A TRIBUTE TO CHARLES RICHARD TAYLOR

CHARLES P. LYMAN PROFESSOR OF BIOLOGY AT HARVARD UNIVERSITY

8 September 1939 to 10 September 1995

Charles Richard Taylor

Charles Richard Taylor, the driving force behind the study reported in the seven papers that follow this tribute, died on 10 September 1995, at the age of 56. One of the leading integrative physiologists, he strived to unravel the intricacies of the way animals work by looking at them as a whole. In 25 years as Director of the Concord Field Station of Harvard's Museum of Comparative Zoology he developed a unique research strategy oriented on systems physiology and he tackled it mainly using the tools of comparative physiology, exploiting the diversity in nature to discover unifying principles of biological design.

After we had, in close collaboration, completed a series of studies on structure–function relationships in the respiratory system, C. Richard Taylor conceived the basic idea of studying, in the same vein, the converging pathways of oxygen and substrates. And he led the investigation to fruition first by recruiting talented collaborators from all over the world and then by actively pursuing the goal with unparalleled determination. The manuscripts were completed in July 1995 while Dick Taylor spent a few days in Switzerland, and they were submitted for publication exactly one month before his death. Without him, this study could never have been done. It is a tribute to his ingenuity as an investigator.

This study also marks the end of 20 years of partnership between Dick Taylor's laboratory at Harvard's Concord Field Station and mine in the Department of Anatomy of the University of Berne; it marks the end of an exciting and particularly fruitful collaboration in which many young investigators have played a most important role as active players.

The origin of a partnership

Dick Taylor and I met for the first time on 5 May 1975, over lunch at the Harvard Faculty Club. By chance I had read one of his papers on the energetics of running animals (1) and this seemed to suggest a solution to one of the paradoxical problems I had encountered in my research on the lung (2). Even before we reached dessert he had suggested that we should launch a joint expedition to Kenya to study the relationship between muscle energetics and the design of the respiratory system in large wild mammals. We had so far worked on totally different fields: Dick Taylor on the efficiency of animal locomotion, and I on the role of structural design in making a well-functioning lung. A single but pivotal parameter was the link between our respective interests: the rate of oxygen consumption and its limit. But with his quick grasp of problems and his vision for solutions, Dick Taylor immediately saw that our two approaches were complementary and that we could, by joining forces, begin to understand the integrated working of a complex functional system where muscles, heart and lung must act together in a coordinated fashion. A system also in which structural design could be an important factor in setting the limits of regulated functions.

The experimental comparative physiologist

Before our collaborative work began, C. Richard Taylor had already developed his research strategy of what I would like to call experimental comparative physiology. He set out to understand physiological mechanisms of adaptation to different functional capacities. In order to do so, he chose primarily a comparative approach, studying the diversity of nature. But he would always test the system by perturbing its function with minimal experimental interventions such as pushing an animal to maximal performance in running up or down a hill or by adding small loads as backpacks, interventions that were near the physiological range.

Beginning with his thesis (1963), the first topic which Dick approached along this strategy was thermoregulation, particularly as it occurs under difficult conditions as in animals running in the hot climate of Kenya. With his mentor Charles P. Lyman, he asked what thermoregulatory role the horns play in antelopes, goats and cows. With Knut Schmidt-Nielsen, who had a great influence on the development of Dick's scientific thinking, these questions were expanded to panting in running dogs, heat regulation in a bird, sweating in the kangaroo and the question of how a desert snail solves its problems of water and heat balance. This culminated in a typical Dick Taylor question: 'Why do bedouins wear black robes in hot deserts?', which was tested in desert experiments together with Dick's close friend Amiram Shkolnik (3). I am not sure that they really answered the question, but they showed that it does not matter for thermoregulation whether the bedouins wear white or black robes and they explained why.

The second broad topic was developed around 1970 as a logical consequence of the study of thermoregulation: energetics of locomotion. Until about 1980 it was to be the dominant research topic which Dick pursued with great ingenuity and imagination, drawing heavily on the comparative approach. He would study animals running up and down hills, or bipedal hopping in kangaroos, and did not shy away from studying cheetahs and lions running on a treadmill. He looked at the effect of limb configuration and of scaling on stride frequency, always in the perspective of energetic efficiency. And here the typical Dick Taylor question was: 'Why do animals change gait?' In their paper published in *Nature* (4), he and D. Hoyt showed that the transitions between walk, trot and gallop in the horse occurred at well-defined running speeds where changing the gait brought an energetic advantage. These were studies of Dick Taylor the Naturalist who rejoiced at exploring the diversity of nature. But this was not all. He engaged in a series of very systematic studies on the energetics and mechanics of locomotion, published in *The Journal of Experimental Biology* between 1980 and 1982, where whole-animal studies were combined with the detailed investigation of muscle fibres to clarify the mechanisms of economic locomotion. Again a Dick Taylor question came up: 'Have African women discovered a way of carrying loads at no cost?' and he showed that they probably have (5).

The respiratory system: use and supply of energy

The studies on the efficiency of locomotion led directly to the topic that brought Dick and me together in 1975: how is the system built that has to fuel locomotory muscles with 'clean energy', i.e. with ATP generated by oxidative phosphorylation, so as to permit endurance locomotion? The rate of oxidative phosphorylation is directly measured by oxygen uptake in the lungs. It was known that oxygen consumption was limited and that this limitation was different between individuals and species. Was this due to properties of muscle cells or was the limitation located higher up in the pathway for oxygen from the lung to the mitochondria? This type of question clearly added a new dimension to Dick Taylor's research.

Our first joint study was originally focused on the question of whether the lung is designed to match the body's maximal oxygen needs. Dick knew how to measure the maximal metabolic rates in running animals, and I knew how to study lung structure quantitatively. We were both interested in the relationships between function and design, and so our basic philosophies were compatible. This facilitated our collaboration in a tough field study in Africa where one does not always work under easy and optimal circumstances. It was impressive to see how Dick could not only convince the authorities that his study was important, but that he could also get wild animals of the size of a wildebeest to perform for him on a treadmill up to their maximal running speeds. Oxygen consumption in animals of different body size varies non-linearly with size such that small animals have a higher oxygen need per unit body mass than large ones. The question we wanted to address was whether the lung's gas-exchange (diffusing) capacity was proportional to the level of maximal oxygen consumption. But when the study was under way in Nairobi we felt that we were missing some important points by restricting the morphological study to the lung. So we decided that the study should be extended to comprise the structure of muscle cells, in particular their mitochondria, the chief consumers of oxygen, as well as the capillaries which supply oxygen to the cells; in fact, we hoped eventually to study the entire pathway for oxygen or what we then called the respiratory system.

The field study in Kenya had streaks of a drama, and Dick enjoyed that: for example, it was very difficult in 1977 – or actually illegal by a newly enacted law – to obtain or capture wild animals for our studies, but they were nevertheless obtained thanks to Dick's persuasive power and to the help of good and influential friends such as Geoffrey Maloiy. To run wild, poorly socialized animals on a treadmill up to their maximal running speed was not easy, but Dick succeeded. Within a period of seven months all the physiological data were collected on 27 animals from 12 species ranging in body mass from a 500 g mongoose to a 250 kg eland antelope. At the end, the animals were killed and lungs and muscle were collected and prepared for an in-depth morphometric study. The physiological data were analyzed at the Concord Field Station of Harvard University, and the electron microscopic and morphometric study was done at the University of Berne. Out of this transatlantic collaboration, nine papers with 19 authors resulted, published as a series in *Respiration Physiology* (6).

This allometric study showed good correlations between maximal oxygen consumption and the morphometric parameters of muscle cells: their mitochondria and capillaries. However, we did not find a good fit between oxygen consumption and lung structure, although this is what we had been looking for: large animals had a relatively larger diffusing capacity than small ones.

The next step, taken at the instigation of Dick Taylor, was to repeat this study by comparing pairs of animals of similar body size whose maximal oxygen consumption differed by 2.5-fold because one is athletic and the other more sedentary, such as in the species pairs dog/goat, pony/calf and horse/cow. Two dozen authors were involved in this study that resulted again in two series with a total of fourteen papers (7–10).

The concept of symmorphosis

We now had a broad data set on the design and function of the pathway for oxygen as it relates to two very different types of variation in maximal rates of oxygen consumption, allometric *versus* adaptive, and we could begin to find answers to some basic questions that had guided our research from the beginning. In our first joint paper on the design of the respiratory system, Dick had entered this sentence: 'In undertaking this task we were motivated by the firm belief that animals are built reasonably' and from this then derived the principle of symmorphosis, which postulates that the quantity of structure an animal builds into a functional system is matched to what is needed: enough but not too much (6). The results of all these studies were synthetized in two papers together with Hans Hoppeler who had assumed, from the beginning, the leadership in the muscle studies (11, 12).

The notion of symmorphosis was exciting, first because it was a great challenge to see whether this is really the way nature works and where the principle breaks down, and second because this bold concept provoked a controversy which helped us to refine our thoughts about structure–function relationships. This controversy culminated in a Symposium held in Ascona in July of 1995 under the leadership of Dick Taylor and which resolved, or at least clarified, many of the issues. The book to be published under the title *Diversity in Biological Design: Symmorphosis – Fact or Fancy?* will be a strong testimony to the legacy that Dick Taylor's concepts have left the world of biology.

Oxygen is not enough

The pathway for oxygen proved to be a good test case for symmorphosis, but it was in fact too simple. Mitochondria also need to be supplied with fuel, carbohydrates and fatty acids, at quite high rates, and so it seemed possible that the design of structures such as the capillaries was not related to oxygen delivery but rather to the supply of substrates for oxidation. Whereas the pathway for oxygen is, in principle, composed of a linear chain of transfer steps, the combined pathways for oxygen and substrates must be described by a network model with parallel limbs converging at the mitochondria. The study of this complex pathway required the expertise of biochemists as well as of physiologists and morphologists, and Dick Taylor succeeded in bringing together a team of outstanding experts to work together and to produce the set of papers that are published in this issue of *The Journal of Experimental Biology* and that were completed just one month before his death. They are further testimony to his extraordinary achievements as a leader in science.

The integrative physiologist

The scientific biography of Dick Taylor shows that he was an integrative physiologist, refusing to do the type of excessively reductionistic research that is today's hallmark of modern biology. He wished to see the grand scheme of how life works. Rather than digging deeper and deeper in a narrow field of interest, he strived to expand to always broader perspectives. His oeuvre is a model case of integrative physiology attempting to unravel and then resynthesize the great complexity and interdependence that is so characteristic of life processes. However, the study of complex functional systems and their design is not an easy matter. No one man, not even one of the stature of Richard Taylor, can carry out such studies all by himself. It demands true interdisciplinary work at the highest levels of competence. I believe it is Dick's greatest achievement that he succeeded in bringing together into joint projects a whole army of the best scientists from all over the world to tackle the problems from very different perspectives and then to synthesize the results into a coherent message. And last, but not least, he attracted many young people to join in and to make novel contributions through their hard work under his leadership.

Dick Taylor's legacy in a nutshell is this: in his nearly three decades as Director of the Concord Field Station of Harvard University he has developed a highly original and unique research strategy whose scientific and conceptual basis was oriented on systems physiology tackled mainly using the tools of comparative physiology, exploiting the diversity in nature to develop and unravel unifying principles of biological design. All this was based on interdisciplinary collaboration, from biochemistry to morphology, and on an international level, from America to Europe, Israel, Africa and Australia. By combining his own high level of competence with the best forces in other fields, Dick Taylor thus established, at the Concord Field Station, a centre of excellence in whole-animal integrative or systems physiology that is unparalleled in the world.

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References

(1) Taylor, C. R. (1973). Energy cost of animal locomotion. In *Comparative Physiology* (ed. L. Bolis, K. Schmidt-Nielsen and S. H. P. Maddrell), pp. 24–42. Amsterdam: North Holland Publ. Co.

(2) Weibel, E. R. (1973). Morphological basis for alveolar–capillary gas exchange. *Physiol. Rev.* **53**, 419–495.

(3) Shkolnik, A., Taylor, C. R., Finch, V. and Borut, A. (1980). Why do Bedouins wear black robes in hot deserts? *Nature* **283**, 373–375.

(4) Hoyt, D. F. and Taylor, C. R. (1981). Gait and the energetics of locomotion in horses. *Nature* **292**, 239–240.

(5) Maloiy, G. M. O., Heglund, N. C., Prager, L. M., Cavagna, G. A. and Taylor, C. R. (1986). Energetic cost of carrying loads: have African women discovered an economic way? *Nature* **319**, 668–669.

(6) Taylor, C. R. and Weibel, E. R. (1981). Design of the mammalian respiratory system I–IX. *Respir. Physiol.* **44**, 1–164.

(7) Taylor, C. R., Weibel, E. R., Karas, R. H. and Hoppeler, H.

(1987). Adaptive variation in the mammalian respiratory system in relation to energetic demand I–VIII. *Respir. Physiol.* **69**, 1–127.

(8) Jones, J. H., Longworth, K. E., Lindholm, A., Conley, K. E., Karas, R. H., Kayar, S. R. and Taylor, C. R. (1989). Oxygen transport during exercise in large mammals. I. Adaptive variation in oxygen demand. *J. appl. Physiol.* **67**, 862–870.

(9) Constantinopol, M., Jones, J. H., Weibel, E. R., Taylor, C. R., Lindholm, A. and Karas, R. H. (1989). Oxygen transport during exercise in large mammals. II. Oxygen uptake by the pulmonary gas exchanger. *J. appl. Physiol.* **67**, 871–878.

(10) Armstrong, R. B., Essen-Gustavsson, B., Hoppeler, H., Jones, J. H., Kayar, S. R., Laughlin, M. H., Lindholm, A., Longworth, K. E., Taylor, C. R. and Weibel, E. R. (1992). O_2 delivery at $\dot{V}_{O_2max}$ and oxidative capacity in muscles of Standardbred horses. *J. appl. Physiol.* **73**, 2274–2282.

(11) Weibel, E. R., Taylor, C. R. and Hoppeler, H. (1991). The concept of symmorphosis: a testable hypothesis of structure–function relationship. *Proc. natl. Acad. Sci. U.S.A.* **88**, 10357–10361.

(12) Weibel, E. R., Taylor, C. R. and Hoppeler, H. (1992). Variations in function and design: testing symmorphosis in the respiratory system. *Respir. Physiol.* **87**, 325–348.