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Robert Boyle's landmark book of 1660 with the first experiments on rarified air

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West, John B. Robert Boyle's landmark book of 1660 with the first experiments on rarified air. *J Appl Physiol* 98: 31–39, 2005; doi:10.1152/japplphysiol.00759.2004.—In 1660, Robert Boyle (1627–1691) published his landmark book *New Experiments Physico-Mechanicall, Touching the Spring of the Air, and its Effects* . . . in which he described the first controlled experiments of the effects of reducing the pressure of the air. Critical to this work was the development of an air pump by Boyle with Robert Hooke (1635–1703). For the first time, it was possible to observe physical and physiological processes at both normal and reduced barometric pressures. The air pump was described in detail, although the exact design of the critical piston is unclear. Boyle reported 43 separate experiments, which can conveniently be divided into 7 groups. The first experiments were on the "spring of the air," that is the pressure developed by the air when its volume was changed. Several experiments described the behavior of the barometer invented by Torricelli just 16 years before when it was introduced into the low-pressure chamber. The behavior of burning candles was discussed, although this emphasized early misunderstandings of the nature of combustion. There were some physiological observations, although these were later extended by Boyle and Hooke. The effects of the low pressure on such diverse physical phenomena as magnetism, sound propagation, behavior of a pendulum, evolution of gases from liquids, and the behavior of smoke were described. This classic book is brimming with enthusiasm and fresh ideas even for today and deserves to be better known.

air pump; vacuum; mercury barometer; pressure-volume behavior; respiration; combustion

IN THE HISTORY OF THE PHYSIOLOGY of high altitude, Paul Bert's book *La Pression Barométrique* (2) stands out as a watershed contribution. This contained the first definitive demonstration that the deleterious effects of high altitude were due to the low partial pressure of oxygen, whether this was caused by a reduction of barometric pressure or a reduced oxygen concentration at normal pressure. As a result, Bert is often rightly referred to as the father of high-altitude physiology.

However, some 200 years before the publication of *La Pression Barométrique*, there was another landmark book in high-altitude studies. The author was Robert Boyle (1627–1691) and the full title was *New Experiments Physico-Mechanicall, Touching the Spring of the Air, and its Effects (Made, for the Most Part, in a New Pneumatical Engine) Written by Way of Letter to the Right Honorable Charles Lord Vicount of Dungarvan, Eldest Son to the Earl of Corke* (3). The importance of this book was that it described the first controlled experiments of the effects of reducing the pressure of the air. The book was not limited to physiology, and in fact this topic occupied only a small portion of the text. But the book was so innovative and stimulating, and such a joy to read, that it deserves to be better known by physiologists.

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THE SETTING

It is interesting to trace the events leading up to the work described in Boyle's book partly because of the great rapidity of progress over a period of less than 20 years. The crucial breakthrough was made by Evangelista Torricelli (1608–1647), who in 1643 invented the mercury barometer. He took a long glass tube, which was closed at one end, filled this with mercury, put his thumb over the open end, and inverted the tube in a dish of mercury. The level of the mercury in the tube fell to ~76 cm, and the nature of the space above it, which we now know as a vacuum, was a topic of great controversy. Torricelli recognized that the column of mercury was supported by the pressure of the atmosphere acting on the surface of the mercury in the dish, and in his letter to Michelangelo Ricci in 1644 he made the dramatic statement that "We live submerged at the bottom of an ocean of the element air, that by unquestioned experiments is known to have weight" (19). This concept was a major breakthrough in an area that had caused much confusion in the past, and, for example, even the great Galileo only some 6 years before was confused about the reason why a suction pump could only raise water ~9 m. The explanation he gave was related to the presumed tensile strength of water (14).

Torricelli's simple but dramatic experiment resulted in a flurry of activity over the next 16 years. In 1648, Blaise Pascal (1623–1662) persuaded his brother-in-law Florin Perier to take a Torricellian barometer up the Puy de Dôme outside Clermont in the center of France, and, as expected, the level of the mercury fell because, on the top of the hill, the pressure of the atmosphere was less. A major advance was then made in 1654 by Otto von Guericke (1602–1686) when he constructed an air pump and demonstrated to the Diet of Regensburg that it was possible to reduce the amount of air in a glass vessel. However, his most famous experiment took place in 1657 when two metal hemispheres were constructed so that they fitted accurately with an airtight seal. When the air was pumped out of these, two teams of eight horses each were unable to break the seal. This was a very colorful demonstration of the enormous force that could be developed by atmospheric pressure.

Boyle learned of Guericke's experiments from a book written by Gaspar Schott in 1657 (17), but he soon realized that Guericke's apparatus had two serious deficiencies. The most important was that the hollow vessel that was evacuated could not easily be opened, and therefore it was impossible to put anything inside it. Because Boyle intended to compare the behavior of various processes both in rarified and normal air, this design was inadequate. Another problem was that Guericke's pump was so inefficient that it required "the continual labour of two strong men for divers hours." Boyle obviously wanted something more convenient than this.

As indicated above, the book by Schott was published in 1657, but by early 1659 Boyle had a much-improved air pump and was ready for experiments. The pump was designed and constructed by Robert Hooke (1635–1703), who was a mechanical genius. He made important contributions to an extremely wide field, including microscopy, horology, mechanics, and architecture. Boyle hardly mentioned Hooke in the 1660 book, but later he acknowledged the great contributions of his assistant. In fact, it seems likely that a number of the experiments described in the 1660 book owed their origin to Hooke's interests. An example was *experiment 26* on the effect of rarified air on the swing of a pendulum, since the motion of a pendulum was one of Hooke's many interests. Boyle finished writing the book on December 20, 1659, and it was published in 1660. Therefore, it was only 16 years between Torricelli's seminal discovery of the barometer and Boyle's completion of this remarkable book.

Fig. 1. Portrait of Robert Boyle (1627–1691). Reproduced from Ref. 18.

THE MAN

The Honourable Robert Boyle (Fig. 1) was one of the most important figures in the history of science in the middle of the 17th century and not surprisingly has been the subject of extensive studies. This is therefore only a brief summary of his career. Robert Boyle was the 14th son of the first Earl of Cork, a man with extensive landholdings in Ireland. As a consequence, Robert was wealthy and lived the life of a 17th-century gentleman. He was initially educated at home by tutors and then at Eton College. After spending some time on the Continent, during which he met Galileo in Florence in 1641–1642, he returned to England and lived in London. He was one of a circle of friends who discussed contemporary scientific issues, and Boyle referred to the group as the "invisible college." This later became the Royal Society in 1662. Boyle moved to Oxford in 1654, taking a house next to University College, where a plaque on the wall can still be found.

Boyle was a prolific writer, and even now some of his material remains unpublished (16). His 1660 book discussed here is arguably his best, but there were several sequels to this, and in addition Boyle wrote extensively on theology, ethics, philosophy, and chemistry.

The prodigious literary output of Boyle occurred despite tremendous political and social upheaval in England. There was a civil war from 1642 until 1646 with continuing unrest after that until King Charles I was beheaded in 1649. The Commonwealth that followed under Oliver Cromwell was also an unsettling period, and when Cromwell died in 1658 and was succeeded by his son Richard, there was even more unrest. The monarchy was restored with Charles II in 1660. Boyle refers to these difficulties in his preface, where he states "I need not perhaps represent to the equitable Reader, how much these strange Confusions of this unhappy Nation, in the midst of which I have made and written these Experiments, are apt to disturb that calmness of Minde, and undistractedness of Thoughts, that are wont to be requisite to Happy Speculations."

THE BOOK

The title page is shown in Fig. 2. This is followed by an 11-page preface in which Boyle gave some of his reasons for the style of the book. An interesting feature is the extent to which he emphasized that he did all the experiments himself (albeit with the help of Hooke). The experiments were described in considerable detail so that readers could reproduce

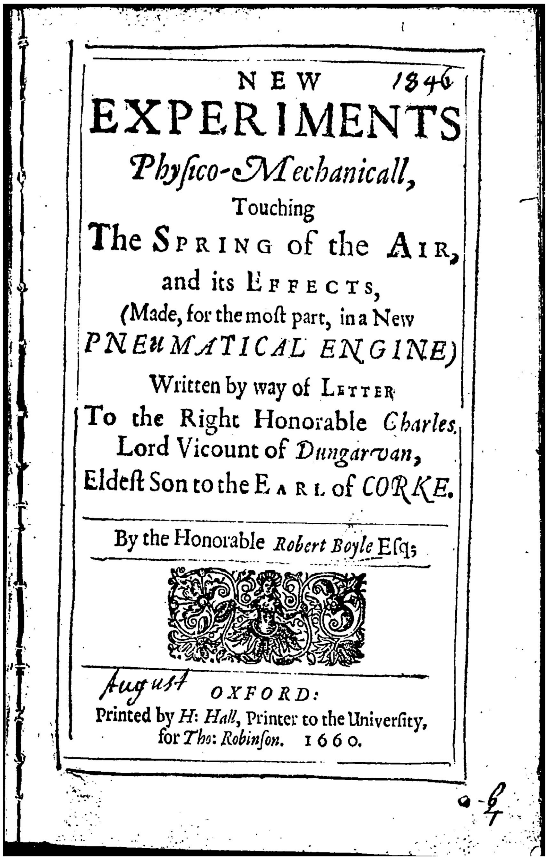
NEW 1846
EXPERIMENTS
Physico-Mechanicall,
Touching
The SPRING of the AIR,
and its EFFECTS,
(Made, for the most part, in a New
PNEUMATICAL ENGINE)
Written by way of LETTER
To the Right Honorable Charles,
Lord Vicount of Dungarvan,
Eldest Son to the EARL of CORKE.
By the Honorable Robert Boyle Esq;
August OXFORD:
Printed by H: Hall, Printer to the University,
for Tho: Robinson. 1660.

Fig. 2. Title page of the 1660 book.

them if they wished. For example, on the second page of the preface, which is headed "To the Reader," Boyle stated, "On my being somewhat prolix in many of my Experiments, I have these Reasons to render, That some of them being altogether new, seem to need the being circumstantially related, to keep the Reader from distrusting them." It might seem strange to the present-day reader that Boyle put so much emphasis on the fact that all the experiments were actually carried out. However, a number of books before this contained a mixture of actual and "thought" or imaginary experiments. As an example, Galileo in his great book *Dialogues Concerning Two New Sciences* (14) discussed how the force or resistance of a vacuum could be measured. He described how a piston could be made to fit perfectly in an inverted cylinder filled with water with all the air excluded. When weights were added to the piston until it fell, the force of the vacuum could be derived. However, this is not an experiment in the sense we now use the term, but an imaginary situation that Galileo developed to explain a concept. Boyle was at great pains to emphasize that his experiments were actually done, and in fact some of the detail is rather tedious.

Another issue briefly referred to in the preface is why the book was written in the form of a letter to Boyle's nephew. In fact, throughout the book, there are numerous allusions to the recipient of the letter, which allowed Boyle to emphasize important points. For example, on *page 17*, after describing the construction of the pump, Boyle writes "Your Lordship will, perhaps, think that I have been unnecessarily prolix in this first part of my Discourse: But if you had seen how many unexpected difficulties we found to keep out the externall Air, even for a little while, when some considerable part of the internal had been suckt out; You would peradventure allow, that I might have set down more circumstances than I have." This little conceit of imagining that he is talking directly to his nephew is somewhat like the format Galileo used in his book referred to above (14) in which the whole of the scientific thesis was given in the form of a dialogue between two people.

After Boyle's preface titled "To the Reader," there is another brief introduction headed "Friendly Reader," but this was written by the editor of the book, Robert Sharrock (1630–1684), who took Boyle's presumably handwritten manuscript and prepared it for publication. At the same time, he prepared a Latin edition because, as he said, "Since the Mountain cannot come to Mohamet, Mohamet will go to the Mountain." By this, he meant that many scientists outside England wanted to read the book but could not understand English. Latin was still the lingua franca of the intelligentsia of the civilized world.

The next section of the book is an expanded table of contents under the heading "A Summary of the chief Matters treated of in this Epistolical Discourse." Boyle explained that the book begins with a "Praemium," an old term for an introduction, that is devoted to a description of the pump. This is followed by brief descriptions of the 43 experiments in the book and a short conclusion at the end.[1]

It should be added here that this 1660 edition does not include what we now know as Boyle's Law, that is the inverse relationship between the volume of a gas and its pressure (20). This was added in the second edition of 1662, as described later.

THE PUMP

The first 19 pages of the book describe the air pump in considerable detail. The description in the text is made much clearer by the fine engraving of the pump shown in Fig. 3. A modern reconstruction of the pump is shown in Fig. 4.

Boyle divided the description into two parts. The first is the glass "receiver" on the top in which the partial vacuum was developed and in which the experiments were carried out. The most striking feature of this is its great size. Boyle stated that it contained ~30 wine quarts, each of them containing "near 2 pound of water." In modern units, this is a volume of ~28 liters, which, if the receiver were spherical, would mean a diameter of ~38 cm. This is the size of the receiver in two modern reconstructions.[2] In fact, Boyle wanted a larger receiver, stating "We should have been better pleas'd with a more capacious Vessel, but the Glass-men professed themselves unable to blow a larger, of such a thickness and shape as

[1] The whole book is available on the web from Early English Books Online (http://eebo.chadwyck.com/). This needs a subscription for access, but the online version is an accurate facsimile of the 1660 edition. A second edition, published in 1662 with some additional material, is available from Books on Demand (UMI, Ann Arbor, MI). The contents of the text are identical but the pagination is different. The 1660 book is also reprinted in volume 1 of *The Works of Robert Boyle* (16). This is the easiest version to read.

[2] There are at least two full-size modern reconstructions of the Boyle-Hooke pump. One is in the Museum of the History of Science in Oxford, UK, and the other is in the Science Museum, Kensington, London, UK. Neither are probably on display but can be seen by appointment. Both are well worth a visit partly because they emphasize the great size of the pump and particularly the receiver.

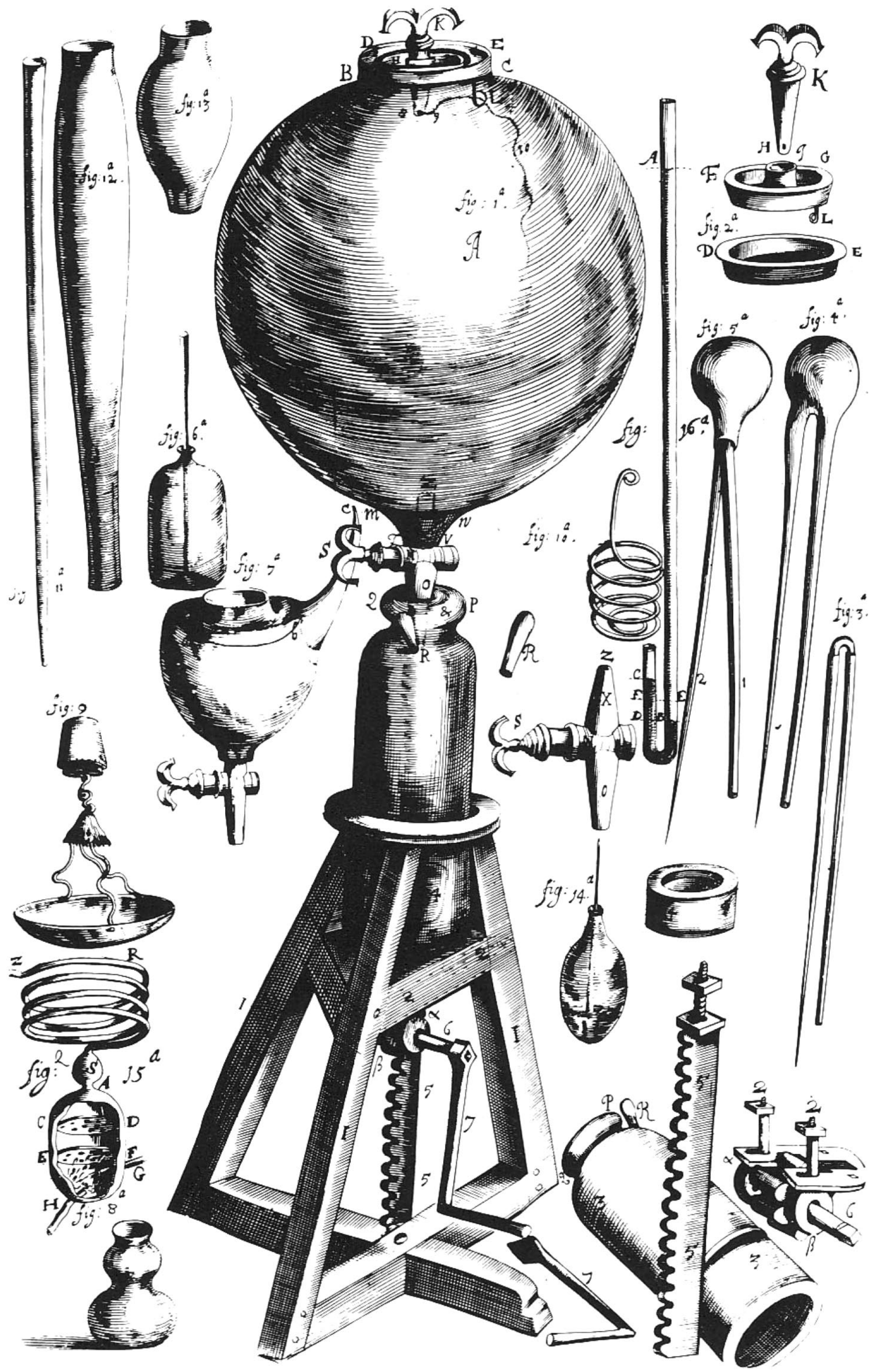

Fig. 3. Engraving of the air pump devised by Robert Boyle and Robert Hooke (1635–1703). The complete pump is shown at *center*, and some of the disassembled parts are at *right*. Various small pieces of equipment that were used in the experiments are also shown. See text for details.

was requisite to our purpose." Boyle apparently recognized the enormous compressing force that would be developed on the receiver when the air pressure was reduced and of course an implosion could have been disastrous. In fact, in one of the experiments, a glass vial containing air at normal pressure exploded and cracked the receiver.

At the top of the receiver, there was a round hole ~4 in. in diameter with a lip of glass almost 1 in. high. This allowed relatively large objects to be introduced into the receiver. The orifice was closed with a brass ring that was cemented in place. The brass ring had a smaller hole in it ~0.5 in. in diameter through which smaller objects could be introduced into the receiver. This hole was closed with a ground brass stopper, which could be rotated so that a string attached to the bottom could control equipment in the receiver. In addition, this stopper could be easily removed and replaced. By contrast, the 4-in. brass ring had to be re-cemented every time it was removed. Incidentally, Boyle makes occasional comments that

Fig. 4. Modern reconstruction of the air pump in the Museum of the History of Science, Oxford, UK. Reproduced by permission. Photographed by the author.

the design could be improved, and at this point he suggests that a better design for the 4-in. hole would be a ground glass taper "in case your Lordship should have such another Engine made for you."

At the bottom of the receiver was a brass stopcock similar to designs used today. The connection between the stopcock and the receiver was a challenge. The solution was to form a piece of "tin" with a conical shape and fill the space between the tin and the receiver with cement made of pitch, resin, and wood ashes "well incorporated." To prevent the cement from plugging the hole in the receiver during this process, a cork was placed in the hole and withdrawn through the top of the receiver with a string after the cement had set. Modern glassmakers are able to form the glass to fit the stopcock, and in fact this is what was done in the modern reconstruction at the Museum of the History of Science, Oxford, UK (Fig. 4).

The second part of the pump was the hollow cylinder together with the piston, which was driven by a rack and pinion. The cylinder was a piece of cast brass about 14 in. long with a hole 3 in. in diameter bored within it. Machining a hole of accurate constant diameter would have been a challenge, but boring large holes in metal was a well-known skill in making cannons.

One of the most critical parts of the pump was the piston or "sucker" as Boyle referred to it. Unfortunately, the description is less detailed than we would like. Boyle simply says that it consisted of two parts, one (marked 44 just above the rack in Fig. 3) "somewhat less in Diameter than the cavity of the cylindre, upon which is nail'd a good thick piece of tan'd shoe Leather, which will go so close to the Cylindre, that it will need to be very forcibly knock'd and ram'd in, if at any time it be taken out." It is not clear from this description exactly how the piston is constructed. Presumably, the first part (44) is made of wood to accept the nails, but where the thick piece of leather was placed is uncertain. Conant (12) in his discussion of the pump shows the leather seal as nailed to the upper side of the wooden piece, but this would not work well to form an airtight seal as the piston was pulled down because the leather would rise up at the periphery. Much better would be to place the leather on the bottom of the wooden piston. This is the arrangement used in reverse in modern bicycle pumps. The reconstruction of the pump in the Science Museum in London interpreted Boyle's description differently, and there the strip of leather is nailed around the periphery of the wooden piston. It is uncharacteristic of Boyle to be so vague about this critically important element of the pump because, of course, the ability of the pump to reduce the pressure in the receiver depended critically on the fit of the piston in the cylinder.

The piston was pulled down using a rack and pinion, which is clear from the engraving. Finally, the cylinder had a small valve at the top consisting of a tapered hole with a well-fitting brass plug that could be easily removed. To operate the pump, the stopcock at the base of the receiver was closed, the plug valve was opened, and the piston was cranked to the top of the cylinder. Then the plug valve was closed, the stopcock was opened, and the piston was cranked down. This process was then repeated as necessary. In some experiments, for example *experiment 37*, the piston was drawn down before the stopcock was opened.

At the end of this description of the pump, Boyle apologized to his nephew, stating that the description may seem to be unnecessarily prolix. However, he then went on to say that he included many details because of the great difficulty of getting the pump to perform satisfactorily. He had many problems with air leaks through the cement at the top and bottom of the receiver, and we can assume that the fit of the piston in the cylinder was always a serious problem. To reduce leaks, he poured into the top of the receiver a little "sallad oyl" to make the stopcock more airtight. Also a "pretty store of oyl" was poured into the cylinder to lubricate the piston. Interesting (and surprising to Boyle) was the fact that adding some water to the oil improved the operation of the pump.

Because of the problem of leaks and the resulting loss of the vacuum in a relatively short time, Boyle divided possible experiments into two types. The first was those that could be carried out in a short time, and the book concentrates on this group. The second type of experiment, such as studies of the preservation of animal or other bodies in a vacuum, or the germination and growth of vegetables, required a sustained partial vacuum over a long period of time, and Boyle conceded that his pump could not provide this.

Despite these imperfections, the pump was a major technological and engineering advance. As such, it owed much to the ingenuity of Hooke. The result was that, for the first time, it was possible to subject various materials and processes to a partial vacuum while setting up an identical control experiment in the air alongside the pump. Alternatively, the experiment could be performed in the receiver at normal atmospheric pressure and again when the air was removed. Boyle himself was quite aware of how innovative all this was, and the modern-day reader of the 1660 book senses the excitement and novelty of it.

How successful was the pump in developing a partial vacuum? As we shall see in *experiments 17–19*, Boyle reported that the level of mercury in a Torricellian barometer could be brought down to 1 in. above the surface of the mercury trough, indicating that the pressure had been reduced to ~3% of its normal value (corresponding to an altitude of ~23 km). Again, in *experiment 33*, Boyle pumped down to a good vacuum and found that it then required ~150 lbs. of weight on the piston to pull it down. If we take the diameter of the piston as 3 in., this represents essentially full atmospheric pressure.

THE EXPERIMENTS

As indicated above, Boyle reported 43 separate experiments (13, 16). However, some of these are clearly related, and it is convenient for us to divide them into seven groups. Because the work was done nearly 350 years ago, it is not surprising that some experiments are more interesting than others. In particular, physiology was in its infancy in 1660, and the experiments reported here precede the important studies of Boyle himself and those of Hooke, Lower, and Mayow later in the century. It should be remembered that Boyle's book appeared only 32 years after William Harvey's groundbreaking *De Motu Cordis* (15), which ushered in a revolution in physiology. Interestingly, Boyle was one of Harvey's patients because of his weak eyes.

Spring of the air (experiments 1–9, 32, 33, and 36). Boyle began his account of the experiments by discussing some of the most obvious properties of the air based on everyday use of his "pneumatical engine" or pump. He wrote, "I hold it not unfit to begin with what does constantly and regularly offer it self to our observation, as depending upon the Fabrick of the Engine it self, and not upon the nature of this or that particular Experiment which 'tis employed to try." He then described how the force necessary to pull down the piston became greater with successive strokes as the amount of air in the receiver was reduced. He attributed this to the fact that "the Particles of the remaining Air, having more room to extend themselves in, will less press out one another." Therefore, the pressure of the normal outside air resisted the downward action of the plunger more. He noted that if the air in the receiver was greatly rarified and the stopcock was opened, the piston was forcibly carried to the top of the cylinder.

Boyle then has a short digression on what he believed was the mechanical basis of the spring of the air. He likened air to a fleece of wool that can be greatly compressed, but if the compressing force is removed, it expands rapidly. He compared this explanation with that given by Rene Descartes (1596–1650), who had an alternative hypothesis, i.e., that the air consisted of particles in restless agitation so that each corpuscle endeavored to beat off all others coming close to it. This is similar to the modern concept of the kinetic theory of gases. Boyle did not choose one model over another, although he thought that the first was easier to understand.

Boyle then argued that the spring of the air is related to its pressure, which is high near the surface of the Earth because of the weight of the air. Here, he was echoing Torricelli's statement cited earlier. Boyle described how it was possible to demonstrate that air has weight by weighing a dry lamb's bladder containing air which was compressed by tying thread around it, and comparing this with the weight of the empty bladder when the air was removed by pricking holes in the bladder. Then, based on the density of air and the pressure at the surface of the Earth, he referred to calculations by others that the atmosphere must be at least 50 miles high in some places.

Another demonstration of the spring of the air in the daily operation of his pump was that if the piston was drawn down with the stopcock closed, it was extremely difficult to remove the small valve at the top of the cylinder. In fact, he stated that people who tried to remove the valve under these conditions were led to believe that there was some large weight attached to the bottom of it.

A further way of demonstrating the spring of the air was to take a lamb's bladder about half full of air, secured at the neck with a string, and place it in the receiver, which was then evacuated. The volume of the bladder increased dramatically but returned to its former volume when the pressure in the receiver was returned to normal. A similar experiment had been performed by Gilles de Roberval (1602–1675) using a calf bladder exposed to low pressure by means of a Torricellian barometer. In fact, Boyle reported that he was able to distend the bladder until it ruptured with a "great report, almost like a Craker." He also showed that a partially distended bladder increased its volume greatly if it was held near a fire, and he suggested that this might be because of increased "Agitation of the Aërial Particles." Again, this explanation is consistent with the modern kinetic theory of gases.

In *experiment 9*, Boyle described how he took a glass vial (spelled viol in the book) partly filled with water but with the neck closed by means of a glass pipe that was cemented in (this is the small container marked fig. 14 in Fig. 3 just to the right of the center of the wooden stand). At the very first descent of the piston, a piece of glass flew out of the vial striking the receiver and cracking it in many places. Boyle was surprised that this glass vessel exploded while others made of thin glass remained intact when the pressure in the receiver was reduced. He surmised that differences in the quality of the glass and the shape of the containers might be responsible. Boyle also observed wryly that receivers "are more easily crack'd then procur'd" and described ways of cementing cracks in the receiver with plaster so that it could continue to be used.

Torricellian experiments (experiments 17–19). Boyle used this term to describe experiments in which he studied the effect of reducing the pressure around the mercury in the dish of a barometer described by Torricelli. He made it clear that these experiments were some of the most important that he planned for his pneumatical engine, and he began his account of *experiment 17* as follows: "Proceed we now to the mention of that Experiment, whereof the satisfactory tryal was the principal Fruit I promis'd my self from our Engine. . . . I considered that, if the true and onlye reason while the Quick-silver falls no lower, be, that at the Altitude the Mercurial Cylinder in the Tube, is in Aequilibrium with the Cylinder of Air, supposed to reach from the adjacent Mercury to the top of the Atmosphere: then if this Experiment could be try'd out of the Atmosphere, the Quick-silver in the Tube would fall down to a levell with that in the Vessel, since then there would be no pressure on the Subjacent, to resist the weight of the Incumbent Mercury." Accordingly, Boyle arranged to have the mercury dish of a Torricellian barometer placed in his receiver while the tube of the barometer passed up through the hole at the top, which was carefully sealed with cement.

When the pressure in the receiver was reduced by cranking down the piston, Boyle was very satisfied to see that the level of the mercury in the barometer tube fell. By hard pumping, it was possible to reduce the height of the column of mercury to ~1 in., but despite laborious pumping the level would go no lower. Boyle attributed this to the fact that it was impossible to prevent small leaks of outside air into the receiver particularly through the cement that was used in several places. Incidentally, Boyle was obviously very pleased with this experiment and repeated it in the presence of three friends, "Famous Mathematick Professors, Dr. Wallace, Dr. Ward and Mr. Wren." This is the same Christopher Wren who built St. Paul's Cathedral in London and was involved in many scientific discussions.

Boyle noted that the extent to which the barometer level fell with the first descent of the piston was greater than with subsequent pumpings, and he correctly surmised that, as the pressure of the air in the receiver fell, less of it could be removed with each exsuction, as he called it. In fact, he argued that if one knew the volume of the receiver and the displaced volume of the piston in the pump, it should be possible to calculate the extent to which the mercury fell. Here, he was close to describing Boyle's Law, that is the inverse relationship between volume and pressure, but this was not done in the 1660 book. Instead, it was part of an addendum to the second edition of the book published in 1662, when he responded to various criticisms of his work, particularly one by Franciscus Linus (20). Boyle also carried out the opposite experiment in which he raised the pressure inside the receiver with the pump and noted that the level of the mercury in the Torricellian barometer rose.

At this point, Boyle has a digression in which he describes variations in the height of the mercury in his Torricellian barometer when it was set up by the window of his bedroom so that he could observe it over a long period of time. He states that, over a period of ~5 wk, the height of the mercury varied by 2 in., although, interestingly, he thought it fell in warm weather and rose in cold weather. He was not able to explain the variations in height, although he wondered whether the phases of the moon and the tides had some effect. He also made a few experiments with a water-filled barometer and noted that it was impossible to reduce the level of this below ~1 ft. above the surface of the water in the trough, and he recognized that this was because of the much lower density of water than mercury.

Burning of candles and other substances (experiments 10–15). When Boyle placed an ordinary tallow candle in the receiver and gradually reduced the pressure, he found that the appearance of the flame changed and that it was eventually extinguished. He stated that after the first two or three strokes of the pump, the flame got smaller, became blue in color, and moved further up the wick until it was only at the very top. The candle then went out. Boyle repeated this experiment with other flammable materials including "Coals, in which it seemed there had remained some little parcels of Fire," matches, and even a pistol containing gun powder! Boyle's interpretation of why these flammable materials went out when the air was rarified emphasizes the early state of knowledge in 1660. For example, he expected the fire to burn more brightly when the air was removed because this would allow greater space for the products of combustion. He stated it thus: "Whereby it seem'd to appear that the drawing away of the ambient Air made the Fire go out sooner than otherwise it would have done; though that part of the Air that we drew out left the more room for the stifling steams of the Coals to be received into." Of course Boyle knew nothing about oxygen at this time; Priestley was not to isolate it until over 100 years later. In the experiment with the pistol, Boyle found that the force of the flintlock was not apparently altered, and that sparks were produced just as in air at normal pressure. However, the gunpowder was not ignited in most of the experiments, although in one the flame appeared to expand more than expected in normal air. Boyle also attempted to ignite combustible material within the receiver by concentrating the sun's rays with a burning glass and succeeded in making smoke, but the results of these experiments were unsatisfactory he said because the thickness of the glass of the receiver impeded the sun's rays.

Physiological observations (experiments 40 and 41). As indicated earlier, measurements on animals form only a small part of the book. Probably one of the main reasons for this was that Boyle was so intrigued by the physical consequences of rarifying air that studies of living things took second place. He subsequently wrote other books and articles that included some physiology including "New experiments concerning the relationship between light and air (in shining wood and fish)" (7), "New pneumatical observations upon respiration" (9), *Spring of the Air, First Continuation* (8), and *Spring of the Air, Second Continuation* (10).

In *experiment 40*, Boyle studied the behavior of winged insects in his receiver as he removed the air. A large fly was introduced, and it dropped down from the side of the receiver where it was walking when the pressure was reduced. A bee fell down from a flower within the receiver when the pressure was lowered, although Boyle was unclear whether this was because the air was too rarified for it to fly, or whether it was weakened by the low pressure. In a footnote, he mentions that a white butterfly at first fluttered up and down but after the pressure was reduced it "fell down as in a swoon, retaining no other motion then some little trembling of the Wings."

These observations led to a much longer account in *experiment 41* on studies on the nature of respiration. A lark was placed in the receiver and sprang to a good height on several occasions when the pressure was normal. But when air was removed, it began to "droop and appear sick, and very soon after was taken with as violent and irregular Convulsions as are wont to be observ'd in Poultry, when their heads are wrung off." Another experiment was carried out on a hen-sparrow, and the bird seemed to be dead ~7 min after the pump was employed. However, when the air was restored, the bird revived and nearly escaped through the top cover, which had been removed. But when the air was removed a second time, the bird convulsed and died. A mouse inserted into the receiver behaved in a similar way, being very active initially but when the pressure was reduced appeared giddy and staggered before falling down unconscious. Again, the animal was revived when fresh air was let in.

In interpreting these experiments, Boyle posed the same questions as he did about the burning of candles referred to above, and which indicate the early state of knowledge about both combustion and respiration. The question was whether "the death of the fore-mention'd Animals preceded from the want of Air, then [than] that the Air was over-clogg'd by the steams of their Bodies, exquisitely pent up in the glass." Boyle argues that his experiments support the former possibility because, when he removed air with his pump, the animals clearly suffered, whereas when he readmitted air they revived.

Boyle then embarks on a long digression on the nature of respiration. He discusses the movement of the lungs and notes that, since they have no muscles themselves, they must be moved by the diaphragm and intercostal muscles. Interestingly, he states that "the Diaphragme seems the principal Instrument of ordinary and gentle Respiration."

There is a long section in which he discusses some of the theories of respiration in the literature, including the belief that its main function is to cool the blood. Much of this is of little relevance today. However, there is an interesting passage where Boyle considers "whether or no, if a Man were rais'd to the very top of the Atmosphere, he would be able to live many minutes, and would not quickly dye for the want of such Air as we are wont to breathe here below." He then referred to the experience of Joseph de Acosta in the high mountains of Peru who, when indisposed by the high altitude, stated "I therefore perswade my self, That the Element of the Air is there so subtle and delicate, as it is not proportional with the breathing of Man, which requires a more gross and temperate Air." The first edition of Acosta's famous book was published in 1590 (1), and it is interesting that Boyle was familiar with it. Boyle concluded from all this that there is a special portion of the air that is essential for life and that when this is removed what remains will not support life.

Boyle found that all living things, including eels that were placed in his receiver, could not survive a prolonged reduction of pressure. However, an exception was house snails, which did not seem to be affected, presumably because the amount of air that they needed was so small.

Effect of rarifying the air on some physical phenomena (experiments 16, 26, 27, and 37). The great curiosity of Boyle (and presumably Hooke) generated a series of interesting observations on physical phenomena, but they will only be referred to briefly. In *experiment 16*, a magnetized needle was placed in the receiver, and Boyle showed that it could still be deflected by a magnet brought to the outside of the receiver after evacuation. This raised the question of how the magnetic influence could be propagated in the absence of air. A similar experiment (*experiment 27*) studied the propagation of sound when a watch was suspended in the receiver by a piece of thread. Boyle found that the sound of the ticking disappeared when the air pressure was lowered. By contrast the sound made by a bell when it was struck was quieter when the air was removed but did not disappear altogether. However, a technical problem here was that the material that suspended the bell may have conducted the sound. A further issue was that since not all the air could be removed by the pump, the residual air might have propagated the sound. Of course, Boyle recognized that light was transmitted through the evacuated receiver because it was still possible to see objects in it.

These experiments raised the question of whether there was another medium called "ether" that continued to be present in the receiver even if all the air was evacuated. Many scientists of the time thought that to transmit light or magnetism through a space required the existence of some medium. They argued that the air pump might able to remove the air but not the ether. Experiments on the possible existence of ether were not followed up in this 1660 book but are described in Boyle's *Spring of the Air, First Continuation* (8).

A particularly ingenious experiment was *experiment 26* on the swing of a pendulum. Boyle, or more likely Hooke who had done extensive studies on pendulums, expected that a pendulum would swing slightly more slowly and that the motion would last longer before decaying in air as opposed to a partial vacuum because the air would impede the motion. Accordingly, two identical pendulums were constructed and set in motion, one inside the receiver, which was evacuated, and one outside. To the surprise of the observers, no consistent differences could be measured between the two pendulums. An interesting sequel to this is that it is now accepted that the viscosity of a gas is independent of its pressure, a finding that is counterintuitive to most people. One of the standard textbooks of fluid dynamics when discussing this refers the reader to Boyle's experiment done 350 years ago (11).

Another surprising finding described in *experiment 37* occurred on some occasions immediately after the piston was drawn down and the stopcock was then opened. The reduction of pressure in the receiver was accompanied by a "kinde of Light in the Receiver, almost like a faint flash of Lightning in the Day-time, and almost as suddenly did it appear and vanish." The phenomenon was not always seen but only when the engine was "in a good humour" as Boyle put it. The "Apparition of Light" could be seen by both candlelight and daylight, and following its appearance the sides of the receiver seemed to be darkened as if some "whitish Steam" adhered to the wall. Boyle was at a loss to understand this phenomenon, but it was probably a transient condensation of water vapor produced by the sudden reduction in air pressure.

Behavior of liquids (experiments 20–25, 28, 35, 42, and 43). When a liquid such as water was placed in the receiver within a vial that was tightly closed with a cork, no changes in the appearance of the liquid were seen. However, if the water was suddenly exposed to the low pressure, for example by breaking the glass neck of the vial, the water immediately started to bubble vigorously. In one experiment, pieces of red coral covered by vinegar were placed in the receiver. The result was the formation of a small number of bubbles at normal pressure, but when the air was rarified with the pump the bubbling increased greatly. In a further experiment, water that had been "boyl'd a pretty while" was placed inside the receiver, and this time no bubbles appeared with the first three descents of the piston. However, when the pressure was further reduced, the water suddenly appeared to boil in the vial "as if it had stood over a very quick Fire."

The results of these experiments are not surprising to us today, but to Boyle they raised the whole question of the nature of gases and liquids and particularly how it was possible for a liquid to contain a gas.

Miscellaneous experiments (experiments 29–31, 34, 38, and 39). Boyle's curiosity and ingenuity resulted in a number of other experiments, which are now of generally minor interest either because the methods were flawed or because the objectives are of little relevance today. He studied the behavior of smoke in a partial vacuum because some philosophers had argued that "Steams or Exhalations" ascend because of "positive levity," i.e., negative weight. The confusion here was the failure to recognize that warming a gas reduced its density. In another experiment, Boyle wondered whether two "exquisitely polish'd" flat pieces of marble would be pressed against each other by atmospheric pressure in the same way as Guericke's hemispheres. However, he was unable to obtain two pieces so exactly ground that they remained in contact for more than 1 or 2 min, which was the time it took him to prepare the experiment. Because he thought that the surfaces were not completely flat, he wondered whether moistening them with "Spirit of wine" would help, but again the experiment was unsuccessful and, in any event, Boyle was not aware of the phenomenon of surface tension.

Experiment 34 was ingenious in that he wondered whether he could demonstrate the buoyancy of air by comparing the weight of a half-filled bladder tied securely at the neck at normal pressure and after reducing the pressure. The weight was obtained by placing the bladder on a balance with metal weights at the other end. The results of this experiment were apparently confused by changes in the weight of the bladder caused by moisture in the air, and Boyle did not reach any clear conclusion.

An experiment in which Boyle introduced a mixture of snow and common salt into the receiver did not give any clear results, but it allowed Boyle to digress on how ice that formed when water freezes can exert enormous pressures resulting in the breaking of stones and other structures. Boyle was unaware of the fact that water expands as ice is formed.

CONCLUSION

The Boyle-Hooke pneumatical engine not only was a triumph of engineering, but it opened up a whole new field of study. In its day, it was famous and, for example, it was often displayed to visitors who came to the Royal Society. Interestingly, Boyle did not immediately continue his experiments on reduced air pressure after 1660 but, for example, in 1661 published a book on chemistry, *The Sceptical Chymist* (5) and, in a completely different area, *Style of the Scriptures* (4). However, in 1662, he published a second edition of the 1660 book with an addendum *Whereunto is Added a Defence of the Authors Explication of the Experiments, Against the Obiections of Franciscus Linus and Thomas Hobbes* (6). Linus had argued that, although the column of mercury in the Torricellian barometer was partly raised by atmospheric pressure, there was another structure called a "funiculus" within the vacuum that helped to support it. Boyle's vigorous response was that Linus' hypothesis of a funiculus was "partly precarious, partly unintelligible, and partly insufficient, and besides needless." But the most enduring feature of his response was the demonstration of the inverse relationship between the pressure and volume of a gas, which we now know as Boyle's Law. Hobbes's argument was more philosophical and had to do with the penetrative characteristics of air as an ethereal fluid, and Boyle contended that the experimental evidence was against this. Boyle's 1660 book makes satisfying reading even today, although some modern readers may be put off by the occasional bizarre spelling and typography. For that reason, a modern version of the text (16) is easier to read. At any event, modern students who are interested in high-altitude physiology should be aware of this classic book.

GRANTS

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