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Point of View

Stephen Hales and the practice of science

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Introduction

It would be regrettable were this year to end without some commemoration of the 250th anniversary of the death of the Reverend Stephen Hales DD, FRS. Clinicians and virtually all biologists rely on some aspect of his research. While most of us work within a relatively narrow range, Hales made significant contributions to plant and animal physiology on which we still depend, while also contributing to chemistry [1], inventing ventilation systems and winnowing machines [2] and an instrument to remove urinary calculi through the urethra [3], and publishing papers on the causes of earthquakes [4] and the control of fires [5]. The very full scientific life of Stephen Hales has much to tell us about the modern practice of science.

Stephen Hales was born in 1677 in Bekesbourne, Kent, and went up to Cambridge in 1696, where he was elected to a Fellowship at Corpus Christi College in 1702. He was appointed to the parish of Teddington, Middlesex, in 1708 and remained there for much of every year until his death in 1761. He had married in about 1719, but his wife died a year later and he never remarried. He was elected to the Royal Society in 1718 and was awarded its Copley Medal in 1739 for his "experiments towards the discovery of medicines for dissolving the stone, and preservatives for keeping meat at sea". In 1753 he was elected a foreign member of the Académie Royale des Sciences. Hales is buried beneath the tower of his church in Teddington, although a monument in Westminster Abbey was erected in his memory at the instigation of the Princess of Wales to whom he acted as chaplain [6, 7].

The experimental approach for which Hales became especially remarkable started in collaboration with William Stuckeley during his Fellowship. In his subsequent work he kept meticulous records of both the methods employed and the observations as is clear from his published work. However, he did not simply observe and catalogue as was common at the time (for example Linnaeus[1] was a contemporary), he also made measurements and then used them and his data to perform calculations. This is another feature of biological research that

[1] Sachs [8: 89] wrote that "[i]t was not Linnaeus' habit to occupy himself with what we should call an enquiry; whatever escaped the first critical glance he left quietly alone; it did not occur to him to examine into the causes of the phenomena that interested him; he classified them and had done with them ... Linnaeus was in fact a dangerous guide for weak minds, for his curious logic, among the worst to be met with in the scholastic writers, was combined with the most brilliant powers of description ...". Using slightly less forthright language, Miall [9: 329-336] argued that Linnaeus contributed significantly to the "...temporary and partial arrest of development ..." of a century of biological science. This may prompt some to think of a powerful modern parallel.

has declined with the dwindling mathematical skills of biologists, although computer-assisted statistical testing proliferates.

Here, we provide a brief survey of four areas of interest to Stephen Hales: plant physiology, the chemistry of air, animal physiology and the ventilation of confined spaces. We then consider the wider significance of his extraordinary body of work.

Plant physiology

Hales' first publication was *Vegetable Staticks* [10], which deals with phenomena involved in plant nutrition, growth, gas exchange and water relations, such as transpiration, root pressure and the absorption and conduction of water. In it, he makes the critical suggestion that light might do more than just heat plants [10: 327]. All of this work has long been highly regarded by plant physiologists, for example Sachs [8: 477] wrote

> ... Hales may be said to have made his plants themselves speak; by means of cleverly contrived and skilfully managed experiments he compelled them to disclose the forces that were at work in them by effects made apparent to the eye, and thus to show that forces of a very peculiar kind are in constant activity in the quiet and apparently passive organs of vegetation. Penetrated with the spirit of Newton's age, which notwithstanding its strictly ideological and even theological conception of nature did endeavour to explain all the phenomena of life mechanically by the attraction and repulsion of material particles, Hales was not content with giving a clear idea of the phenomena of vegetation, but sought to trace them back to mechanico-physical laws as then understood.

Many of the techniques Hales' described in *Vegetable Staticks* are still useful [11, 12].

The care with which Hales described his methods and the use to which he put his results are apparent from the very first experiment described in *Vegetable Staticks* [10] in which he investigated the water use of a sunflower. In assessing the loss of water from the leaves (now known as transpiration), he had to estimate the total surface area of the leaves on the plant, which he managed with typical simplicity

> I cut off all the leaves of this plant, and laid them in five several parcels, according to their several sizes, and then measured the surface of a leaf of each parcel, by laying over it a large lattice made with threads, in which the little squares were ¼ of an inch each; by numbering of which I had the surface of the leaves in square inches, which multiplied by the number of the leaves in the corresponding parcels, gave me the area of all the leaves [10: 5-6]

He went on to estimate the length of the root system and to *calculate* the corresponding surface area. The analysis of root systems remains a considerable technical challenge even given modern technology [13]. Using these values he then compared the flux of water into the plant through the roots with the transpiration from the leaves. The first four chapters systematically develop various aspects of plant water relations, including the uptake of water by the roots, root pressure and fluid movement.

Chapter VII [10: 317-357] deals with the growth of plants and includes the statement that

> [w]e may therefore reasonably conclude, that one great use of leaves is what has been long suspected by many, *viz.* to perform in some measure the same office for the support of the vegetable life, that the lungs of animals do, for the support of the

> animal life; Plants very probably drawing thro' their leaves some part of their nourishment from the air. [10: 325]

Two pages later Hales makes another important speculation

> And may not light also, by freely entering the expanded surfaces of leaves and flowers, contribute much to the ennobling the principles of vegetables; for Sir *Isaac Newton*, puts it as a very probable query, "Are not gross bodies and light convertible into one another! and may not bodies receive much of their activity from the particles of light, which enter their composition?" [10: 327]

In these two passages Hales captured the essence of the dark and light reactions of photosynthesis [14, 15], in which the absorption of light provides the energy to drive the synthesis of the ATP and NADPH (the light reactions) needed to incorporate CO_2 into carbohydrate (the dark reactions).

Chemistry of air

In Chapter V of *Vegetable Staticks* [10: 148-155], Hales described a series of experiments showing that "... air freely enters plants, not only with the principal fund of nourishment by the roots, but also thro' the surface of their trunks and leaves..." [10: 153]. While we now distinguish between CO_2 and O_2, among other atmospheric gases, Hales did not, despite Chapter VI of *Vegetable Staticks* [10: 155-317] which contains

> [a] specimen of an attempt to analyze the air by a great variety of chimio-statical experiments, which shew in how great a proportion air is wrought into the composition of animal, vegetable, and mineral substances, and withal how readily it resumes its former elastick state, when in the dissolution of those substances it is disengaged from them. [10: 155]

That Hales experiments did not prompt him to develop a theory has been portrayed as a failure by some [16: 28-37] and many critics quote a passage from *Vegetable Staticks* [10: 315] which ends

> ... our atmosphere is a *Chaos,* consisting not only of elastick, but also of unelastick air particles, which in great plenty float in it, as well as the sulphureous, saline, watry and earthy particles, which are no ways capable of being thrown off into a permanently elastick state, like those particles which constitute true permanent air.

It is argued that he did not do any experiments to test the nature of the material he distilled and that he did not realise that air was not an element. However, Lavoisier made the similar criticisms of Hales' successors and acknowledged his own debt to Hales [17]. Furthermore, John Mickleburgh, Professor of Chemistry at Cambridge from 1718 until 1756, suggested that Isaac Newton's chemical "... hints and notices have since been reduced by the reverend and ingenious Mr. Stephen Hales into plain facts and rendered even visible to our eyes by an almost infinite variety of experiments" [18].

While Hales' work on the chemistry of air is often discounted, the pneumatic trough used to collect gases is of lasting value [1]. The trough facilitated the progress in the chemistry of gases due to Cavendish, Priestley and others that stimulated Lavoisier in creation of the new chemistry. Holmyard [19: 159] wrote of the trough

> [s]o simple is the device that, having once seen it in use, we are apt to take it purely as a matter of course and rarely regard it as a supreme achievement of the inventive genius. Perhaps this indifference is only natural, but what an immensity of labour lies

> behind the trite instruction of the text-book: 'Collect the gas over water at the pneumatic trough'!

Of course the design of the trough was adjusted subsequently, but Hales facilitated important progress in the chemistry of gases.

Animal physiology

Hales began his work on animal physiology during his collaboration with William Stuckeley at Cambridge. After a break during his early years in Teddington, when he concentrated on plant physiology and chemistry, he resumed animal experiments. The main record of this work is contained in *Haemastaticks* [20] which comprises experiments on blood pressure and circulation using a variety of species, respiration and urinary calculi.

Hales was the first to measure arterial pressure using techniques reminiscent of those described in *Vegetable Staticks* [20: xviii]. A series of experiments are graphically described in *Haemastaticks* [20] and are reproduced in various biographies [6, 21]. In essence, in experiments I and II he inserted a cannula into the crural artery of a horse and to that he attached lengths of glass tubing through which blood flowed to a height of about 9 feet (about 2730 mm) corresponding to roughly 210 mm Hg ($\approx$ 2730 mm blood $\times$ 1060 kg m^{-3} blood/13534 kg m^{-3} Hg).

The combination of measurement and calculation apparent in *Vegetable Staticks* is applied in the experiments described in *Haemastaticks*. For example, in one experiment [20: 20-21] he measured the internal surface area of the left ventricle (A) and the height of the column of blood supported by the contracting ventricle (h) from which he estimated that the total volume of blood (V) involved was $V = Ah$. Using the density of blood (ρ) he then calculated the mass of blood supported by the ventricle using ρV. His work is filled with quantitative measurements and analysis. While we might not consider that this is especially remarkable, it was rare among biologists at the time [22].

These experiments are disconcerting to us, but they also worried some of Hales' contemporaries. According to Joseph Spence [23: 293], Regius Professor of Modern History from 1742 to 1768, Alexander Pope said of Hales

> ... he is a very good man; only I'm sorry he has his hands so much imbrued 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, or even for some use to us?

Certainly, it is difficult to believe that he would obtain ethical approval for such experiments today. In defence of Stephen Hales, Smith [24], citing a manuscript letter from Hales to John Mickleburgh dated 17 May 1733, suggests that Hales was concerned by his own experiments. Some support for this suggestion can be found in the preface and in the introduction to *Haemastaticks* [20: ix and xvii], where Hales states that the "disagreeableness" of his animal experiments discouraged him from pursuing them, but that the hope of deeper insight eventually spurred him on [20: ix]. Moreover, after the publication of *Haemastaticks* in 1733 Hales again ceased animal experiments and pursued other interests.

Ventilation of confined spaces

Hales knew that exhaled air becomes unfit for respiration [2: 44] and of the long history of mortality associated with crowding in unventilated spaces [25, 26]. The gaols, workplaces and homes of the 18th century were often unventilated and the prevalence of infection was high. The combination of these two factors often had devastating consequences. The problem was especially significant on board the ships of the period and Hales [2: v-vi] argued that

> ... sea-farers, that valuable and useful part of mankind, have many hardships and difficulties to contend with, so it is of great importance to obviate as many of them as possible: and as the noxious air in ships has hitherto been one of their greatest grievances, by making sick and destroying multitudes of them; so the finding of a means to prevent this great evil, is of vastly more consequence to navigation, than the discovery of the longitude; as being a means of saving innumerable more lives, than that would do.

His focus on ships may have been political expedience, because the system was soon installed in several prisons [27], but he was not alone in this approach. In 1741, Mårten Triewald FRS, 'Captain of Mechanicks and Military Architect' to the king of Sweden, devised a similar system that was used in Swedish ships blockading St. Petersburg that summer in the Russo-Swedish War of 1741-1743. The following April, he reported his work to the Royal Academy of Sciences of Sweden and Frederick I ordered that the ventilators be installed in all in his ships. Triewald also sent one of his engines to France where it was approved by the Académie Royale des Sciences, whereupon Louis XV ordered the ventilators to be installed in all his ships.

While Hales' ventilation system had been installed in several prisons [27], the process was accelerated by one extraordinary event. After a sitting at the Old Bailey in May 1750, the Lord Mayor of London, a Lord Chief Justice, two judges, an alderman and at least forty other people died [28, 29]. For much of that day, 300 prisoners from Newgate Prison were crowded into a small space adjacent to the courtroom and it was thought that they were the source of gaol fever, later suggested to be typhus [25]. This event prompted the establishment of a committee to investigate how to procure for Newgate Prison "... such a purity of air, as might prevent the rise of those infectious distempers, which not only had been destructive to the prisoners themselves, but dangerous to others ..." [30: 42]. A ventilation system was installed in Newgate Prison in April 1752 [31, 32] and within a year Hales [27] had some evidence that it had had some effect. Later he reported on the benefits of installing his ventilation system on board ships [33], as Mårten Triewald had been able to before him [34].

What else can we learn from Hales?

Stephen Hales combined elegantly simple experiments with calculation. While this might seem commonplace today, it was novel among biological scientists of the eighteenth century [22]. This prompted Sir Francis Darwin to write

> ... though essentially a physiologist, he seems to me to have been a chemist and physicist who turned his knowledge to the study of life, rather than a physiologist who had some chemical knowledge. [35: 67]

Darwin went on to cite Whewell [36: 431], who argued that "why" meant "through what cause" to a physicist, but "to what end" to a physiologist, and suggested that by this test Hales would be a physicist.

Hales himself felt that he had to justify his approach because, in the preface to *Haemastaticks*, he writes

> In natural philosophy, we cannot depend on any mere speculations of the mind; we can only with mathematicians reason with any tolerable certainty from proper data, such as arise from the united testimony of many good and credible experiments.
> ...
> Yet it seems not unreasonable on the other hand tho' not far to indulge yet to carry our reasonings a little further than the plain evidence of experiments will warrant; since at the utmost boundaries of those things which we clearly know, there is a kind of twilight cast from what we know, on the adjoining border of terra incognita, it seems therefore reasonable in some degree to indulge conjecture there; otherwise we should make very slow advances in future discoveries, either by experiments or reasoning. [20: vi-vii]

It is regrettable that too often modern scientists report measurements, but are reluctant to 'indulge conjecture'.

The second message apparent from the work of Stephen Hales is that breadth of interest can be an advantage. In each of the four aspects of his work that we have outlined, which does not exhaust the range of his activity, he made significant contributions. Hales was too modest a man to make this point himself, but his extraordinary range of interests reflects an unwillingness to be dissuaded from a path by artificial discipline boundaries.

Even 250 years after his death, Stephen Hales is remarkable. To the modern scientist, often constrained to work on a single problem by convention and career considerations, the scope of his research is almost inconceivable. The elegant simplicity of his experiments is a challenge to us all.

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