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Galen, Gaia and global climate change: Harvey and the history of air

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ABSTRACT Harvey's scientific method was taken up by his pupils and successors and led to the discovery of carbon dioxide and oxygen and their role in animal metabolism. The carbon cycle was discovered in the 19th century and by the end of that century the role of carbon dioxide in the greenhouse effect had been demonstrated. The late 20th century saw the gradual appreciation that industrialisation and combustion of fossil fuels were making an important contribution to rising carbon dioxide levels in the amosphere and that the earth's capacity to absorb the excess was limited. We are now at a point where it would be seriously imprudent not to take global action to reduce emissions, in view of the likely consequences of further global climate change. All individuals in the prosperous world need to take action to reduce their carbon footprint; paying it lip service is no longer sufficient.

KEYWORDS William Harvey, oxygen, carbon cycle, global climate change, history

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INTRODUCTION: THE IMMORTAL DR HARVEY

I wish to take you back to a room in William Harvey's brother Eliab's house 350 years ago. Harvey lay on his sick bed awaiting death, which came on 3 June 1657. He was close to 80 years old and must have looked back on his life with a mixture of satisfaction and sorrow. He perhaps reflected on his achievements in describing the circulation of the blood and the development of the embryo, achievements so well known that he was in his lifetime characterised as 'the immortal Dr Harvey'. He had also achieved extraordinary recognition as a physician, being appointed Physician Extraordinary to King James I and VI in 1618 and serving him and his successor, Charles I, who was executed in 1649. He was an establishment figure, and a doughty defender of the exclusive right of the Royal College of Physicians of London to determine who could and could not practise physic.

But he must also have thought of his disappointments; the loss of his wife, his childlessness, his hardships during the Civil War, including loss of his house and his book on insects, and the execution of his friend and sovereign, King Charles I, eight years earlier. England's experiment with republicanism was failing. Cromwell was old and dying, and his succession was unclear. London was becoming anarchic, and religious sects, including Quakers and Anabaptists, were spreading discord and riots. A further three years were to pass before the restoration of the monarchy and the return of Charles II.

It may reasonably be speculated that Harvey welcomed the release death gave from the pain of his chronic gout and the misery of the times around him. But the immortality of his work was assured; he had lit a candle that still burns brightly to this day.

EARLY CONCEPTS OF AIR AND HARVEY'S DISCOVERY

It is hard today to credit that when Harvey went to Cambridge in 1593, the teaching of medicine was based on the work of Galen, Hippocrates and Aristotle. The emphasis was on the classical languages, rhetoric and philosophy, but there is evidence that some dissection and demonstrations of anatomy took place. He would have learned that animal life was supported by *pneuma*, or air, and that this mixed with innate heat in the left ventricle to form vital spirits that, conveyed by the arteries, gave life to the body. Blood was formed in the liver, the source of the veins, and modified *pneuma* to form natural spirits that were conveyed distally by those veins to nourish the body. Vital spirits in turn were modified in the brain to form animal spirits that gave movement and sensation to the body via the nerves. Blood flowed from the three major organs, heart, liver and brain, to the tissues of the body, returning from the liver to the heart, where part went to the lungs and part through pores in the septum. This was the orthodox understanding of physiology from about AD160 until Harvey's time.

Equally, the practice of medicine was dominated by Galen's writings, central to this being the concept, dating back to the ancient Greeks, of the four humours, black bile, yellow bile, blood and phlegm, imbalance of which caused disease. Thus, Harvey learned and practised blood-letting, purging and all the other discomforts visited upon unfortunate patients by physicians from ancient times. This clinical practice was not to be changed by his discoveries, although the iconoclast Paracelsus (1493–1541) had already sown the seeds of an unorthodox but ultimately dominant medicine in the early sixteenth century in which disease was attributed to environmental factors affecting the body.

Harvey's eyes must have been opened when he was at Padua from 1600–1602. For over a century, Italian artists had explored the human body. The greatest of these, Leonardo da Vinci, drew the human body in exquisite detail. He noted the structure of the aortic valve and worked out its function in haemodynamic terms. How such a lateral thinker failed to go one step further and describe the circulation is a mystery; perhaps he just had too many ideas to pursue all to their logical conclusion. However, this artistic interest led directly to Andreas Vesalius, a Belgian Professor of Anatomy in Padua, dissecting and illustrating human anatomy and commenting on the lack of pores in the interventricular septum. His successor, Fabricius, was Harvey's teacher, and he presumably introduced Harvey to the venous valves that Da Vinci had missed. Fabricus first saw these valves in 1574 and claimed to describe them for the first time in a book published in 1603. However, Vesalius and Fabricius, probably inhibited by the general acceptance of Galen's work by the Church, missed the point of their observations, and it was left to Harvey to make the final leap of imagination.

It is likely that Harvey would have contemplated the fate of his soul, though he was not to know how far his influence would stretch in the search for its anatomical seat. However, we know virtually nothing about his religious opinions – in his time, it was probably wise to keep them secret! He had been responsible for initiating the experimental method of philosophical enquiry. In other words, he may be regarded as a founder of modern science. In investigating the function of the heart, he had shown that the heart drives the blood into the arteries, that the amount of blood ejected could not possibly be generated afresh but must circulate, and he revealed the true function of the venous values. While he was not the first to suggest the circulation of the blood, he was certainly the first to demonstrate it experimentally and thus was the initiator of experimental medicine. He had the good fortune to live long enough for his contributions to be recognised in his lifetime and he must have derived satisfaction from seeing his pupils taking his work forward.

Harvey's most important work had been in London and it was while he lived in Oxford with the King during the Civil War that his house in London was plundered. Oxford became the place to which an extraordinary group of polymaths followed Harvey. Chief among these

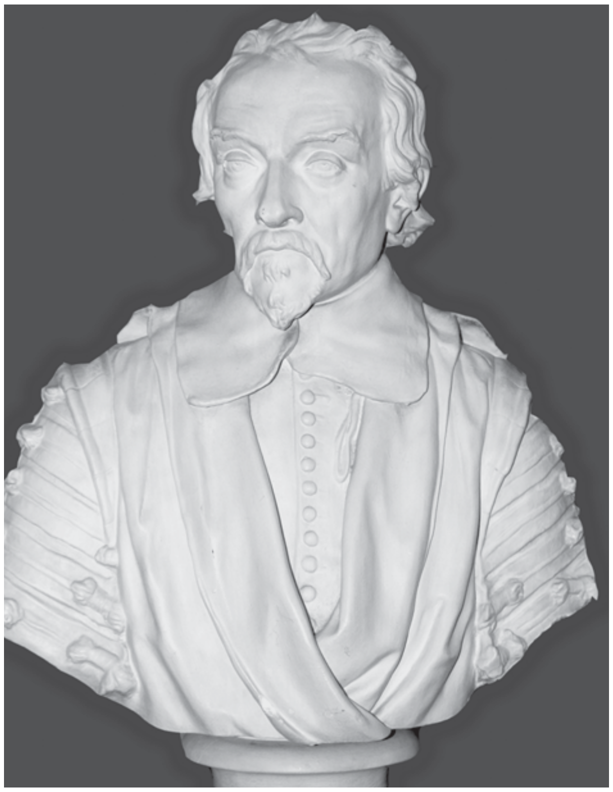

FIGURE 1 Bust of William Harvey in the Great Hall of the Royal College of Physicians of Edinburgh.

was his most notable pupil, Thomas Willis (known for his work on fevers and for founding neurology in his search for the seat of the soul). He was joined by Robert Boyle (known for the discovery that life depends on something in air and for proposing a particulate theory of chemicals), Robert Hooke (known for his work on vacuums and microscopy) and Christopher Wren (known at that time as an astronomer and dissector but soon to be remembered for his architecture). These men together laid the foundations on which were built modern chemistry, physics and biology. John Mayow had in 1668 demonstrated the action of the lungs in taking something (thought of by Boyle as particles) from air into the blood to give it life; in doing this he may be credited with the discovery of oxygen. Hooke and another member of the group, Richard Lower, had by 1670 shown that blood turned red when passing through the lungs of dogs. Prior to this, in 1661, the lung capillaries had been discovered in the frog by Marcello Malpighi, thus solving the mystery of the movement of blood from arteries to veins.

THE ORIGINS OF EXPERIMENTAL SCIENCE

After the restoration of the monarchy in 1660, the Oxford philosophers founded the world's first scientific society, The Royal Society, and its Philosophical Transactions provided the first means of communicating scientific results. A regular correspondent was Antoni van Leeuwenhoek whose extraordinary drawings, made through his single-lens microscopes, included capillaries

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and red blood cells, but further understanding of the relationships between air and life had to wait almost a century for the next big steps in chemistry.

Joseph Black was born in Bordeaux, the son of a Scottish wine merchant, but educated in Glasgow. He was fortunate to be a pupil and later successor to William Cullen, professor of medicine in Edinburgh, who had been the first to introduce chemistry (or chymie) into the medical curriculum. Both Cullen and Black became Presidents of the Royal College of Physicians of Edinburgh. While Black was at Glasgow University, he discovered carbon dioxide. His great innovation was the careful weighing of the products of chemical reactions, and in 1754 he was able to show how the carbonates of magnesium and calcium lost weight when heated, giving off a gas. Following Boyle, he showed that this gas did not support life and that the slaked lime residue reconverted to calcium carbonate when exposed to air. After Black moved to Edinburgh, he passed the problem of the residual air after removal of oxygen to his pupil, the medical student Daniel Rutherford, who later became Regius Professor of Botany. In 1772, Rutherford discovered nitrogen, which he called phlogisticated air.

Although Mayow had shown in 1668 that there was something in air that was necessary to life, it was not until 1771 and 1775, respectively and independently, that the Swedish apothecary Carl Scheele and the radical cleric Joseph Priestley produced oxygen chemically. Scheele called it fire air and Priestley called it dephlogisticated air. Priestley again showed that this was the gas that maintained life. Antoine Lavoisier in Paris, in the first human metabolic experiments, showed that oxygen, the name he gave to the gas, was taken up by man and carbon dioxide excreted in exchange. The first part of the cycle of life on earth, the carbon cycle, had been explained, coinciding with the great advances in chemistry, physics and engineering that led to the Agricultural and Industrial Revolutions.

THE POPULATION EXPLOSION, INDUSTRIALISATION AND THE CYCLE OF LIFE

In 1798, Thomas Malthus published his *Essay on Population*, in which he pointed to the dependence of populations on the availability of resources, and noted that increases in the former followed increases in the latter, that these changes depended on individual cost-benefit decisions and that checks operating when a population exceeded its supply had notable socio-political consequences. The greatest constraint on population growth is the availability of food but, as Malthus was writing, the Agricultural Revolution was taking place, based on mechanisation and rotation of crops. The evidence of this to our modern eyes is the presence still of elegant Georgian farmhouses around the British countryside. Later, this revolution was to receive a boost from the researches of Justus von Liebig, the founder of biochemistry. In the 1830s–1840s, he showed that plants required carbon dioxide and nitrogen, together with essential minerals, for their growth. This led him to develop artificial fertilisers and thus allow unforeseen increases in agricultural productivity. But also, very importantly, he showed that plants take up carbon dioxide and release oxygen, demonstrating the second half of the carbon cycle.

From this time onwards, Malthus' theory that increasing availability of resources allows population growth was confirmed. People migrated to cities and the world's population grew exponentially to its present level of more than six billion. In line with this, and with a switch from the early use of water power to the use of coal and steam, industrial and domestic pollution increased. Even before industrialisation, air pollution had become a problem in London. The diarist John Evelyn wrote 'Fumifugium, or the smoake of London dissipated', in 1661 in the vain hope that Charles II would take some action to reduce pollution from coal burning by dyers, soap boilers, lime burners and others. The reality was that massive increases in industrialisation and in the populations of cities from the late eighteenth century through to our own time led to progressive pollution of the air, but its effects on health, suspected by the people, were not formally recognised until the middle of the twentieth century.

It is not surprising that the emphasis has until recently been on the visible and malodorous components of industrial pollution, the particles and sulphur dioxide. However, it is interesting that in 1824 the mathematician Jean-Baptiste Fourier showed that solar radiation was reflected back from earth and proposed the theory that the temperature of the earth was dependent upon the effect of the atmosphere in preventing all this radiation being reflected back into space. He showed that glass had this effect, thus demonstrating the greenhouse effect.

The chemist John Tyndall showed experimentally in 1860 that elemental gases such as oxygen and nitrogen were transparent to infrared radiation, but that compound gases such as carbon dioxide, hydrocarbons and water vapour absorbed it, thus explaining the ability of our planet to support life. This was taken further by the Swedish chemist Svante Arrhenius in 1896 when he estimated that a doubling of carbon dioxide would be expected to raise the earth's temperature by about 5°C. At the time, and indeed throughout most of the 20th century, this was taken to be no bad thing since it might have been expected to increase agricultural productivity, support the growing population and prevent another ice age. Arrhenius became best known for his demonstration of ionisation of chemicals, a discovery that won him a Nobel Prize and that plays a part later in this story.

AIR POLLUTION, SEEN AND UNSEEN

Air pollution caused by the massive industrial and domestic exploitation of coal was recognised to have serious effects on mortality only in the mid-twentieth century, following dramatic episodes in the Meuse valley in Belgium in 1930, Donora, Pennsylvania, in 1948, and most significantly in London in 1952. This last week-long winter episode was associated with more than 3,000 deaths and led, as had the Thames water pollution episodes in Victorian times, to government action, resulting in a series of effective Clean Air Acts. Over the next 50 years, the traditional coal pollution was replaced by a less noisome but similarly toxic effluent from vehicle exhausts. Nevertheless, over the 1960s to the 1990s, particulate and sulphurous pollution in Britain fell dramatically and for a time the problem seemed to have been solved. But a more insidious and even more serious problem began to become apparent.

It had been recognised since the work of Arrhenius that increasing use of fossil fuel implied increasing production of carbon dioxide and that this might raise global temperature. This was generally regarded as likely to be beneficial. The capacity of vegetation and the oceans to absorb the gas was thought to be close to infinite and certainly adequate to deal with the excess amounts produced. But a note of warning was sounded by an engineer and amateur meteorologist, Guy Callender, who suspected that atmospheric carbon dioxide was rising and in 1938 pointed out that the capacity of the oceans to absorb this gas was limited to the surface few centimetres, with equilibration with the deep ocean taking centuries. In the 1970s, the Green movement drew attention to the loss of vegetation, especially from the tropical rain forests.

These two most important sinks for carbon dioxide were not as capacious as had been assumed. In 1957 the American oceanogapher Roger Revelle, one of whose interests was ocean chemistry and the complex reactions of ions within it, and Hans Suess, an expert on carbon dating, calculated that the capacity of the ocean surface was limited and that with the rapid rises in carbon dioxide emissions then occurring, a point is reached at which the sea starts to release the gas back into the atmosphere. They set up an atmospheric station on Mauna Loa in Hawaii. This station has produced a time series of measurements up to the present day, showing rises from 310 to 390 parts per million (ppm) over 40 years.

GLOBAL CLIMATE CHANGE

It has been possible to relate these rises in carbon dioxide to global temperature change, although this did not become altogether clear until relatively recently. Reliable temperature measurements date back to the 1850s and show a steady rise from about 1920 to 1945, with a plateau up to 1980 and a rapid rise thereafter. Recent modelling by the UK's Tyndall Centre has shown that the shape of this graph is most likely to represent a period with a reduced temperature rise after the war, as a consequence of particulate pollution restricting the incoming solar radiation – an effect now neutralised by anti-pollution regulation in the developed world.

The atmospheric scientists have now gone much further. Challenged by sceptics, they have developed methods for examining atmospheric gases and even temperatures in ancient times by analysing the gases and isotopes present in tiny bubbles trapped in ice cores drilled from glaciers in mountains and polar regions. All tell the same story; carbon dioxide levels are now higher than at any time in the recorded past. Two observations in particular give cause for anxiety. First, ice core measurements now take direct measurement of carbon dioxide back 400,000 years and have shown regular fluctuations between about 180 and 270 ppm, the nadirs coinciding with ice ages related to changes in the earth's axis. As the last peak appeared to be approaching, levels have continued to climb and are now 390 ppm. Certainly it looks as though Arrhenius was right in suggesting that rises in anthropogenic carbon dioxide would prevent the next ice age!

Secondly, geologists, examining fossil leaves laid down in Antarctic rock at the time of the Pliocene period, three million years ago, when man first emerged in Africa and the polar regions were free of ice in the summers and had some vegetation, have estimated from the density of stomata in the leaves that this was the last time that carbon dioxide levels were similar to today's. It does seem likely that rises in global temperature and carbon dioxide are causatively linked to man's exploitation of fossil fuels.

While some may still argue that the link has not been proven and others that a bit of warming is no bad thing, there seems enough evidence now to persuade all but the most hardened sceptic. Dramatic loss of water from inland seas such as Lake Chad, reduction of glaciers in Greenland, the West Antarctic and the high mountain ranges, failure of rain in many parts of central Africa and Australia, death of rainforest and of oceanic algae associated with temperature rise, and oceanic acidification all speak for widespread and potentially catastrophic climate change. And these apparent consequences of rising carbon dioxide levels bring with them further threats of accelerating change, by a process of positive feedback. The death of forests and algae imply a further reduction of the capacity of the earth to absorb the greenhouse gases. The melting of huge amounts of land-based ice at the poles implies rise in sea levels and reduction of the earth's capacity to reflect solar radiation into space. Melting of the permafrost may allow the escape of methane, a greenhouse gas 20-times more potent than carbon dioxide and one that has also been shown to be rising exponentially over the past century, partly in relation to modern agricultural and waste disposal practices. Sea level rises have now been clearly documented and may be

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demonstrated by the frequency with which the Thames barriers protecting London now require to be activated.

It is sometimes forgotten how vulnerable some parts of Britain are to flooding; in 1953 a tidal surge drowned 300 people in the Thames estuary and East Coast of England area. Worldwide, Bangladesh, the Netherlands and many small oceanic islands are at immediate risk and many of the world's great low-lying cities are very vulnerable. The flooding of New Orleans in the US in 2005 has already demonstrated this. Other devastating weather events may be related to global atmospheric change; the frequency and strength of hurricanes, which derive their power from the heat in the oceans, and the frequency of el Niño events are two that illustrate the complexity of atmospheric science and the hazards of modelling these effects. Nevertheless, for these reasons most climate scientists now believe that climate change is accelerating and it is generally held that a further rise of 2°C would put the earth into an irreversible situation, with catastrophic consequences for the biosphere. Assuming the relationship between carbon dioxide and temperature is robust, without dramatic preventive action such a rise may not be more than a few decades away, unless some other unforeseen climatic event occurs.

GAIA AND THE EARTH'S CIRCULATORY FAILURE: IS THERE A SOLUTION?

Much more important than speculating about possible alternative causes of climate change is to consider what can be done to prevent likely consequences. Already, the less fortunate in the world are suffering – Africa from crop failure, the Middle East and Australia from water shortage and Bangladesh from flooding. How many of the world's problems relate directly or indirectly to resource problems exacerbated or caused by climate change? It is worth looking back to Thomas Malthus and the concept that individual cost-benefit decisions determine changes in population and production. It has been pointed out by the scientist James Lovelock, the formulator of the Gaia theory of the earth as a self-regulating organism, that climate change implies dramatic reductions in the human population. But it is probably not too late for effective action to prevent this. Whether this will happen is up to us, but global political action is necessary.

For us in the West to take a lead, we must set an example and take the opportunities to benefit from embracing a low energy future. In bald terms, each individual in the West needs to reduce his or her energy usage by about 75%, while giving our governments authority to invest heavily in renewable and nuclear energy, greenhouse gas capture and altered agricultural and food distribution practices, and to negotiate international agreements that still allow for development of the poorest nations. It is a tall order given the general attitudes prevalent in the consumer society, but essentially it means a move back to the levels of consumption with which we existed relatively easily in the 1950s and 1960s.

CONCLUSION

Looking back 350 years, it is possible to see that Harvey was far more than the initiator of physiology and embryology. His single-minded pursuit of scientific truth by experiment opened up the way in which science was done and led directly to collaboration of the greatest minds across many different areas and the foundation of The Royal Society. He discovered the circulation of the blood, the basis of man's necessary role in the carbon cycle. His successors founded modern chemistry and physics and showed that the circulation of carbon was the basis of life.

In recent times science has fragmented into different disciplines that rarely communicate with each other, yet the lessons from Harvey's successors are clear – transdisciplinary research opens opportunities that cannot be seen from within one discipline. This sort of thinking has led to the concept that the earth is itself an organism, sustained by its own circulation, that of carbon. The story I have recounted, the history of air, is the story of the discovery of this circulation. We now know enough to realise that Gaia, the earth goddess, is in incipient circulatory failure. As we all know, this is a serious illness requiring immediate treatment. We need to move quickly; it is up to all of us as individuals to play our part.

Editor's Note. The Harveian Society of Edinburgh was founded in 1782; its first meeting on 12 April coincided with the anniversary of William Harvey's birthday. The founder of the Society and its first president was Andrew Duncan, a remarkable man who was First Physician to the King in Scotland, Professor of the Theory of Medicine at Edinburgh University, and twice President of this College. Initially, the Society was called the Circulation or Harveian Club, and it acquired its current name in 1829. The annual festival celebrates Harvey's life and the highlight is the presidential oration on some matter related, however tangentially, to Harvey and his achievements. This year is the 350th anniversary of Harvey's death, and to mark the event, this Harveian Oration given by the President, Professor Anthony Seaton, at the Harveian Festival in the College on 1 June 2007 has been published here.

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