could do so with ease; to the stomach if it could be reached with less difficulty; in one case only I have taken the colon. The immediate results have been surprisingly good, for no patient yet has died, and the relief has been in all very considerable. I was at first a little apprehensive when the fistula was made into the stomach, but such cases seem to differ in no recognizable particular from those in which the duodenum has been available. Bile flowing freely into the stomach does not seem to impede the full activities of gastric digestion.⁴ In two of these cases it is certain that a mistake in diagnosis was made, for after a lapse of two and a half and three years the patients are quite well, have lost all tinge of jaundice, have gained weight and are in active work. They were doubtless examples of that most interesting and remarkable condition, chronic pancreatitis. I am not sure whether in these later days the pancreas is not sometimes accused of inflammatory transgressions when innocent. But it is quite certain that it may be accused of malignancy when it does not deserve the reproach. The older writers tell us nothing of chronic pancreatitis—the recognition of it is due to the investigations carried out upon the common bile duct in the search for stones impacted therein. When, as sometimes happened, a large hard mass was discovered, malignancy was imputed and a bad prognosis given, which the patient made haste to falsify. Riedel and chiefly Mayo Robson are entitled to the credit of this highly important advance in our knowledge. We are now fully aware of the fact that chronic pancreatitis depends very often for its development upon an infection from the common duct, which is set going by stones in transit or in arrest there. The danger of the condition lies in its continued development long after the original cause has been removed. In a few of my cases, after the lapse of years, glycosuria has developed and the patient has died comatose, no doubt from an implication of the islands of Langerhans in an interacinar inflammation. Glycosuria can be found from time to time in the urine of patients who suffer from cholelithiasis, and it may perhaps rightly be considered as the most urgent of all indications for early operation. In a very large proportion of the cases the pancreatic complication does not need to be specially considered; the removal of the cause, nearly always a calculus, with the subsequent drainage of the bile to the surface, is quite enough to ensure a subsidence of the inflammation. The fact that when a certain limit is overstepped the process of chronic induration will continue unchecked, and that the death of the patient from diabetes may thereby be caused, should, however, urge upon us the necessity of early operative rescue in all these patients.

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¹ BRITISH MEDICAL JOURNAL, November 16th, 1907. ² *Proc. Roy. Soc. Med.*, 1911, vol. iv, No. 3, p. 61. ³ BRITISH MEDICAL JOURNAL, November 28th, 1908. ⁴ *Ibid.*, 1901, vol. i, p. 1136.

DURING the year 1911, we learn from the New York *Medical Record*, there were 2,145 deaths among medical practitioners in the United States and Canada. On an estimate of 140,000 physicians the rate was 15.32 per 1,000. For the nine previous years the death-rates were as follows: 1910, 16.96; 1909, 16.2; 1908, 17.39; 1907, 16.01; 1906, 17.0; 1905, 16.36; 1904, 17.14; 1903, 13.7; and 1902, 14.74. The average annual mortality was 16.11 per 1,000. The age of death varied from 23 to 99, with an average of 59 years and 10 months. The chief causes of death in the order named were cerebral haemorrhage, "heart disease," senility, pneumonia, external causes, and kidney disease.

In connexion with his visit to India, the King has been pleased to confer the following promotions and appointments in the Royal Victorian Order upon members of the medical profession: Lieutenant-Colonel Sir Richard Havelock Charles, K.C.V.O., Serjeant-Surgeon to His Majesty, is promoted to be Knight Grand Cross; Fleet Surgeon Robert Hill, M.V.O., R.N., H.M.S. *Medina*, is appointed a Commander, and Lieutenant-Colonel Robert Bird, C.I.E., Professor of Surgery, Medical College, Calcutta, and Dr. William Turner, Surgeon, Colonial Hospital, Gibraltar, are created Members of the Fourth Class.

An Address

ON

COMPRESSED AIR ILLNESS AND EXPERIMENTAL RESEARCH.

DELIVERED BEFORE THE DUBLIN BRANCH OF THE MEDICAL RESEARCH SOCIETY, JANUARY 25TH, 1912.

BY

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I COME before the Society this evening at a time when there is great hope for the progress of medicine—a time when we look forward to discoveries which will eventually result in an enormous amount of relief to suffering mankind, and a time when this society ought to have very little difficulty in defending itself from the attacks of those who wish to suppress medical research. Within the last year or so we have seen the discovery of a synthetic drug which has given us the means of curing one of the worst diseases that afflict humanity. Ehrlich's great discovery has opened up before us a new field of work, and, further, has inspired us with the belief that similar discoveries may shortly be forthcoming in other departments of medicine. The hope as to the imminence of such discoveries has recently been strengthened by a communication from Morgenroth to the effect that in his laboratory he has succeeded in curing 50 per cent. of the mice infected with the pneumococcus, a septicaemia which kills 100 per cent. Morgenroth has synthesized a drug and standardized the dose, by means of which he has been able to cure half the animals thus infected. We now look forward with some anticipation to see whether the same drug can be used in cases of pneumonia in man; the problem is not only to determine the dosage of the drug which will be effectual in man, but also to prove that the same drug which acts upon the pneumococcal infection in a mouse will also succeed in the human organism. Within the last few weeks also we have learned from Wassermann that he has synthesized a compound of selenium with eosin, and with this he has succeeded in curing cases of cancer in mice. The discovery is only just at its beginning, and in many cases the drug has destroyed the mouse, while in others it has destroyed the cancer and cured the mouse. But from this discovery we entertain the hope that something ultimately will come which will help to alleviate one of the greatest scourges of mankind.

All the great advances have been gained by experiments on animals, and I bring before you to-night a branch of inquiry in which I have been engaged for some fifteen years, hoping to demonstrate to you, again by experiments on animals, that it has been made safe for man, with suitable precautions, to work in compressed air. These precautions have been established by scientific methods and by the methods of research which this society helps to maintain.

Work in compressed air has accounted for a vast amount of sickness, suffering, and loss of life. Ladies who wear ropes of pearls, or pearl ornaments of any kind, are generally unaware of the mortality which follows those engaged in the pursuit of these gems. In the pearl fisheries off Broome in Western Australia, where Japanese are engaged as divers, I understand that the loss of life is something like 7 per cent., and the cemetery at Broome contains scores upon scores of graves of those who have lost their lives in the search for the pearls which decorate the woman of fashion. All this loss of life can be entirely prevented if the scientific methods which have been worked out upon animals are followed; and not only so, but the pearl fisheries can be safely extended with great economic advantage. The same thing holds good for many other branches of industry in which divers or workers in compressed air are employed. Compressed air enters into all great subterranean undertakings of to-day—tunnelling, harbour building, shaft sinking, drainage, pier and bridge constructing, and salvage work, as well as in diving for pearls and sponges. The means of

intercommunication in all the great cities of the world depend upon the tunnels built with the aid of compressed air under the rivers which pass through them; but all such work is limited to a certain depth by the pathological effects produced in the workers. The caisson worker, or diver who uses the diving dress, is surrounded with compressed air and breathes in it freely. The body of either is pressed upon by the air, and it is necessary that the air pressure be kept just greater than that of the water in order that the water may be kept out of the dress or the caisson. I can demonstrate this point on a model diver and a model diving bell or caisson that I have here. As this little model diver descends in the water and I pump air through the dress it will be seen that the pressure of the air, as indicated by the manometer, always remains just greater than the pressure of the superincumbent water above the diver's head. Whether it be the air or water that uniformly presses upon the body, the tissue fluids transmit the pressure equally, and although it is computed that an extra atmosphere means an additional total pressure of 30,000 to 40,000 lb. on the body of a man, no mechanical effect is produced. Living matter is a jelly containing about 80 per cent. of water, and, like water, it is practically incompressible.

Fig. 1.—Diagram of caisson showing air-lock.

Since attention was first drawn to compressed-air illness in the middle of the last century a large number of medical writers, ignorant of physical laws, have supposed that exposure to compressed air mechanically alters the distribution of blood, forcing it inwards and causing a congestion which on decompression is suddenly and dangerously altered. One of the common kinds of illness in compressed-air work is paralysis, and it was supposed that this paralysis was caused by blood being pressed out of the periphery into the central nervous system and then on decompression—that is, on emerging from the compressed air—this blood underwent a sudden revolution and caused haemorrhages in the nervous system, which, in their turn, produced paralysis. I have noticed that the same false views are even now put forward in the daily press to explain the symptoms shown by aëroplanists when in contact with the rarefied air at high altitudes. The sickness at high altitudes suffered by mountain climbers, balloonists, and aëroplanists has nothing to do with the mere mechanical effect of compressed air. On going into a caisson up to a pressure of several atmospheres no effect is visible upon a man's circulation; no change in the complexion indicates any alteration in the blood-flow through the face, there is no difference in the heart beat, there is nothing, in fact, to suggest that the slightest mechanical effect is produced. Almost the only mechanical effect which is produced on the body by a change in the barometric pressure is an alteration in the pressure in the middle ear, and this is easily relieved by opening the Eustachian tube. Under compressed air also there takes place a compression of any gas which may happen to be in the alimentary canal, and this leads a man to tighten his belt.

The illness which occurs at high altitudes is entirely due to want of oxygen. At an altitude of 18,000 ft., where the barometric pressure is one-half, a man on filling his lungs with air takes in only half the weight of oxygen which he absorbs at sea level. His respiratory and circulatory organs are scarcely able to work sufficiently hard to get the required amount of oxygen. After a time, of course, he gets into training at high altitudes by the exercise and strengthening of his respiratory and circulatory organs, by the increased formation of haemoglobin which carries the oxygen to the tissues, and by the alteration in the alkalinity of the blood, thereby increasing the readiness with which haemoglobin gives up to the tissues its oxygen. The breathing of oxygen entirely removes mountain sick-

ness. It is interesting to note that, while a man depends upon the pressure of oxygen in the atmosphere, a fire depends upon the percentage. At ordinary atmospheric pressure a man can breathe 17 per cent. of oxygen without feeling the slightest symptoms, while at this percentage a fire will not burn. On the other hand, at great altitudes, where the partial pressure of oxygen is halved but the percentage of oxygen remains the same, a man becomes distressed but a fire will burn. Hence the danger of aëroplanists trying to beat altitude records.

No symptoms of illness ever occur when a man is under compressed air. All the illness results from decompression, and the fact that the mere mechanical pressure uniformly applied is of no importance to living matter is shown by the existence of life in the greatest depths of the sea yet sounded, where the superincumbent pressure may equal two, three, or even five miles of water. With the help of Sir Charles Parsons of turbine fame, and a most powerful hydraulic press which he has constructed, I have recently been able to investigate the effect of high pressures of water upon life. So powerful is this press that Sir Charles Parsons has compressed water to 80 per cent. of its bulk. Some years ago a French observer, Regnard, compressed living aquatic animals, frog's muscles, etc., to 500 or even 1,000 atmospheres, and he found that at these high pressures the tissues became stiff and took up water, and that life was destroyed. Sir Charles Parsons and I have found the same thing to happen. Frogs' muscles, exposed to 300 atmospheres for two hours, remain normal in appearance, and excitability is retained, not only in the muscles, but in the nervous system also.

Fig. 2.—Circulation in frog's web demonstrated under pressure.

The reflex action, the response of the nerves to excitation, the beat of the heart, are all unchanged. But 400 atmospheres' pressure for two hours entirely destroys the microscopic structure and abolishes excitability altogether. Furthermore, the question is one of time as well as of pressure. A frog with the skin intact will stand ten minutes at 500 atmospheres without much hurt, but with the skin off, the nerves and muscles are destroyed in that time, becoming opaque in appearance, and showing on microscopic examination that the muscle fibres have broken in places, and the cross striations have been destroyed. From the nerve fibres the myelin can be teased out in droplets quite easily and the empty sheath left. The nature of the skin protects certain animals. For example, a gnat's larva survived two hours at even 700 atmospheres, but was killed in a similar time at 900 atmospheres. Oysters survived an exposure to 700 atmospheres for ten minutes, but were killed, as was shown by their shells gaping open and by their opaque appearance, after a brief exposure to double that pressure.

All our experiments go to prove that life is destroyed by several hundred atmospheres of water pressure, the water apparently becoming of such a concentration as to destroy the chemical structure of the living protoplasm. These experimental results are to a certain extent contradictory to those obtained by deep-sea soundings, for many forms of life, fish and otherwise, have certainly been found at depths of two or three miles. If life exists at the greatest depths, where the pressure may be a thousand atmospheres, we may be sure that the protoplasm has become evolved in such a way as to be immune to the high pressure of water. By means of a small chamber fitted with transparent windows, together with a hydraulic pump, I have been able to submit goldfish, which possess a swim-bladder, to

a thousand pounds of pressure within a few seconds and to observe their behaviour. They sank like a stone to the bottom immediately, owing to the sudden compression of the swim-bladder. After a time, having adjusted the amount of gas in the swim-bladder—no doubt by secretion—they began swimming about again, unharmed by pressure. I have also projected on the screen the shadow of the beating heart of a frog, submitting it to 50 atmospheres. The delicate structure of the heart continued to carry out its rhythmic beat unaffected by this enormous and sudden alteration of pressure. Similarly, muscle contracts normally when suddenly submitted to a pressure of air equal to 50 atmospheres. It is true that after a time the contraction languishes, but this is not due to pressure *per se*, but to poisoning by the high pressure or concentration of oxygen. The mechanical theories of compressed air are also refuted by this experiment. I stretched the frog's web over the glass window of the small pressure chamber and illuminated it by the arc light, so that the circulation of the blood was projected on to the screen. I found that the circulation remained unchanged on the pressure being rapidly raised by 20 or even 50 atmospheres. The manometric records of blood pressure taken from mammals show no noteworthy change when the pressure is raised to 3 atmospheres.

In the helmet of the diving-dress which, by the kindness of Messrs. Siebe Gorman and Co., I am able to demonstrate this evening, there is an inlet valve con-

Fig. 3.—Experimental chamber. The photograph was taken when Mr. Greenwood was inside.

nected with the pump by the air-pipe and an outlet valve. The air pumped into the dress keeps the water from entering at the wrist-cuffs, and the whole body remains dry, warm, and equally compressed. By means of the outlet valve the diver can adjust his specific gravity so that he is only slightly heavier than the water and can move easily along the bottom. He fills his dress more or less with air just as a fish fills its swim-bladder. He can go down rapidly, 100 ft. in two minutes, but it is dangerous to fall down, for if the pump does not keep up with the water pressure a cupping effect is produced and the diver may suffer haemorrhage from the lungs. If the dress becomes over-filled with air—and this may happen when the men who are pumping send down too large a quantity—the diver is blown up to the surface, and in the case of the old style of dress he may become helpless and unable to open his valve, arms and legs being blown stiffly out. To prevent this accident, in the new diving-dress the legs are laced up. The helmet also is provided with an emergency valve or spit-cock, which the diver can open and thus let out excessive air.

Divers have in the past been unable to stay down for any length of time at the greater depths owing to a feeling of oppression, which they have ascribed to the pressure of the water. Mr. Major Greenwood and I have exposed ourselves in our compressed air chamber to + 92 lb. (7 atmospheres) and to + 75 lb. (6 atmospheres) respectively, and we have found the breathing to be just as free and easy as at atmospheric pressure. Beyond an increased nasal twang of the voice no symptoms were produced, and there were no signs by which the pressure could be estimated. Dr.

John Haldane has done good service by proving that the oppression is due to an increased partial pressure of carbonic acid in the helmet owing to deficient ventilation. It is not the percentage, but the absolute pressure of the carbonic acid which controls the breathing. There is normally about 5 per cent. of an atmosphere of carbonic

Fig. 4.—Bubbles in vessels of mesentery (v. Schrötter).

acid in the lungs, and the respiratory centre so works as to keep the partial pressure always the same. Thus, while in our lungs at 1 atmosphere we found 5 per cent. carbonic acid, at 5 atmospheres we found on analysis 1 per cent. But the partial pressure was 1×5 , so that the proportion still remained 5 per cent. of an atmosphere. In order to keep the carbonic acid in the helmet down to a bearable concentration it is necessary that the same volume of air should be sent through the helmet, the volume being measured at whatever pressure the diver happens to be subjected to—that is to say, at 2 atmospheres the amount of air, adequate at 1 atmosphere, which is driven down to the diver must be doubled, at 3 atmospheres trebled, at 6 atmospheres increased six-fold. Under the old conditions of working, often with leaking pumps and tired men to pump them, the ventilation has generally been actually less than at atmospheric pressure, not six times greater, as it ought to be at a depth of 165 ft. A small increased partial pressure of carbonic acid, even up to 2 or 3 per cent. of an atmosphere, will not stop the diver from doing efficient work; but at 4 or 5 per cent. of an atmosphere the pulmonary ventilation is increased from 200 to 300 per cent., and if the diver is working hard, his breathing will become distressing and the feeling of oppression intense.

In order to get adequate ventilation at deep pressures several pumps must be linked up together, and a great many men are required to keep them working. To avoid this excessive labour, Mr. R. H. Davis (of Messrs. Siebe Gorman and Co.) and I are at present engaged upon an improvement of the diving helmet which will enable the

Fig. 5.—Heart and coronary vessels full of gas (v. Schrötter).

diver to do efficient work at deep pressures even when only one pump is employed. This device ought to save a good deal of hard pumping work. We have also contrived the self-contained diving dress which I demonstrate to-night. It is fitted with cylinders containing compressed air enriched with oxygen to 50 per

cent., and it has a caustic soda chamber. The oxygen supply is delivered 5 litres per minute to the helmet by a reducing valve, and the force of the oxygen stream is utilized by means of an injector to circulate the air in the helmet through the caustic soda chamber. No life-line or air-pipe is carried, only a light telephone cable, and this makes the dress suitable for the exploration of flooded mines, tunnels, shafts, etc., through which it is

Fig. 6.—Capillaries of kidney full of gas. Bubbles in the tubules taking the place of fat droplets

impossible for the driver to carry great lengths of heavy air-pipe and life-line. Air containing 50 per cent. of oxygen is used in place of pure oxygen, in order to avoid the risk of oxygen poisoning.

I come now to the cause of compressed-air illness. In all the great compressed-air works from first to last the men have suffered from illness and loss of life; there is no risk in going into or staying in a caisson. As Pol and Watelle said, "*On ne paie qu'en sortant.*" These observers gave particulars of 64 workers who were employed in the sinking of a coal shaft through wet soil at an absolute pressure of $4\frac{1}{2}$ atmospheres. There were 14 cases of slight illness, 16 cases of more or less severe illness, and two deaths. At the St. Louis bridge works, out of 352 workers there were 119 cases of illness, 56 being cases of paralysis, and 14 deaths. The absolute pressure reached $4\frac{1}{2}$ atmospheres. In the East River tunnels at New York—one of the greatest works undertaken with compressed air, but carried out under well-regulated conditions—the percentage of illness was 0.66, and of death 0.0035, in 557,000 man-shifts. The absolute pressure employed was 3 atmospheres. Out of the 3,692 cases at these East River tunnels over 88 per cent. were of the kind known as "bends"—that is, severe pain in the joints and muscles—1.26 per cent. gave symptoms of pain and prostration, 2.16 per cent. nervous symptoms, 5.33 per cent. vertigo, 1.62 per cent. dyspnoea and oppression, called "chokes," and 0.46 per cent. loss of consciousness

Fig. 7.—Liver cells blown out by gas bubbles.

and collapse. The number of deaths was 20. Yet mules which were kept for a year in the Hudson tunnel at 3 atmospheres' pressure were healthy enough to kick and bite at all corners, so that it is clearly decompression, and not exposure to pressure, which causes the trouble.

The cause of the illness which has such a protean manifestation was suggested by Hoppe-Seyler and made clear by Paul Bert, the latter showing by experiments on animals that nitrogen gas is dissolved in the blood and tissue fluids in proportion to the pressure of the air, and

that the dissolved gas on too rapid decompression bubbles off and effervesces in the blood of animal or man. The bubbles, by blocking up the capillaries and cutting off the blood supply here and there, produce the symptoms. Exposure to high atmospheric pressure has no ill effect until the pressure becomes so great that the partial pressure or concentration of oxygen acts as a tissue poison. The illness which occurs on decompression is prevented by making the period of decompression sufficiently slow to allow time for the dissolved nitrogen to escape from the lungs. When Robert Boyle submitted animals to the action of his air-pump, he observed that bubbles of air might be set free in the blood, aqueous humours, etc. And in these experiments we find the germ of the discovery which was completed by Paul Bert. It is astonishing how the researches, published by this renowned scientist in a volume

Fig. 8.—Lesion in posterior columns of cord produced by air embolism (v. Schrötter).

of many pages, were almost totally neglected by engineers and the medical officers of their caisson works, both in this country and in America. When I began the investigation of the subject some fifteen years ago I discovered that Paul Bert's work was almost unknown, and that the causation of compressed-air sickness was generally attributed to causes entirely at variance with physical laws and physiological facts. I myself had independently carried out many experiments which proved that the cause of the illness was due to the setting free of bubbles of nitrogen after decompression, without being aware of the fact that similar experiments had previously been made by Paul Bert, so that the same conclusions were independently reached by me. Exposed to 1 atmosphere at body temperature, the blood dissolves a little less than 1 per cent. of nitrogen; at 2 atmospheres 2 per cent., at 3 atmospheres 3 per cent., and so on. The tissue fluids take up the dissolved gas in the blood, and with time the whole body becomes saturated. This process of saturation takes a certain time, since the blood forms but 5 per cent. of the whole body weight, and the blood must carry the nitrogen from the lungs to the tissues. Probably some 5 kg. of blood circulate through the lungs per

Fig. 9.—Bubbles of oxygen in brain of mouse compressing cerebral cells. Decompression from 12 atmospheres O_2 . Mice can recover from such, the O_2 being absorbed.

minute, and this blood conveys the dissolved nitrogen to a tissue weight of 60–80 kg. Vernon has shown that fat dissolves some five or six times as much nitrogen as water, and the discovery of this important fact makes it clear to us that the fat man will dissolve far more nitrogen than the lean man and become saturated much more slowly. On decompression, the reverse process has to take place. The excess of nitrogen dissolved in the tissues must be carried back by the blood to the lungs and there make its

escape. If the decompression is made too rapidly for this to take place, the supersaturated blood and tissues may give up their nitrogen in the form of bubbles. It is clear, therefore, that fat men must be eliminated from all high-pressure work. Out of 30 autopsies which have been done on fatal cases of caisson illness, gas bubbles have been visible in the blood vessels in 19 instances. Most of the other cases were old-standing lesions of the spinal cord. The paralysis so often produced is due to the local death and degeneration of the spinal cord owing to the blocking of the circulation there by the bubbles.

One of the proofs that the nitrogen gas is so dissolved is that the blood collected from the artery of an animal while under pressure, when analysed with the gas pump, shows that the amount of dissolved nitrogen varies with the pressure—roughly speaking, we found 1 per cent. per atmosphere. We have exposed rats to 10 or 20 atmospheres, killed them by instant decompression, then opened their bodies under water and collected and analysed the gas which has been set free. We found from 6 to 16 per cent. of carbonic acid, a trace of oxygen, and 80 to 87 per cent. of nitrogen, the volume of nitrogen corresponding roughly to the saturation at the pressure employed. Major Greenwood and I have tested upon ourselves the rate of saturation, using the urine as a test fluid. We were compressed in a large boiler placed at our disposal by Messrs. Siebe Gorman and Co., who have generously helped us in our researches. The chamber was fitted with electric light, telephone, and taps for slow decompression. The pressure was raised by means of a diving-pump driven by a gas-engine. Having found out what was safe for animals, we exposed ourselves to the same kind of tests, and spent as long a time as seven hours enclosed in this steel prison which I demonstrate now upon the screen. We drank a quart of water, and some half an hour afterwards, when the kidneys were freely secreting, we collected samples of urine at varying pressures and times. The urine collected in sealed bulbs was evacuated by the gas pump, and we found that the urine secreted during the next ten minutes after reaching any given pressure was saturated with nitrogen at that pressure. But in spite of slow decompression we often found that our urine was still supersaturated as we came out of the chamber. A certain

amount of supersaturation is not dangerous. The colloidal nature of the blood prevents the bubbles of nitrogen from forming easily. To demonstrate the bubbling off of nitrogen on rapid decompression, I spread the web of a frog's foot or a bat's wing over the glass window of the small pressure chamber. The circulation of the blood is projected on the screen with the aid of a microscope and an arc light, and we are able thus to observe the circulation under 20 atmospheres of air pressure and to watch the bubbles forming in the capillaries on rapid decompression. We are able to see that recompression diminishes the size of the bubbles and finally drives them back again into solution. When the larger mammals, such as cats and dogs, are exposed to the high pressure of, say, 8 atmospheres for an hour or so and are then decompressed in a few seconds, they die in one or two minutes. On the other hand, small mammals, such as mice and rats, may escape owing to their small bulk and to their rapid respiration and circulation. The heart of a mouse may beat 700 times per minute as against our own 70. Paralysis in the limbs follows too rapid decompression, or the animals fall over and become unconscious. The gurgling of gas bubbles in the heart may be heard, respiration becomes embarrassed, and the animals die. On dissection the peritoneal cavity may be found distended with gas, or the gas may be confined to the stomach and intestines. Some of the gas rises in the fermentative processes of digestion and from air swallowed during compression. Such gas may possibly be the starting point for the setting free of bubbles in the blood, and it is therefore important that men suffering from

flatulence should not work in high pressures. The vessels, both arteries and veins, may show chains of bubbles, as exemplified in the photograph I am able to produce of the coils of the intestines and the mesenteric vessels. The bubbles are seen in the fat, the joints, the veins of the brain, etc., and the coronary vessels. The right side of the heart itself may be distended with them. The gas in the heart produces embolism of the pulmonary vessels, obstructs the circulation, and brings about sudden death. In the larger animals, when decompressed from eight atmospheres in five seconds, we have found the cells of the liver, kidneys, etc., vacuolated or even burst with bubbles. We have collected gas set free in the heart, and found about 80 per cent. of it to be nitrogen. The bubbles may take a long time to form, and if they form only in the fat and veins and in such organs as the liver they may do little harm, but if they are swept on into the heart and pulmonary circulation or enter the arterial system and block up the vessels of the brain and spinal cord, then it is manifest that the symptoms will be grave.

Among caisson workers some are affected and others not, and immunity is not given by continued work in compressed air. We may look for the explanation in such phenomena as the varying state of the blood, the varying vigour of the circulation and respiration which are affected by fatigue and by vasomotor changes during compression when the air is chilled, fermentative processes going on in the alimentary tract, and the relative

amount of fat in the individual. A young man in perfect health, wiry, small, and spare, with powerful heart and deep respiration, can expel the dissolved nitrogen from his lungs far more readily than the old, the intemperate, the stout, and those who are over-fatigued by excessive labour. The records of caisson workers show that men under 20 generally escape, and that the percentage of cases is highest for men over 40. The longer the shifts the more complete the saturation of the body, and the higher the pressure the greater will be the risks and the gravity of the symptoms. The men who work the airlocks and, in passing material through, undergo frequent but brief compression and decompression are not affected. The records show that practically no cases occur at a pressure below 2 to 2½ atmospheres absolute.

Fig. 10.—Section through wall of bronchial tube and pulmonary alveoli. Showing inflammation produced by exposure to four atmospheres of oxygen.

Much has been made of the impurity of the air—in particular of the percentage of carbonic acid—as a contributory cause of caisson sickness. The ventilation of the tunnels built by the London County Council under the Thames has been carried out at an increased and, in my opinion, needless expense in order to keep the carbonic acid percentage down to a very low level. Recently I have carried out many experiments on ourselves and on students, who have been sealed up in a small air-tight chamber, and I have found—like Fluegge and his school in Germany and Haldane in this country—that it is the heat, moisture, and stillness in the air which cause discomfort and fatigue, and not excessive CO₂, deficiency of oxygen, or any supposed organic poison in the air breathed. There is no evidence standing the criticism of investigation to prove, or even to make it likely, that there is any organic chemical poison exhaled in the breath. In the absence of any toxic gases, such as an escape of coal-gas or other trade product, the problem of ventilation becomes a question of movement, heat, and relative moisture of the air. It is these latter qualities of the air which affect the skin and respiratory tract, and, through their influence upon the vast area of cutaneous nerves, give us feelings of comfort or discomfort. In open-air treatment the coolness of the air and its movement are the essential qualities which promote health by stimulating activity and metabolism and the nervous well-being of the body. Hot, moist air causes fatigue by taxing the cooling mechanism. Blood which might be going through the viscera, muscles, and brain is sent to the skin to be cooled. A rapid heart-beat has to be maintained, and this fatigues the heart.

The fatigue, increased by a hot, moist atmosphere, makes greater the danger of decompression. Heat causes more blood to come to the skin and brings about a more complete saturation of the subcutaneous fat with nitrogen. The cold in the decompression chamber, due to the expansion of the air, causes vaso-constriction, impels the blood from the skin, and stops its desaturation. The money spent on excessive ventilation really raises the heat of the caissons, for compressed air is heated by the compression, and it would be better spent in the cooling of the caissons. To secure efficient work the wet bulb temperature should be kept below 70° F. The men should not pass from a warm caisson to a cold air-lock and a cold outer world. They should go through a warm air-lock to a warm room. An excess of CO₂ in the air-lock or diver's helmet during decompression—by "excess" I mean 2 or 3 per cent. of an atmosphere—is favourable, as it increases pulmonary ventilation and the out-breathing of nitrogen. The safety of compressed air workers depends upon the relation of the period of decompression to that of compression. The proper periods of compression and of decompression have been worked out in an extensive series of experiments on goats by Haldane, Boycott, and Damant, and on pigs and goats by Major Greenwood and myself. We chose the pig as being in shape, diet, and habit of body—and perhaps in habit of mind!—more like to man than the goat. The Admiralty now use a table regulating the descent, working period, and decompression of the diver, which is based very largely upon experiments on animals, and the use of this table has prevented all serious accident. The decompression periods given in this table can be shortened considerably if active exercise is taken, for by this means the ventilation of the lungs and the rate of the circulation can be increased, perhaps, by six times. When

Table showing Dissolved Gas in Urine when (1) Air, (2) Oxygen, was breathed during Decompression.

I. Breathed air at 3 atmospheres. After 15 minutes emptied bladder. Sample I collected 7 minutes later at 3 atmospheres. Decompressed to 1½ atmospheres in 3 minutes. Sample II collected 6 minutes later at 1½ atmospheres. Decompressed to 1 atmosphere in 3 minutes. Sample III collected 3 minutes later at 1 atmosphere.

	Nitrogen.	Oxygen.	Pressure Atm.	Nitrogen calculated (0.85 per atm.)
Sample I	3.04	0.151	3	2.55
Sample II	2.850	0.144	1½	1.416
Sample III	1.609	0.81	1	0.85

II. At 3 atmospheres for 44 minutes. Empty bladder and breathed oxygen for 9 minutes, then took sample I. Decompressed to 1½ atmospheres in 2 minutes. Took Sample II 4 minutes later. Decompressed to 1 atmosphere in 1½ minutes. Took Sample III 5 minutes later.

	Nitrogen.	Oxygen.	Pressure Atm.	Nitrogen calculated.
Sample I	2.691	0.297	3	2.55
Sample II	0.8835	0.1885	1½	1.416
Sample III	0.551	0.0911	1	0.85

doing hard work in the caisson a man rapidly saturates himself with nitrogen, and it is very disadvantageous that he should sit quietly in a cold air-lock during decompression, with heart and respiration working at low level owing to fatigue. By arranging air-locks so as to give staged decompression, and making the men climb out of the tunnel from one air-lock to another, they can be made to do hard work, and the work itself helps to wash the nitrogen out of their bodies, and thus very greatly increases the safety of decompression.

Another means by which the decompression period can be shortened with safety is by the breathing of oxygen. If oxygen is breathed at the full pressure just before decompression there will be a vacuum for nitrogen in the lungs, while the pressure will prevent any bubbles of nitrogen from forming in the tissues. Unfortunately, high pressures of oxygen act as a poison. Four atmospheres of oxygen convulses animals in from 30 to 60 minutes, and causes inflammation of the lungs. Bornstein and other engineers have breathed oxygen for 30 minutes at a pressure of 3 atmospheres. Such a period is the limit of safety. Oxygen can be breathed economically by means of the Siebe Gorman apparatus for use in mines, and I demonstrate this apparatus in use this evening. At the Howe Bridge rescue station squads of miners are trained in its employment, and the efficiency and utility of the dress was fully demonstrated in the recent great colliery explosion at Bolton. J. F. Twort and I have investigated the effect of the breathing of oxygen on the volume of nitrogen dissolved in the urine. Precautions were taken to collect the urine without contact with the atmosphere. A large quantity of water was drunk so that samples of urine could be collected every seven minutes or so. The oxygen apparatus was taken

into the chamber and the oxygen breathed at 3 atmospheres of pressure just before and during decompression. Our results show that while the urine is supersaturated after decompression in twelve minutes when no oxygen is breathed, it is under saturated after the breathing of oxygen.

It may be possible in deep-sea diving work, as in the pearl fisheries, so to arrange a supply of hydrogen and oxygen that the diver may breathe such a mixture during decompression in great depths. As he comes nearer to the surface the hydrogen supply will be cut off, and he will be given oxygen only. The hydrogen is used to prevent oxygen poisoning (v. Schrötter). The ideal method for safe decompression in high pressures, which has been worked out by experiments on animals, is rapid decompression to some two atmospheres of pressure, and then a pause, during which oxygen is breathed and exercise taken, followed by gradual decompression to one atmosphere, while oxygen breathing and exercise are continued.

Paul Bert proved that the one method of cure for the illness is recompression. Caisson workers suffering from "bends" have found relief by going back under pressure. Recompression chambers or medical locks are now instituted at all large caisson works. Experiments on animals show that recompression must be applied very quickly in dangerous cases before vital parts are killed by the interference of the bubbles with the circulation. "Bends" may be relieved hours, or even days, after they have come on. Recompression cured 90 per cent. of the cases

Fig. 11.—Diving bell with air-lock for decompression of divers.

in the East River tunnel, and all but 0.5 per cent. were partly relieved by this means. Oxygen breathing can be employed with advantage in a medical lock. Decompression from the medical lock after the cure is effected must be very slow, for some of the bubbles, having run together to form larger bubbles, only shrink on recompression, and do not quickly go into solution. These may expand again on decompression. For deep-diving work a recompression chamber should be at hand. I have contrived a double-chambered diving-bell, one chamber being open to the sea and the other closed save for a man-hole communicating with the first. The divers, after completing their work, enter the inner chamber and close it, the bell is raised on deck, and the man is decompressed a stage further. Such a contrivance prevents exposure to the cold during slow decompression in the ordinary way when the diver climbs a shotted rope. It also eliminates the risk of the prevention of gradual decompression by bad weather.

I hope that I have now given you sufficient details of these researches to make it clear that the workers on this subject in this country and abroad have done much to perfect a safe method of carrying out work in compressed air by scientific investigations carried out on animals, and that the fruits of their labours have a great economic importance. A full account of these researches and of work in compressed air will be found in my book on caisson sickness, now in the press (Arnold).