Stephen Hales

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Life and career

The Hales family was one of the most ancient and distinguished in Kent, dating at least from Tonne, Lord of Hale and Luceby in Norfolk in the time of Edward the Confessor (c1003-1066). Stephen Hales was the sixth and last son of Thomas (c1640-1692) and Mary Hales (?-1687); he was born at the family home at Bekesbourne in Kent on September 17, 1677. Little information is available regarding his early life and education, except his own statement that he was educated at Kensington under St. Claire and then at Orpington under the reverend Richard Johnson.1 2 Following the death of his father he was put under the guardianship of his grandfather Robert Hales. After “being properly instructed in Grammar Learning” he was sent to Cambridge University in 1696 and admitted a pensioner at Bene’t College (as Corpus Christi was then called) under the tutorship of Robert Moss (1669-1729), later dean of Ely. Theology was the central subject of the curriculum since most of the students were candidates for ordination; nevertheless enough time was left for the study of classics, mathematics, science, and philosophy. Hales received special instruction in divinity from his tutor Moss, and it was on his merits as a student of theology that, after taking his first degree in Arts in 1699, he was pre-elected into a Fellowship in April 1702. This achievement meant that he would become a formal fellow of the College as soon as there should be a vacancy, a condition that that was satisfied on February 1703. In 1703 he took the degree of Master of Arts and on September 19 of the same year, Gardner, Bishop of Lincoln ordained him Deacon at Budgen.1

Hales was also diligent in the study of astronomy; after learning the Newtonian system, he built a machine moved by wheels machine to represent the motions of all planets,
upon the same principles, and nearly in the same manner as the machine built
afterwards by John Rowley (1683-1728), Master of Mathematics to King George I. The
University and the College taught Hales physical science, but it was his friend and
colleague, William Stukeley (1687-1765), an undergraduate and medical student, who
initiated his interest in biology. On August 1709, Hales left Benet’s College to become
Perpetual Curate, or Minister, of the parish of Teddington, a country village with a
population of less than five hundred persons, in the county of Middlesex. ¹

In 1719, Alexander Pope (1688-1744), the poet, bought a house near. Pope was one of
the few intellectuals at that time who wrote against cruelty to animals and their use in brutal
amusement. Although he was a Roman Catholic and was horrified with Hales’
experiments with living animals, they became friends. Pope used to say “I shall be very
glad to see Dr. Hales’. Yes, he is a very good man, only I am sorry he has his hands so
much imbued in blood…Indeed, he commits most of these barbarities with the thought
of being of use to man. But how do we know that we have a right to kill creatures that
we are so little above as dogs for our curiosity”? ¹

At the age of forty-three Hales married Mary Newce (-1721), the daughter of Richard
Newce of the parish of Much Hadham and Rector of Hailsham in Sussex. His married
life was brief; just a year after the wedding his wife died and left childless. ¹

In 1728 Hales resigned his fellowship in Benet’s College, to take a further position as
Rector of Porlock. Hales probably never went to see or preach in his new parish. He
continued to live at Teddington, and, as was the custom, hired a curate to do the work at
Porlock; the balance left over after the curate had been paid, added to his income. After
four years he resigned his position at Porlock to take a new one at Farrington, near
Winchester. Once again, he hired a curate to take care of this new position, although this
time he used to visit the place often and for extended periods. At Farrington Hales
devoted much time to farming and invented several agricultural machines, among them,
a winning machine or “back-heaver”, which Hales said would winnow and clean corn
both much sooner and better than by the common method of doing it. At a later date,
this machine was improved so that it would “clean and clears it of very small corn,
seeds, blacks, and smut balls to such perfection as to make it fit for seed corn”. ¹, ³, ⁴

Hales outstanding work on animal physiology gained him, in 1718, election as Fellow
Royal Society, at the proposal of Stukeley. In 1733 Oxford conferred on Hales the
doctorate of divinity and in 1739 the Royal Society awarded him the Copley medal. In
1750 he was appointed almoner (distributor of the charities) to the princess dowager of
Wales (1719-1772; Augusta, daughter of Frederick 11, Duke of Saxe-Gotha). Hales was
one of the founders of the Society for the Encouragement of Arts, Manufactures, and
Commerce (later renamed the Royal Society of Arts) and became one of its vice-
presidents in 1755. In 1753 he was elected a foreign associate of the Académie des
Sciences, replacing Sir Hans Sloane (1660-1753), President of the Royal Society, who
had died earlier that year. He was very active in the Society for the Promotion of
Christian Knowledge from 1722. In 1724 he became one of the Georgia trustees for the
colonization of Georgia, for the “thorough instruction in the Christian Religion the
young Children of the Negroe Slaves” in the West Indies, which developed out of the
bequest from Abel Tassin, Sieur D’Allone. ¹ John Ellis (c1710-1776), a linen merchant
and naturalist, who was governor of the Georgia colony and a correspondent of
Linnaeus, named after him a genus of American flowering shrubs Halesia (Carolina
silver bell).

Hales passed away at Teddington on January 4th, 1761, after a short illness. A
monument in Westminster Abbey was erected to his memory by the princess of Wales,
with a bas-relief of “the old philosopher” in profile. In his last will and testament written
in 1759, Hales wrote: “As for my Body, I desire it may decently interred, without pomp or state or giving gold rings, and without a leaden coffin...under the new tower of Teddington Church...” He bequeathed all his property to his niece Sarah Margaretta, who had recently married the reverend William Johnson; all his books were to be send to a public parochial library in Georgia. He also left small sums of money to different people and societies. His niece and husband were appointed executrix and executor of the will.¹

Like all his contemporaries Hales believed that God had created the world so "nature works according to the laws established at her first institution". Every living creature had been specially created by God for a particular reason and all their members and organs had been designed by the Creator so as to fulfill the specific function that they were intended to serve: “The study of nature will ever yield us fresh matter of entertainment, and we have great reason to bless God for the faculties and abilities he has given us, and the strong desire he has implanted in our minds, to search into and contemplate his works, in which the farther we go, the more we see the signatures of his wisdom and power...And the farther researches we make...we see in them...the being, power and wisdom of the divine Architect, who has made all things to concur with a wonderful conformity, in carrying on, by various and innumerable combinations of matter, such a circulation of causes and effects, as was necessary to the great ends of nature...”¹,⁵

According to Hales, the experimental method, (which he named “statical way of investigation”) was the only way to advance science. In the preface to his book *Haemastaticks* he wrote⁵: “Though we can never hope to attain to the complete knowledge of the texture, or constituent frame and nature of bodies, yet may we reasonably expect by this method of experiments to make farther and farther advances...to reward our pains...All the real true knowledge we have of Nature is entirely experimental...we may lay this down as the first fundamental unerring rule in physics. That it is not within the compass of human understanding to assign a purely speculative reason for anyone phenomenon in nature. So that in natural philosophy we cannot depend on any mere speculation of the mind; we can only with the mathematicians reason with any tolerable certainty from proper data such as arise from the...testimony of many good and credible experiments...For new experiments and discoveries do usually owe their first rise only to lucky guesses and probable conjectures and even disappointments in these conjectures do often lead to the thing sought for: thus by observing the errors and defects of a first experiment in any researches, we are sometimes carried to such fundamental experiments, as lead to a large series of many other useful experiments and important discoveries...In which method we may be continually making farther and farther advances in the knowledge of nature, in proportion to the number of observations which we have: but as we can never hope to be furnished with a sufficient number of these, to let us into a thorough knowledge of the great and intricate scheme of nature, so it would be but dry work to be ever laying foundations, but never attempting to build on them...The farther advances we make in the knowledge of nature, the more probable and the nearer to truth will our conjectures approach: so that succeeding generations, who shall have the benefit and advantage both of their own observations, and those of preceding generations, may then make considerable advances, when many shall run to and fro, and knowledge shall be increased (Dan. XII: 41)”.¹

Hales' first recorded experiment was to make with Stukeley a cast of a dog's bronchial tree. As described by Clark-Kennedy⁶ they first they distented and dried the lungs with hot air repeatedly blown down the trachea through a very hot gun barrel; then they
poured in molten lead by the same method. Hales' early experiments related to the measurement of animal blood pressure, the blood circulation systems, and the factors affecting them. After noting the small size of muscle capillaries and the slow movement of their corpuscles, he wanted to test his ideas by finding what the 'force of blood' (blood pressure) actually was. This was typical of his usual approach: "It is by...Conjectures that I have been led on, Step by Step, thro' this long and laborious Series of Experiments; in any of which I did not certainly know what the Event would be, till I had made the Trial, which Trial often led on to more Conjectures and farther Experiment ... In which method we may be continually making further Advances in the knowledge of Nature in proportion to the Number of Observations which we have". Hales succeeded in measuring the blood pressure in the arteries and in the veins and made many other observations regarding the mechanics of the circulation. For example, he thought that blood became red because it was agitated by its rapid passage through the lungs as when agitated in a glass vessel. He qualified this conclusion by adding: "Tis probable that the blood in the lungs may receive some important influence from the Air", implying that some component of the "elastic' air became fixed" in the blood. In 1727 he communicated to the Royal Society an account of "An Attempt to Analyse the Air by a Great Variety of Chymio-Statistical Experiments". Isaac Newton, the President of the Society ordered that Hales’s papers should be printed. This took place as an appendix to his first book Vegetable Staticks. As was the custom of those days, Hales solicited royal patronage for his work by dedicating his first book to the Prince of Wales, afterwards George II (1683-1760). In the book Vegetable Staticks he also described an ingenious mercury gauge used to determine the pressure exerted by peas expanding in water, and this led him to imagine its adaptation as a "sea gage" to measure the depths of the ocean. He applied his chemical knowledge to suggesting the preservation of sides of beef by injecting brine into the arterial system, to check the spread of fires, to speculate on the causes of earthquakes, to remedy the bad taste of milk, of ways for keeping water sweet during long sea voyages and exploring the problem of distilling fresh from salt water. He was very interested and active in medical questions, such as urinary stones, medical potions, and the bad effect of vitiated air. The latter led him to design a "ventilator" (a modified organ-bellows) to remove fetid air from prisons, hospitals, ships, and grain elevators. His ventilator was successful in reducing the mortality in the Savoy prison, and it was introduced into France by the aid of Henry Louis Duhamel du Monceau (1624-1706). His ventilator was used in drying and ventilating grain. He also built a ventilated greenhouse for the Dowager Princess of Wales; it markedly improved the plants growing in it. Hales played an active part in the fight against public sale of alcoholic beverages and their evil effect upon society. During 1754-1755, Hales supervised the construction of a system of ditches that brought a new water supply to the village of Teddington from a series of springs. In 1729 James Oglethorpe (1696-1785) had been appointed chairman of a committee to investigate and report upon conditions of debtors’ prisons. The knowledge of social conditions that he had gained in this capacity led him to think of founding a new colony in North America to serve as an asylum for the paupers and debtors who crowded the Fleet and other London prisons, and as a refuge for the persecuted Protestants of Europe. On June 9th, 1732, the King granted a charter for the foundation of the colony of Georgia. According to Clark Kennedy, the new colony had its origin in an attempt to remedy the social conditions of England by extending the British Empire beyond the seas. Georgia was both a philanthropic and an imperialistic enterprise.
Scientific contribution

Hales published about 20 papers and six books on scientific, medical, social, and religious subjects. Several of the publications are short letters to the President of Royal Society describing his findings and theories regarding problems such as calculi, conveying liquors into the abdomen, earthquakes, prevention of fires, sweetening of water, and preservation of foods. His main discoveries are contained in two books, *Vegetable Sticks* and *Statical Essays Containing Hæmasticks*, containing a detailed summary of his work on plant physiology and animal physiology, respectively.

Animal physiology

In 1698 James Keill (1673-1719) published his book *An Account of Animal Secretion, the Quantity of Blood in the Human Body, and Muscular Motion* in which he tried to illustrate how selected physiological questions might best be investigated by using measurement and mathematics in general, and more particularly, by assuming an attractive force between particles of matter. Using mathematical abstractions he reached some results wildly apart from modern knowledge, e.g., his proposal that in the smallest arteries it would be possible for blood to flow at the rate of one quarter of an inch in 278 days. According to his own statement his was the first to attempt to determine the absolute velocity with which blood ran out of the aorta and traveled through the various arterial branches. Keill’s results probably arose the curiosity of Hales to study the flow of fluids in animals and in plants, as illustrated by the following writings in one of his books: "...if we reflect upon the discoveries that have been made in the animal œconomy, we shall find that the most considerable and rational accounts of it have been chiefly owing to the statical examination of their fluids, viz. by enquiring what quantity of fluids, and solids dissolved into fluids, the animal daily takes in...And with what force and different rapidities those fluids are carried about in their proper channels...”

Many attempts had been made to calculate blood pressure but not direct measurements of it had been attempted. Hales approach to the problem was again based on his statical way of investigation: “Several ingenious persons have from time to time, attempted to make estimates of the force of blood in the heart and arteries, who have...widely differed from each...for want of a sufficient number of data to argue from...For since we are assured that the animal fluids move by hydraulic and hydrostatic laws, the likeliest way therefore to succeed in our inquiries into the nature of their motions, is by adapting our experiments to those laws.” Hence his audacious and bloody experiments in vivo (anesthesia was not known at his time) on blood pressure and its flow: He tied a live 14 years old mare on her back, opened the left crural artery, inserted into it a brass pipe fixed to a glass tube nine feet high, untied the ligature, and noted that the blood rose more than two meters above the level of the left ventricle of the heart and that the height increased and decreased at and after each pulse. The same phenomenon was observed when using other animals (ox, sheep, a fallow doe, horses, and several dogs). Hales made a rough estimate of the cardiac output by multiplying the pulse rate of an animal by the internal volume of its left ventricle. The latter was measured making a wax cast of it, after the animal had been killed. He tied a vertical tube into the pulmonary vein and poured melted wax down it. The wax entered the left ventricle, forced the aortic valve and appeared in the tube tied into the carotid artery; the aorta was now tied, and the wax allowed to harden *in situ*: "So that this piece of wax thus formed, may reasonably be taken to be nearly commensurate to the quantity of blood received into this ventricle at each diastole, and is thence propelled into the aorta at the subsequent systoles." His results also indicated that the pulse was faster in small
animals than in large ones and that the blood pressure was somewhat proportional to the size of the animal. Hales realized that his results may be criticized because "by fixing tubes to these large veins and arteries, the course of a considerable stream of blood was for that time stopped; and that consequently the force of the blood must be proportionately increased in all the veins or arteries; and therefore also in all the veins or arteries to which the tube is fixed. And doubtless to some degree it is so". To obviate this limitation, he substituted the initial end-manometer by a lateral one, in which the artery or vein was cemented within a tube section from which the long manometer tube projected vertically at a right angle. Blood pressure was, again determined by the height to which blood was forced from the pierced vessel up the long tube.

From his experiments Hales understood that the force of arterial blood in the capillaries "can be but very little" and inappropriate for "producing so great an Effect, as that of muscular Motion." This "hitherto inexplicable Mystery of Nature must therefore be owing to some more vigorous and active Energy, whose force is regulated by the Nerves." Stephen Gray (1666-1736) had recently reported that a cork becomes electrified when rubbed and that electricity can be flow. Hales used this information to suggest that these "animal spirits," might be caused by electricity because this force "...will not only be conveyed along the Surface of Lines to very great Lengths, but will also be freely conveyed from the Foot to the extended Hand of a human Body suspended by Ropes in...the Air; and also from that Hand to a long Fishing Rod held in it, and thence to a String and a Ball suspended by it".

Hales understood that his explanation lacked experimental evidence: "Having read the unsatisfactory conjectures of several, about the cause of muscular motion, it occurred to me, that by fixing tubes in the arteries of live animals, I might find pretty nearly, whether the blood, by its mere hydraulic energy, could have a sufficient force, by dilating the fibers of the acting muscles, and thereby shortening their lengths, to produce the great effects of muscular motion...The violent straining (of the mare) to get loose, did, by the acting of most of her muscles, especially the abdominal, impel the blood from all parts to the vena cava, and consequently there was a greater supply for the heart, which must therefore throw out more at each pulsation, and thereby increase the force of the blood in the arteries. For the same reason too, it would be somewhat increased in height upon deep sighing, because the lungs being then put into greater motion, and more dilated, the blood passed more freely, and in greater quantity, to the left auricle, and thence to the ventricle".

To get an idea of the resistance offered by the small arteries, he first measured the arterial blood pressure in a dog by tying a tube into the carotid artery as in his previous experiments. After the animal was killed, he tied the two crural arteries, divided longwise the descending thoracic aorta, bared the guts, and split them open along their whole length opposite the line of mesenteric attachment. A glass tube was introduced into the peripheral end of the cut aorta, and the "slit guts" were perfused with warm water at a pressure equal to the normal arterial pressure. "This water passed off thro' the orifices of innumerable small capillary vessels, which were cut asunder thro' the whole length of the slit gut. But notwithstanding it was impelled with a force equal to that of the arterial blood in a live dog, yet it did not spurt out in little distinct streams, but only seemed to ooze out at the very fine orifices of the arteries, in the same manner as the blood does from the capillary arteries of a muscle cut transversely". Other experiments were done to determine the output of the heart per minute and the mechanics of the peripheral circulation in the small vessels.
His first conclusion was that blood flowed very rapidly in the capillaries of the lungs. The peripheral resistance was studied by adding different substances (e.g., brandy, decoction of Peruvian bark, and various saline solutions) to the perfusion fluid and noting the time it took to flow through the intestines of a recently killed dog. A rate of flow below the normal indicated that the added substance caused vasoconstriction, a rate above the normal indicated vasodilatation. His results indicated that hot water caused vasodilatation and cold water, decoction of Peruvian bark, chamomel flowers, and cinnamon resulted in vasoconstriction. Brandy contracted the fine arteries of the gut and water soon relaxed them again.5

Hales published his experiments on animal circulation under the title *Hæmastaticks*, putting as part of his book, *Statical Essays*, describing all his experiments on plant and animal physiology.5

**Plant physiology**

While conducting his experiments on animal blood pressure, Hales records that “About twenty years... I made several hæmastatical experiments on dogs...horses and other animals, in order to find out the real force of the blood in the arteries: at which time I wished I could have made the like experiments to discover the force of the sap in vegetables; but despaired of ever effecting it, till about seven years since, by mere accident I hit upon it, while I was endeavoring by several ways to stop the bleeding of an old stem of a vine, which was cut too near the bleeding season, which I feared might kill it. Having...tied a piece of bladder over the transverse cut of the stem, I found the force of the sap did greatly extend the bladder; whence I concluded that if a long glass tube were fixed there in the same manner, as I had before done to the arteries of several living animals, I should thereby obtain the real ascending force of the sap in that stem, which succeeded according to my expectation: and hence it is, that I have been insensibly led on to make farther...researches by variety of experiments.” Hales was impressed by the analogies that he noticed between the animal and the vegetable worlds. Since the growth of plants "and the preservation of their vegetable life is promoted and maintained, as in animals, by the plentiful and regular motion of their fluids, which are the vehicles ordained by nature, to carry proper nutriment to every pan," then the same methods he had used to study the animal economy should also be appropriate for "the statical examination of their fluids".5

Experiments carried on during the bleeding season, in which long glass tubes were connected to the cut end of a branch of a grapevine, showed that the sap rose in these tubes "according to the different vigor of the bleeding state of the Vine" from one foot up to twenty-five feet. To measure the sap pressure Hales fixed a "mercurial gage," a bent tube filled with mercury, to the cut branches of the vine, and observed the pressure variations at different times of day. He measured the force with which trees imbibe moisture from the earth, with "aqueo-mercurial" gauges; He observed that when the gauges were filled with water and immersed in a vessel of mercury, the root "imbibed the water with so much vigor" that in six minutes the mercury rose eight inches. These experiments were carried out in the summer months when the trees and vines were in leaf. Hales noted that the more the sun shone on the plants, "the faster and higher the mercury rose".

In early autumn he cut off a vine flush with the ground and connected the cut stem with a vertical glass tube. The sap rose 43 feet in it. He had discovered and measured root pressure5: "This force is near five times greater than the force of the blood in the crural artery of a horse, seven times greater than in that of a dog, and eight times greater than in that of a fallow doe...".8
Transpiration, the loss of water by evaporation from the surfaces of plants, had been little studied; the magnitude of it had not been realized, and its physiological significance was not yet understood. Hales's experiments on transpiration were carried out in the summer months of 1724. He grew a large sunflower in a garden pot covered tightly with a thin lead plate pierced by the plant, by a small glass tube to allow some communication with the air, and by another short, stoppered tube through which the plant could be watered. These measures were taken to prevent any evaporation of water except through the plant itself. He weighed the pot and plant twice a day for fifteen days and the end of the experiment he cut off the plant, cemented the stump over, and then found that the unglazed porous pot "perspired" two ounces every twelve hours. Subtracting this from his earlier weighings, he found that the plant perspired in that period an average of one pound, four ounces of water. During sunny days and fine warm nights the sunflower would lose weight from "perspiration" of water. On wet days and dewy nights the sunflower would gain weight by "imbibition" of water. The overall balance indicated that the loss of weight from "perspiration" exceeded the gain of weight by "imbibition", and the plant had lost water by transpiration from the leaves at an average rate of 34 in 3 in twelve hours. He then cut off all the leaves and measured their total surface area; estimated the surface area of the roots, and measured the cross-section of the main stem. With this information he was able to calculate the actual velocity of the flow of sap in different parts of the plant, just as he had determined the speed of the blood in the arteries, capillaries, and veins of animals. His results indicated that the sap flow was very fast in the stem, intermediate in the roots, and slowest of all in the leaves; this order corresponded to the rate of movement of the blood in the arteries, veins, and capillaries of animals. The same procedure was used to determine the average perspiration rates in a variety of plants and trees and to conclude that evergreens perspired less than plants and deciduous trees.1

He now took the trunk of a young apple tree, free of leaves and lateral branches, placed its lower end in water and cemented the other end into a vertical glass tube. After standing for a considerable time, the upper end still remained moist. This showed that water was being continuously imbibed by the stem to compensate the loss by evaporation above: "I then dug up the tree by the roots, and set the root in water, with the glasses affixed to the top of the stem; after several hours nothing rose but a little dew; yet it is certain by many of the foregoing experiments, that if the top and leaves of the tree had been on, many ounces of water would in this time have passed through the trunk, and been evaporated through the leaves. These last experiments all show, that though the capillary sap-vessels imbibe moisture plentifully; yet they have little power to protrude it farther, without the assistance of the perspiring leaves, which do greatly promote its progress".8

In order to follow the relative growth of leaves and shorts, Hales made marks on them and observed their change at different periods of time. The results indicated clearly that vegetable growth was asymmetrical: "I found in them all a gradual scale of unequal extensions, those parts extending most which were tenderest. The whole progress of the first joint is very short in comparison of the other joints...But as the season advances, and the leaves enlarge, greater plenty of nourishment being thereby conveyed, the second joint grows longer than the first, and the third and fourth still on gradually longer than the preceding; these do therefore, in equal times, make greater advances than the former".8

Many botanists believed that sap circulated in plants in a similar manner as in animals, the sap ascended through the older wood and descended again in the layer of recent wood and between the wood and bark. In order to investigate the possibility that the sap
could flow in both directions, Hales cut the branch of a dwarf golden pippin tree, bent it down and cemented into a wide glass tube of water connected below with a mercury manometer. His results “proved that branches would strongly imbibe from the small end immersed in water to the great end; as well as from the great end immersed in water to the small end”. This resulted gave support to Hale’s idea that transpiration from the leaves was the most important issue in the rise of the sap and its continuous movement. As water evaporated away from their surfaces, sap rose continuously by capillarity in the capillary sap vessels, and compensated the loss: “By this principle it is that plants imbibe moisture so vigorously up their fine capillary vessels; which moisture, as it is carried off in perspiration, thereby gives the sap-vessels liberty to be almost continually attracting of fresh supplies; which they could not do, if they were full saturate with moisture, for without perspiration the sap must necessarily stagnate, notwithstanding the sap-vessels are so curiously adapted by their exceeding fineness, to raise a sap to great heights, in a reciprocal proportion to their very minute diameters. Though vegetables (which are inanimate) have not an engine, which, by its alternate dilatations and contractions, does in animals forcibly drive the blood through the arteries and veins; yet has nature wonderfull contrived other means, most powerfully to raise and keep in motion the sap?”.

Urinary calculi
In the eighteenth century, renal and vesical calculus, "the distemper of the stone", was a very common disease and many unsuccessful attempts had been made to find a cure. In the introduction to the description to his work on calculi, contained in an appendix to Hæmastaticks, Hales wrote: “I am sensible that some may be apt to think it favours too much of vanity and presumption, for anyone, after such innumerable fruitless researches of the ablest chymists, to attempt to find out a safe dissolvent of the stone in the bladder. Yet in a matter of so great importance to the ease and welfare of a considerable part of mankind, we ought not wholly to despair.” Sloane and John Ranby (1703-1773), sergeant-surgeon to George II, supplied Hales with different varieties of human calculi for his experiments. On distilling the stones Hales found that the calculus and tartar of wine yielded more air on distillation than any other substance, whether animal, vegetable, or mineral. Because of the amounts and so air released by heating or dissolution, Hales named calculi “animal tarts for as animal and vegetable substances greatly differ in their salts and sulphurs when chymically analysed, so do also their respective tartar...we see that unelastic Air particles…which are so instrumental in forming the nutritive matter of Animals and vegetables, is by the same attractive power, apt sometimes to form anomalous concretions as the Stone, etc. in Animals, especially in those places where any animal fluids are in a stagnant state, as in the Urine and Gall Bladders...The great quantity of strongly attracting unelastic air particles which we find in calculus...should rather encourage than discourage us, in searching after some proper dissolvent of the Stone in the Bladder...” Since various chemical agents were known to release this "strongly attracting, unelastic air," he thought it at last possible to find a solvent to dissolve the calculi and obviate the painful operation of being "cut for the stone." The pertinent experiments are described in detail in Hæmastaticks, under the title An Account of Some Experiments on Stones in the Kidneys and Bladder. He was unable to discover any chemical solvent, strong enough to dissolve calculi in vitro, which could be administered to man. The only practical outcome of Hales’s efforts was the invention of an instrument for physical removal of stone without surgery, which proved sufficiently effective to be employed by many contemporary surgeons. It consisted of a spring forceps within a
catheter; the instrument was passed into the urethra until the stone was reached, the catheter was then withdrawn just far enough to release the jaws of the forceps and allow them to embrace the stone, and then slipped forward again fixing the stone securely within the forceps. The instrument and stone were withdrawn together. In Hales’s words: “I cut off the lower end of a strait catheter, which made it a proper canula for a stillet or forceps to pass through; the lower end of the forceps was divided into two springs, like tweezers, whose ends were turned a little inwards: these springs were made of such a degree of tenderness and pliancy, as not to bear too hard against the sides of the urethra, by their dilatation. When this instrument is used, the springs are drawn up within the canula; which being passed into the urethra as far as to the stone, the canula must then be drawn back, so far as to give room for the forceps to dilate; which dilated forceps then thrust down a little further so as to embrace the stone, then the canula must again he slid down, to make the forceps take fast hold of the stone, so as to draw it out. I sent this instrument to Mr. Ranby to have his opinion of it, who tells me, that upon repeated trials he found it extracts these stones with great ease and readiness; and that it is so well approved by other surgeons, that many of them make use of it”.

(The reader should remember again that all this was carried on without anesthesia!). Years later Hales proposed a method for helping the stones get off more easily from the bladder: “It hence immediately occurred to my thoughts, that all passable stones which have lately fallen from the kidneys into the bladder, or which have broken off from larger ones, might readily and easily be brought out thence, by conveying into the empty bladder, by a catheter, some very mucilaginous substance, such as syrup of marsh-mallows, or a solution of gum Arabic, or barley water. Such substances would bring the stones away soon, and with great ease to the patient, and thereby not only prevent much teasing pain…” To prove his point, Hales took a glass tube, 1-in diameter and 14.5 in deep, filled with urine, put inside a nearly cubical piece of a large human stone, and measured the time it took to fall through the tube. In other experiments he substituted the urine with olive oil, a water solution of gum Arabic, and warm barley water. His results indicated that addition of the mucilaginous substances to urine increased substantially the impelling (flushing) force for passing the stone into the bladder.

Hales work in developing a medicine that would dissolve stones led him study the medicinal value of various spring waters and also to his appointment to an official board to examine Mrs. Stephens' remedy, a famous nostrum at the time for the stone, which Hales came to support. Hales received the Copley Medal from the Royal Society for his work on a medicine for the stone.

The role and composition of air

By the time of Hales, Robert Boyle (1627-1691) and John Mayow (1643-1679) had established most of the prevalent beliefs about the composition and role of air in different processes. Boyle believed that “atmospheric air consists of three different kinds of corpuscles; the first, those numberless particles which in the form of dry exhalations or vapours, ascend from the earth, water, minerals, animals, etc., in a word, whatever substances are elevated by the celestial or subterranean heat and thence diffused into the atmosphere. The second…consists of those exceedingly minute atoms, the magnetic effluvia of the earth, with other innumerable particles sent out from the bodies of the celestial luminaries and causing, by their impulse, the idea of light on us. The third is its characteristic and essential property, I mean, permanently elastic parts”.
Mayow had shown that fire is supported not by air as a whole but by a more active and subtle part of it, which he called *spiritus igneo-aereus*, or sometimes *nitro-aereus*. In combustion the particulae nitro-aereae, either pre-existent in the thing consumed or supplied by the air, combined with the material burnt. He named the portion left behind after combustion *mephitic air* (carbon dioxide) or air injurious to life and incapable of supporting combustion. The extinction of a candle in an enclosed space was due to the extinction of a specific component of air.\(^29\)

Hales noticed that vegetables and other materials (plums, cherries, peas, hog’s blood, tallow, etc.) released air when placed under vacuum: “A good quantity of air was producible from vegetables…into exhausted and unexhausted receivers…” After much experimenting on the subject he wrote: “Whence it is reasonable to conclude that our atmosphere is a chaos, consisting not only of elastic, but also inelastic particles, which float in it, as well as sulphureous, saline, watery, and earthy particles”.

In his first experiments on the bleeding vine Hales had observed "a continuous series of air bubbles constantly ascending from the stem through the sap in the tube, in so great plenty as to make a large froth at the top of the sap... (this) shews the great quantity of air which is drawn in thro' the roots and stem". These observations led him to begin experimenting on vegetable nutrition "to prove that a considerable quantity of air is inspired by plants". His conclusion was that "air freely enters plants, not only with the principal fund of nourishment by the roots, but also through the surfaces of their trunks and leaves, especially at night, when they are changed from a perspiring to a strongly imbibing state...the leaves are...instrumental in bringing nourishment from the lower parts within the reach of the attraction of the growing fruit...But the leaves seem also designed for many other... important services...The new combinations of air, sulphur, and acid spirit, which are constantly forming in the atmosphere, are doubtless very serviceable in promoting the work of vegetation when being imbibed by the leaves, they may not improbably be the materials out of which the more subtle and refined principles of vegetables are formed. We may reasonably conclude, that one great use of leaves is to perform in some measure the same office for the support of vegetable life that the lungs of animals do for the support of animal life; plants very probably drawing through their leaves some part of their nourishment from the air".\(^8\)

In a long series of experiments he subjected various animal, vegetable, and mineral substances to distillation, fermentation, the action of acids, and other chemical procedures, and collected the gases that were evolved over water. This process was carried on in a glass or iron retort cemented and luted to a globular vessel with a long neck, called a bolthead. In other experiments he subjected weighed or measured quantities of various substances to the action of heat, and the volume of gas evolved (or absorbed) determined; the weight of gas was then calculated, and expressed as a fraction of the weight of the substance from which it had been derived. Hales used the bolthead to measure the air produced by weighed amounts of hog's blood, tallow, powdered oyster shell, amber, honey, and a variety of vegetable materials. Among the many gases he prepared he noted that the "distilled air" of peas "flushed" and that of "Newcastle coal" killed a sparrow; nevertheless he regarded them all as "true air", and showed by weighing that they were not "mere flatulent vapours".

Hales concluded that "air" could exist in two states: an "elastic" or gaseous state in which the particles repelled each other, and a "fixed" or solid state in which the particles were attracted by some other substance. "It is by this amphibious property of air that the main and principal operations of nature are carried out." "Fixed air" was present in all sorts of animal, vegetable, and mineral substances. Air is "very instrumental in the production and growth of animals and vegetables," serving in its fixed state as the bond
of union "and firm connection of the several constituent parts" of bodies, that is, the chief elements or principles of which things are made: "their water, salt, sulphur and earth." He concluded that air should take the place of "mercury" or "spirit" as a fifth element: "Since then air is found so manifestly to abound in almost all natural bodies; since we find it so operative and active a principle in every chymical operation... may we not with good reason adopt this now fixt, now volatile Proteus among the chymical principles, and that a very active one, as well as acid sulphur; notwithstanding it has hitherto been overlooked and rejected by Chymists, as no way intitled to that denomination".1,8

Hales repeated Mayow's experiments on respiration and combustion; he placed a candle on a closed vessel, ignited it with a burning glass, and noted the shrinkage in volume. Same size candles put in vessels of different capacities burned longer in the larger ones and "there is always more elastic air destroyed in the largest vessel." Hales realized that during this process something was generated which vitiated the atmosphere inside the container: "The candle cannot be lighted again in the infected air by a burning glass: but if I first lighted it, and then put it back into the infected air, it was extinguished in 1/5 part of the time". He found a candle burned longer in a closed receiver when the walls were lined with flannel well soaked in a solution of "sal tartar", hence "this must be owing to the sal tartar in the flannel lining, which must needs have absorbed one third of the fuliginous vapours, which arise from the burning candle...It is plain from these effects of the fumes of burning brimstone, lighted candle, and the breath of animals, on the elasticity of the air, that its elasticity in the vesicles of the lungs must be continually decreasing by reason of the vapours it is there loaded with... I then placed a half-grown rat under a vessel, whose capacity above the surface of the water was but 594 cubick inches, in which it lived 10 hours; the quantity of elastick air which was absorbed, was equal to 45 cubick inches, viz. 3/13 part of the whole air, which the rat breathed in: a cat of three months old lived an hour in the same receiver and absorbed 16 cubick inches of air, viz. 1/30 part of the whole; an allowance being made in this estimate for the bulk of the cat's body. A candle in the same vessel continued burning but one minute, and absorbed 54 cubick inches, 1/11 part of the whole air".8 These results led Hales to carry the experiment on himself; he constructed inspiratory and expiratory valves and inspired a measured volume of air out of a container. After returning his expired air back into the container, he found that 1/136th of its original volume had disappeared. This result confirmed the belief that some of the inspired air entered into combination with the blood in the lungs: "I made some attempts... (using) both by fire and also by fermenting and absorbing mixtures, to try if I could deprive all the particles of any quantity of elastick air of their elasticity; but I could not effect it... There is therefore no direct proof from any of these experiments, that all the elastick air may be absorbed, tho' it is very probable it may, since we find it in such great plenty generated and absorbed; it may well therefore be all absorbed and changed from an elastick to a fixed state". Once again, he connected his conclusions with his religious beliefs to explain that the process took place "by a wonderful artifice are admirably contrived by the divine Artificer, so as to make their inward surface to be commensurate to an expanse of air many times greater than the animal's body".8

Hales rejected the notion held by Wilhelm Homberg (1652-1715) and Louis Lemery (1677-1743) that fire was "a particular distinct kind of body inherent in sulphur;" for him fire was "a Body heated so hot as to emit Light copiously," and flame was only a "Vapour, Fume or Exhalation heated red hot". According to him, the extinction of the candle and the death of the animal in an enclosed space were both due to vitiation of the atmosphere and not to exhaustion of Mayow's specific constituent: "If the continuance
of the burning of the candle be wholly owing to the *vivifying spirit*, then supposing in the case of a receiver, capacious enough for a candle to bum a minute in it, that half the *vivifying spirit* be drawn out with half the air, in ten seconds of time; then the candle would not go out at the end of those ten seconds, but burn twenty seconds more, which it does not; therefore the burning of the candle is not wholly owing to the *vivifying spirit*".8

Hales’s results led him to suggest a respirator: “In several unwholesome trades as the smelters of metals, the ceruss-makers, the plumbers etc., it might not unlikely be of good service to them, in preserving them, in some measure at least, from the noxious fumes of the materials they deal in; to prevent which inconvenience the workmen might, while they are at work, make use of pretty broad mufflers, filled with two, four, or more diaphragms of flannel or cloth dipped in a solution of sal tartar or pot-ash, or sea-salt and then dried. The like mufflers might also be of service in many cases where persons may have urgent occasion to go for a short time into an infectious air: which mufflers might, by an easy contrivance, be so made as to draw in breath thro' the diaphragms, and to breathe it out by another vent”.8

**Ventilation**

As mentioned before, Hales’s rebreathing experiments carried out on him convinced him that animal respiration "vitiates" the air with the corresponding physiological danger; "elastic" air, free from noxious fumes, was necessary for respiration. These theories fitted well with the current belief that many diseases were attributable to bad air and "miasmas." He also knew of the high mortality wherever people were crowded together without ventilation. So at the age of 63 he designed his ventilators, describing them to friends, then to the Royal Society in 1741 and two years later in his 160-page *Description of ventilators*.1,19,21,30 These apparatuses were to be used to remove fetid air from prisons, hospitals, and slave ships. Although they did not eliminate airborne bacterial or viral diseases, they seem to have saved many lives in ships, hospitals and prisons: At Newgate Prison, London the annual death rate was reduced by over 100 and at the Savoy prison from 150-100 to only one. They also helped miners to continue working underground.7

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