The Physiology of Life in the Andes.[1]

By J. BARCROFT, C.B.E., F.R.S.

THE recent expedition to Peru was initiated under the auspices of the Royal Society. So far as the British members were concerned, it was financed in part by a grant made by that body, in part by two substantial private subscriptions from Sir Robert Hadfield, then on the Council of the Royal Society, and Sir Peter Mackie, who has on previous occasions been a staunch supporter of anthropological research undertaken by the Royal Society. In part also its expenses were met by grants from the Moray and Carnegie funds in Edinburgh. These grants paid some of the expenses of the expedition as a whole, together with the personal expenses of three of its members—namely, Dr. J. C. Meakins, professor of therapeutics in Edinburgh; Mr. J. H. Doggart of King's College, Cambridge; and myself. The project was warmly supported by a number of institutions on the American continent, each of which sent a member of the party at its own expense. Harvard Medical School was represented by Dr. Bock, Dr. Forbes, and jointly with Toronto Medical School by Prof. Redfield; the Presbyterian Hospital, New York, by Dr. George Harrop; and the Rockefeller Institute by Dr. Carl Binger. The American and British parties sailed from New York and Liverpool respectively in the middle of November, the American section arriving in Peru a fortnight or more before we did.

I have perhaps given the impression that the party consisted of two sections from different continents, sharply marked off from one another, and neither of which had seen the other before. This impression is erroneous, for the whole idea of the expedition grew from the fertile soil of collaboration in the researches carried out under a single roof. Dr. Redfield and Dr. Bock had been working in Cambridge (England) throughout the previous year, and Dr. Harrop had been there for a short time. There the scheme had been hatched, the methods standardised, and a number of the controls carried out.

Why did we go to Peru, or, more precisely, to Cerro de Pasco? The question may most easily be answered by comparing Peru with some of the other localities to which we might have gone, and to which others have gone before us; for example, Monte Rosa, Pike's Peak in Colorado, the Peak of Teneriffe, and the Himalayas. Without going at length into the merits of each, the advantages of Peru will be sufficiently apparent if I compare it to one of the above, and I will select one of which I have personal experience, namely, the Peak of Teneriffe. Peru and Teneriffe have in common the merit of being close to the sea. In either case the baggage can be put on board at Liverpool or Southampton and taken to your mountain base without further transhipment. Peru, however, possesses the first necessity of laboratory equipment—an abundant supply of water—up to a height of 16,000 ft., *i.e.* 4000 ft. higher than the Peak. In the latter place the highest altitude at which I know of water is 7000 ft., while at 11,000 ft.—near the situation of the Alta Vista hut—there is an ice-cave from which water may be obtained by melting the ice.

Again, the conditions of transport are vastly different in Peru from what they are in Teneriffe. In Teneriffe everything goes up the mountains by mule. The amount of apparatus which can be taken up is therefore small; and if it arrives whole at its destination the worker is fortunate. If it arrives broken, there is little hope of mending it. We were very fortunate, at an early stage of our preparations, in getting in touch with Mr. Oliver Bury, the chairman of the Peruvian Corporation. The Peruvian Corporation owns, among other railways, the trunk line which goes directly inland from Lima, climbs the Andes to a height of almost 16,000 ft., and then drops down to Oroya (12,000 ft.), situated on the pampa between the two parallel ranges of the Cordilleras. From Oroya railways run north to Huancayo, and south to Cerro de Pasco (14,200 ft.), which place was to become our principal seat of operations. To the Peruvian Corporation we owe our laboratory. For the purpose we were assigned a luggage van, 45 ft. in length, together with a goods van which we used as a store; and these they offered to take to any locality on their system at which we desired to work. While the American members of the party awaited our arrival at Lima, they fitted up the luggage van and made a very fine laboratory of it. At one side the door was closed up and windows put in its place, benches and shelves were fitted, electrical wiring was installed, and ultimately we had electric light, power, and heat. What greater contrast in efficiency could exist than between our mobile laboratory at Cerro, jacked up off the bogies to prevent vibration, fitted with X-ray plant and apparatus for the measurements of hydrogen ions, on one hand, and the Alta Vista Hut in Teneriffe, with its paraffin stoves which emitted little but smuts and barely sufficed to melt a few handfuls of ice. Of more account, however, than all these advantages was the fact that, up to an altitude of 16,000 ft. in Peru there is a population most of which is connected with the mining industry. This population may be divided into two categories, namely, the Anglo-Saxon officials and the native labourers. The latter are of Indian descent, and as a race have lived at this altitude for many generations. In Cerro they are designated "Cholo," a name that has no exact anthropological significance, but I shall use it and so avoid an assumption of anthropological knowledge which I do not possess.

To judge from the customs which prevail in the outlying villages, the Cholo is not far removed from a very primitive civilisation. Within a mule-ride of Gollarisquisga there are communities in which private ownership of land does not exist; the land, as in some of the Russian communities which are, or were, on the Canadian prairie, belongs to the village. The produce, if the village is small, is placed in the church; in the larger villages there is a store for this purpose. If the stock of some commodity has run out, some person goes to such a market as Huancayo and buys some more, not for himself, but for the village. I said "buys"; but there are places to which money has scarcely penetrated, and where the exchange of commodities is still a process of barter. The condition of medical science in these villages may be gathered from the fact that such

[1] From a discourse delivered at the Royal Institution on Friday, June 9.

nostrums as horse-dung and well-kept human urine occupy an honourable place in the pharmacopœia, and that a custom appears to linger by which, when the practitioner has done his best—or worst—and failed, the services of another official are called in. He is the "despenador" or "putter out of pain." I need say no more of his or her duties than to give the following quotation from Bensley's "Spanish and English Dictionary": "Despenadora—a woman who is supposed to push her elbow into the stomach or breast of dying persons to relieve them from agony."[1]

It seems clear then that the Cholo, not the Cholo of Cerro de Pasco or Oroya, but of some of the far outlying districts, has been little touched by the Spanish or even the Inca civilisation, and that in him we have a subject for physiological research whose like has varied little for generations. In physique he is short in stature and sallow, or with some blood in his cheeks. That part of his anatomy which was principally of interest to our party was his chest. We made a considerable number of chest measurements. As regards the chest circumference the following statement sums up our findings. We based our measurements on Prof. Dreyer's tables, accepting his estimate of the normal ratio between the trunk length and the chest circumference. We ascertained that the average circumference of the Cholo chests which we measured would normally be 79 cm. It was, in point of fact, 92 cm. As a rough check we measured our own trunk chest ratios and those of the American and British engineers, a community of fine physical development. The circumference of the Anglo-Saxons was little in excess of Dreyer's estimate. The lowest level at which we came across one of these small people with chests which appeared out of proportion to the rest of his stature was at Matucana (8000 ft.), and on inquiry we found that he was a native of Huancayo (12,000 ft.).

To pass to the more strictly physiological aspects of the work of the expedition, one must reflect that the desire to investigate mountain sickness goes back at least to the middle of the last century. It is remarkable, when one comes to think of it, how recently our knowledge of the causation of disease has grown. The lure of mountain sickness to the physiologist lay originally in the fact that it was a disease to which a definite cause could be assigned. You go a certain height up the mountain—any mountain—and when your ascent corresponds to a given fall in the barometer you suffer from mountain sickness; when you descend, the malady leaves you. Mountain sickness, or as it is called in Peru, "seroche," seemed to form a sort of opening into the ætiology of disease.

In recent years the centre of interest has to some extent shifted. The cause of mountain sickness is universally regarded as insufficient oxygen supply to the tissues of the body, though there may still be some doubt as to the directness of the connexion between the deficiency of oxygen pressure in the blood and the activity of the nerve cells responsible for the continence of food in the stomach. Interest latterly has centred rather around the methods which the body has at its disposal for adapting itself to such a condition. But the same thread still runs through the fabric; this particular instance of adaptation to environment is studied because our knowledge of the conditions with which the body has to deal are so exact and the conditions themselves so easily produced or abolished.

Partly, of course, it has another interest, namely, that imperfect oxygenation of the blood is a factor in a number of pulmonary complaints and an analysis of those complaints demands an investigation of this particular factor. That is the definitely medical aspect, of which I shall say but little. Rather I shall turn my attention to the extent to which adaptation can take place, and the means by which it is brought about.

Some of the Cholos appear at first sight to have acquired an astonishing capacity for physical effort at high altitudes. An example may be cited. Near Cerro de Pasco there is a mine worked in the old Spanish way. The ore is raised from the bowels of the earth on the backs of porters, who carry their loads up a rude staircase. The mine is about 250 feet below the surface, and the staircase about 650 feet in length. It opens under a sort of hut. The first porter whom we saw emerge was a little fellow, who said that he was ten years old. We so far doubted his word as to place his age at thirteen or fourteen years. He had on his back a load of ore which I estimated at 40 lbs.—and that at an altitude at which the barometer stood at only 458 mm., or about 18 inches. Shortly a more mature boy appeared—perhaps seventeen or eighteen years of age—his load was about 100 lbs. To understand these feats, it must be remembered that exercise may be of two kinds, spasmodic or continuous. In the case of continuous exercise, such as that of long-distance running, the subject must maintain an approximate equilibrium between the oxygen which he uses and that which he absorbs. His oxygen account must, so to speak, balance approximately at any given time. In the case of spasmodic exercise it is otherwise. If the subject is prepared for the exercise to cease after a very short time, he may expend oxygen at a greater rate than he takes it in, and thus overdraw his oxygen account. A limit is, however, set to the overdraft, and when that limit is reached he must rest till his oxygen account has righted itself. This formed the subject of a most interesting investigation carried out by Dr. Lupton recently in the laboratory of Prof. A. V. Hill. The porters in the old Spanish mine raise their loads by a series of spasmodic efforts, each of which is followed by a rest of considerable length accompanied by great respiratory distress.

Of the means by which the body acclimatises itself to oxygen want, real or alleged, we investigated the following:

1. *Secretion of oxygen by the pulmonary epithelium.* Numerous direct estimations were made of the oxygen pressure in the arterial blood, and in the alveolar air. The two usually came out within two or three millimetres of one another, which is approximately the experimental error of the method. Such a coincidence can only mean that the oxygen passes into the blood by a process of diffusion through the very attenuated partition of epithelium which separates the air from the blood in the lung. Thus the view that the lung could enable the body gradually to overcome the effects of altitude by creating a sort of forced draught

[1] I am indebted for this quotation and much else to Mr. Murdock, manager of the coal mine at Quishuarcancha.

and maintaining the oxygen pressure in the blood at its sea-level value is unfounded.

However, the blood as it leaves the lung must contain appreciably less oxygen than its hæmoglobin would normally absorb. It is, to use the American phrase, *un*saturated to a considerable degree. Such blood, of course, would lack the bright scarlet colour of true arterial blood. The actual colour of the blood as withdrawn from the radial artery entirely bore out this view; as it flowed into the syringe it was of a dull red colour often verging on chocolate, and in the case of the natives was 82-86 per cent. saturated with oxygen, instead of 95-96 per cent. as at the sea level.

Curves giving the relation between the percentage saturation of the blood and the partial pressure of oxygen in lungs at Lima and Cerro de Pasca for different members of the party are shown in Fig. 1, from which it is apparent that at high altitudes the partial pressure required to secure a percentage saturation sufficient for life decreases considerably.

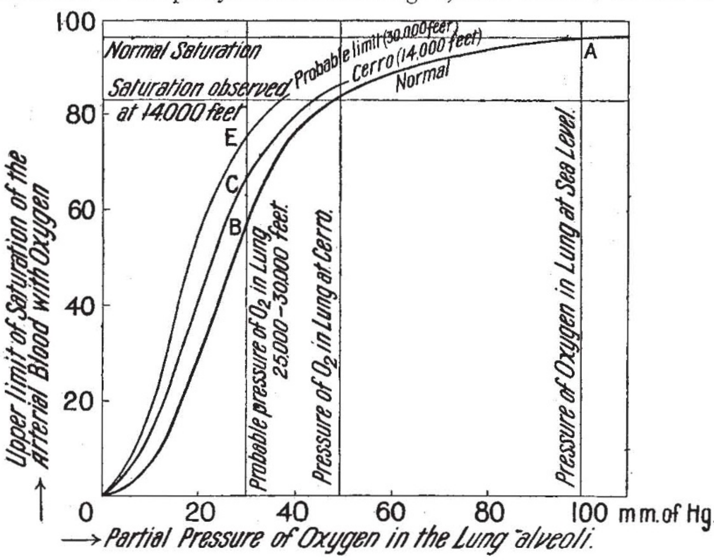

FIG. 1.

The establishment of the fact that life can be supported with some degree of efficiency with the blood in this condition is of great importance, because in recent years there has been a tendency to assume that a small degree of unsaturation of the arterial blood must of necessity produce very grave results. Fig. 1 shows that there is some adjustment of the blood to the new conditions. At Cerro the unsaturation of the blood was written on the faces of the inhabitants. Any one who had any colour in his face was appreciably cyanosed.

2. *Increased pulmonary ventilation* has been shown by all recent observers to be of great importance as a factor in adaptation to high altitudes. In our case, had our respiration been the same in rate and depth at Cerro as it was at Lima we would have had about 40 pressure mm. of carbonic acid and 35 mm. pressure of oxygen in the air of our lungs. In fact, owing to increased respiratory effort, we reduced the carbonic acid to about 25 mm. and raised the oxygen to about 52 mm. The importance of these facts is enhanced by the certainty that it is the partial pressure of oxygen in the alveolar air which regulates the degree of saturation of the blood.

While the increased ventilation of the lung had been demonstrated by previous observers, the mechanism which was responsible for it had been much in dispute. This we investigated. The mechanism of hypernœa *at rest* seems to be that first suggested by Haldane, namely, that the want of oxygen heightens the activity respiratory of the respiratory centre, resulting in a mild degree of forced respiration—so mild as not to be apparent to the subject, yet sufficient to reduce the carbon dioxide content of his blood. Incidentally this process acting alone would make the blood more alkaline. The measurements of hydrogen ion concentration in the blood of persons at rest bore out this view; either the blood was more alkaline than at sea level, or it was of approximately the same reaction.

The effect of exercise on the blood has been more fully investigated, though for the most part by indirect methods. Our results support those already obtained, namely, that a given increment in the hydrogen ion concentration of the blood is produced by less exercise at high altitudes than at the sea level. Thus the dyspnœa of exercise is the cumulative effect of two factors—an increased response of the respiratory centre to a given stimulus, and an increase in the stimulus evoking the response.

3. I have already alluded to the size of the Cholos chest. With it appears to be associated an interesting modification of its configuration. Fig. 2 shows two X-ray photos of the left sides of two chests photographed from behind. Both pictures were made at Cerro de Pasco. That on the right is my own, and is fairly typical of our party; that on the left is a typical Cholo chest. There is a marked difference in the angle at which the ribs are carried; my own slope down from the vertebral column at a quite considerable angle, while those of the native are much more horizontal. It seems highly probable that this horizontal carriage of the ribs indicates a compensatory effort designed to increase the facility with which the blood obtains oxygen, for it is acquired at sea level by persons suffering from emphysema and other complaints in which there is shortness of breath. Several of the mining engineers, of whose chests we took radiograms, showed a similar tendency. At this point another peculiar physical conformation may be mentioned, namely, clubbing of the fingers, which, when found at sea level, is frequently associated with some trouble which prevents sufficient oxygen from reaching the extremities. Though they are not the rule, clubbed fingers are by no means unusual at Cerro de Pasco in persons without any circulatory or respiratory lesion.

4. An increase in the number of red blood corpuscles in each cubic mm. of blood has long been known to occur at high altitudes. Systematic researches carried out principally under the direction of Dr. Haldane have shown that the increase in the number of red blood corpuscles is associated with an increase in the quantity of hæmoglobin present. These two observa-

tions we have verified, and to them have added a third, namely, that the chemical conditions under which the hæmoglobin is held in the red blood corpuscle confer on it the peculiarly useful property of acquiring more oxygen when exposed to rare atmospheres than is the case with normal blood.

5. We sought in vain for any such form of acclimatisation as might be afforded by the driving of an increased volume of blood round the body in unit time. A rather natural supposition would be that, if the hæmoglobin of each cubic centimetre of blood were deficient in oxygen, the tissues might be fed with sufficient oxygen by the simple process of giving them more blood; but this is not so. It is true the heart quickened with exercise, but the quickening seems to have been rather a signal of distress than a compensatory mechanism.

Three principal forms of compensation have been described: they are increased total ventilation, increased expansion of the chest, increased hæmoglobin, and increased affinity of the blood for oxygen; their relative importance is a matter for future research. Jointly or severally they may mitigate the effects of oxygen want, but they cannot entirely abolish them; at some altitude the human frame must always succumb. We were naturally somewhat interested in the question of whether we could foretell which of our own party would succumb most quickly, and various members of the party worked out systems of prophecy which differed not only in character but in the prophetic order in which the various individuals would prove susceptible to altitude. One of these proved quite successful. It was based on the determination of Bohr's diffusion constant (the ratio of the quantity of oxygen absorbed per minute to the average difference of pressure between the oxygen in the alveolar spaces and alveolar capillaries) for the lung, and was suggested by Prof. Krogh. The members of the expedition could be divided into two distinct groups—those who had a constant for oxygen of more than 40 and those who had a constant less than that figure. One group with the higher diffusion constant suffered from obvious symptoms of mountain sickness, while the other did not. It is true that of the four who suffered the salient feature was different in each case: in one it was faintness, in another vomiting, in a third high temperature and intense headache, and in the fourth deafness and indistinct vision. Only further research can show whether the coincidence was fortuitous, or whether any causal relation exists between the diffusion constant and the tendency to "seroche." The hint, however, seemed to be worth taking, and in consequence an arrangement has been come to by which persons intending to go to the mining districts in the Andes are being tested in the Rockefeller Institute in New York.

I must also make some allusion to the goodwill which was extended to us by every one with whom we came in contact in Peru, from the President down to the humblest employee of the Cerro de Pasco Copper Corporation. Of the manager and the officials of this company we can only say that their kindness in placing themselves and their resources at our disposal was one of the most potent factors in enabling us to achieve such scientific results as we obtained. No less can be said of the officials of the Pacific Steam Navigation Company.

The problem of Everest from the point of view of physiology, upon which our work in the Andes throws some light, may be stated thus:

Every cubic centimetre of arterial blood which leaves the lung must contain a certain quantity of oxygen, expressed as a percentage of the maximum which the blood can hold, if life is to be maintained at a level consistent with any degree of efficiency. It is not known what this quantity of oxygen may be. The following considerations, however, give some clue to it:

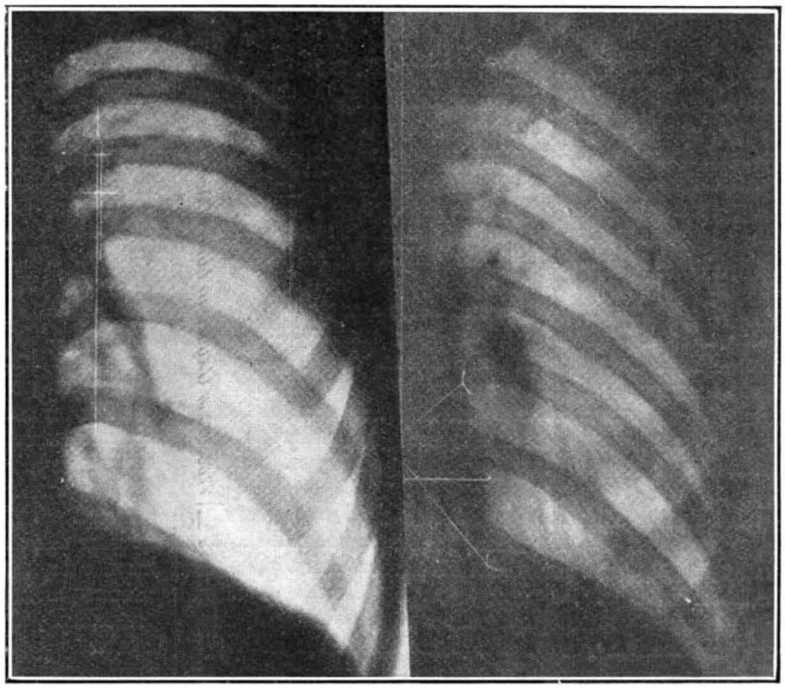

FIG. 2.

(*a*) Let the maximum quantity of oxygen (shown on the ordinate of the graph in Fig. 1) which the blood can hold be called 100.

(*b*) There is a certain relation in the blood for normal persons between the amount of oxygen it can hold and the pressure of oxygen to which it is exposed; that relation is shown in the graph labelled "normal." (The partial pressure of oxygen forms the abscissa.) At the sea level the oxygen pressure in the lung is about 100 mm. and the quantity of oxygen in the blood 96 per cent. of the possible load. (See the point A on the graph.)

(*c*) Until recently it was supposed that the curve did not alter, and therefore the graph labelled "normal" stood for all altitudes.

(*d*) Also the most competent authorities regarded an oxygen load of about 90 per cent. of the possible maximum as being required for the conduct of life—apart from short exposures.

(*e*) The probable partial pressure of oxygen in the lungs at 25,000-30,000 feet is calculated by a process of exterpolation to be about 30 mm. Combining *c*, *d*, and *e* above, the quantity of oxygen in the arterial blood on Everest would be 58 per cent. of the maximum—far below that necessary.

(*f*) The recent expedition to Cerro de Pasco has brought out two new points:

(1) That natives lead a reasonably normal existence with blood charged only up to 82 per cent. of the possible, and Europeans with 85 per cent. of the possible, load of oxygen.

(2) That the graph changes in position, and for natives and Anglo-Saxons approximates to that labelled Cerro (14,000).

(*g*) On this graph a partial pressure of 70 mm. of oxygen in the lung might saturate the blood up to 67 per cent. (*c*).

(*h*) It is scarcely likely that the curve moves further than that marked "Probable limit (30,000 ft.)." On that curve, however, the blood would be charged up to 76 per cent.—a figure within a reasonable distance of what has actually been observed in the Andes.

Obituary.

H.S.H. PRINCE ALBERT OF MONACO.

NOT infrequently in the past have princes and nobles been munificent patrons of science and played a useful part in promoting the advancement of knowledge—would that we had more such at the present day—but it must be rare indeed for a reigning prince to attain recognition and distinction as a practical, working, man of science. The late Prince of Monaco, whose death took place recently, was both. He has given to France and the world of science at least three research institutions of first-rate importance, and throughout many years of his life, during the last half-century (since, in January 1873, on one of his early expeditions he met the *Challenger* at Lisbon), he has himself planned and carried out many notable investigations in both physical and biological oceanography.

His Serene Highness Prince Albert Honoré Charles, a descendant of the ancient House of Grimaldi, was born in 1848, and succeeded his father, Prince Charles III., as ruler of the principality of Monaco in 1889. In his early youth Prince Albert served as lieutenant in the Spanish Navy, and since then has shown a life-long devotion to the sea and a rare enthusiasm for its scientific exploration. Probably the most characteristic representation of the Prince is the statue in the entrance hall of the Museum of Oceanography at Monaco showing him in plain sailor's uniform standing at the rail on the bridge of his yacht. He must have spent a large portion of his life, and much of the ample funds at his disposal, in the many expeditions which he conducted in the successively larger and more perfectly equipped yachts *Hirondelle* (a 200-ton schooner) and the first and second *Princesse Alice*—the last a magnificent ocean-going steamer of 1420 tons, built by Lairds' on the Mersey in 1898, and fitted with all necessary machinery and apparatus for every form of modern oceanographic research, and for the capture of whales. By means of these vessels the "Gulf Stream" in its various parts, and its effect on the coast of France, the Azores, the seas around Spitsbergen, the Mediterranean, and much of the Atlantic from the equator to within the Arctic Circle, were systematically investigated in both their physical and their biological characters. Among his companions and assistants on these expeditions have been Baron Jules de Guerne, Dr. Jules Richard, and occasionally our own countrymen Mr. J. Y. Buchanan and Dr. W. S. Bruce; and the results of more than thirty annual cruises have been made known to science first by the Prince's preliminary reports in the *Comptes rendus*, and later, in full detail, in those beautifully illustrated, sumptuous memoirs in the series entitled "Résultats des Campagnes Scientifiques accomplies sur son Yacht par Albert I[er] Prince Souverain de Monaco," dating from 1889, and the later series of the Bulletins and the "Annales de l'Institut Océanographique."

It is chiefly in connexion with the devising of apparatus for deep-sea research, and with the introduction of new methods of investigation, that the Prince's personal influence was felt on his expeditions. Among other new appliances which have yielded notable results may be mentioned his huge baited traps (the "Nasse"), his various types of trawls and nets for use in different zones of water, and his use of submarine electric lights to attract free-swimming animals with power of vision, such as fishes and Crustacea. There can be no doubt that his practical knowledge as an experienced sailor and as a mechanical engineer has added greatly to the efficiency and success of all his work on the yachts. His chief assistant, Dr. Jules Richard, who has charge of the museum and laboratories at Monaco, gave full descriptions and useful illustrations of many of these appliances for oceanographical investigation in a special volume of the Bulletin series that was published about 1900.

All the Prince's successive voyages have been very fruitful of scientific results, and biology owes its knowledge of many deep-sea Atlantic animals to the special memoirs issued from the Monaco Press; but none of these have been more remarkable, novel, and almost sensational, than the results of the Prince's whale-fishing expeditions, when he obtained the more or less perfect remains of various new, and in some cases gigantic, cuttlefishes (such as Lepidoteuthis and Cucioteuthis) from the stomachs of captured sperm whales. Some account of these discoveries and exploits, and of Homeric combats when, for example, three huge killer-whales attacked one of the boats and tried to crush it between their bodies, and again when a large Cachalot died under the keel of the yacht which