J Physiol 599.5 (2021) pp 1713–1714

LETTER TO THE EDITOR

Contributions by the Cologne group to the development of lactate exercise testing and anaerobic threshold concepts in the 1970s and 1980s

I have enjoyed reading the excellent review on the anaerobic threshold celebrating the abundant work arising from the premise originally put forward by Prof Karlman Wasserman (Poole *et al.* 2021). However, the review has regrettably missed some important contributions published in German by the sports medicine group in Cologne. The aim of this letter is certainly not to criticize the review, as we cannot reasonably expect the authors of the review to include non-English papers, but it is to draw attention to key contributions by the Cologne group on the anaerobic threshold and on the development of blood lactate exercise testing.

In 1976, Prof. Wildor Hollmann's group published a paper on lactate performance tests in *Sportarzt und Sportmedizin* (Mader *et al.* 1976), 3 years after a key paper by Wasserman *et al.* on the ventilatory anaerobic threshold (Wasserman *et al.* 1973). This paper was possible because in the early 1970s Mader and Haase managed to measure lactate in 20 μl of capillary blood. The 1976 paper used this method to measure lactate during graded exercise tests pre- and post-endurance training, in students, long-distance runners, national team soccer players, Olympic hockey players professional cyclists and the 'best professional cyclist in the world' which, in 1976, must have been Eddy Merckx. We know that Eddy Merckx was tested in Cologne and the fact that the rider reached 4 mmol/l of lactate at ~430 W with a $\dot{V}_{O_2max}$ of 78 ml/min/kg suggests that this must indeed have been Eddy Merckx. Because of this journal's style, the paper is an unusual mix of a review and an experimental paper without a methods section. To me, the major new ideas of Mader *et al.* (1976) are that:

(a) the power or speed at the fixed anaerobic threshold of 4 mmol/l of lactate is a sensitive biomarker of endurance performance;
(b) power or speed at 4 mmol/l lactate is a more sensitive biomarker of endurance performance than the $\dot{V}_{O_2max}$ (Hill & Lupton, 1923);
(c) lactate tests can be used to define three training zones, which are extensive endurance training below 4 mmol/l lactate, intensive endurance training at around 4 mmol/l and highly intensive training above 4 mmol/l;
(d) lactate and other performance tests need to be specific for the sport, and the duration of each step and the incline of a treadmill are important design considerations for graded exercise tests.

A potential weak point of this 1976 paper was the pragmatic, fixed anaerobic threshold at 4 mmol/l of blood lactate. This stimulated a flurry of studies attempting to determine individual anaerobic thresholds (Heck & Benecke, 2008; Faude *et al.* 2009). The Cologne team realized that the only way to identify a true, individual anaerobic threshold was to make volunteers perform several bouts of ~30 min near the suspected individual anaerobic threshold and to identify the maximal intensity where the blood lactate concentration remained stable (now defined an increase of $\leq$1 mmol/l during the last 20 min of a constant load exercise). The authors termed this the maximal lactate steady state, abbreviated as maxLass or MLSS (Heck *et al.* 1985). The authors compared the maxLass to the anaerobic threshold as described in the 1976 paper (Mader *et al.* 1976), and further investigated the effect of step duration and gradient during treadmill tests, and thereby published a mathematical model describing the behaviour of the lactate concentration during exercise and discussed anaerobic threshold concepts (Heck *et al.* 1985). In contrast to the 1976 paper, the 1985 paper achieved international impact and the maxLass concept is discussed today (Jones *et al.* 2019).

The third and final piece of work discussed here is the paper of Prof. Alois Mader (Mader, 1984). In this article he developed a complex mathematical model of human energy metabolism which he programmed as a computer simulation in the early days of PCs. In the model, he calculated the concentrations of phosphocreatine, ATP, ADP, and related metabolites (McGilvery & Murray, 1974) in relation to ATP usage. He additionally modelled the rate of glycolytic ATP synthesis based on ADP and the pH and the rate of oxidative ATP synthesis based on ADP. The computer model additionally allowed for entry of workload, anaerobic and aerobic capacity of the simulated individual and then plotted the curves of phosphocreatine, ATP, blood lactate and oxygen uptake all at the same time. Unfortunately, this work was largely un-noted outside Germany and many German students and colleagues struggled to appreciate all those curves. Mader published his model in 2003 (Mader, 2003), but its complexity has discouraged many exercise physiologists from a careful reading. However, it is my opinion that it is worth reading because the simulation models well what others saw in ^{31}P-NMR, lactate and oxygen uptake studies. It even modelled (see Fig. 5 in Mader, 2003) the much debated $\dot{V}_{O_2}$ slow component during exercise above the anaerobic threshold (Jones *et al.* 2011). According to Mader's model, during such exercise the decreasing pH inhibits glycolytic ATP resynthesis, so that oxidative ATP synthesis and thus the VO_2 must rise to compensate. This model is a useful tool for simulating individual exercise responses and for teaching energy metabolism during exercise as it shows how energy metabolism functions, how the different pathways interact and how metabolism is regulated during exercise.

In summary, to me the Cologne group around Profs Wildor Hollmann, Alois Mader and Hermann Heck has made important contributions to exercise physiology, including the development of modern lactate exercise testing, the conceptualization of lactate-based thresholds and a 1980s mathematical model of human energy metabolism that was far ahead of its time. Unfortunately some of the key publications were only in German and this has prevented this body of work from becoming internationally appreciated.

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DOI: 10.1113/JP281142

Edited by: Ian Forsythe & Michael Hogan

Linked articles: This Letter to the Editor has a reply by Gladden *et al*. To read this reply, visit https://doi.org/10.1113/JP281169. These Letters refer to an article by Poole *et al*. To read the article, visit https://doi.org/10.1113/JP279963.

References

Faude O, Kindermann W & Meyer T (2009). Lactate threshold concepts: how valid are they? *Sports Med* **39**, 469–490.

Heck H & Benecke R (2008). 30 years of lactate thresholds – what remains to be done? *Dtsch Z Sportmed* **59**, 297–302.

Heck H, Mader A, Hess G, Mücke S, Müller R & Hollmann W (1985). Justification of the 4-mmol/l lactate threshold. *Int J Sports Med* **6**, 117–130.

Hill AV & Lupton H (1923). Muscular exercise, lactic acid, and the supply and utilization of oxygen. *Quart J Med* **os-16**, 135–171.

Jones AM, Burnley M, Black MI, Poole DC & Vanhatalo A (2019). The maximal metabolic steady state: redefining the 'gold standard'. *Physiol Rep* **7**, e14098.

Jones AM, Grassi B, Christensen PM, Krustrup P, Bangsbo J & Poole DC (2011). Slow component of VO_2 kinetics: mechanistic bases and practical applications. *Med Sci Sports Exerc* **43**, 2046–2062.

Mader A (1984). *Mathematische Modellierung des Energiestoffwechsels auf der Ebene der Muskelzelle*. Cologne.

Mader A (2003). Glycolysis and oxidative phosphorylation as a function of cytosolic phosphorylation state and power output of the muscle cell. *Eur J Appl Phys* **88**, 317–338.

Mader A, Liesen H, Heck H, Philippi H, Rost R, Schürch P & Hollmann W (1976). Zur Beurteilung der sportartspezifischen Ausdauerleistungsfähigkeit im Labor. *Sportarzt Sportmed* **27**, 80–88.

McGilvery RW & Murray TW (1974). Calculated equilibria of phosphocreatine and adenosine phosphates during utilization of high energy phosphate by muscle. *J Biol Chem* **249**, 5845–5850.

Poole DC, Rossiter HB, Brooks GA & Gladden LB (2021). The anaerobic threshold: 50+ years of controversy. *J Physiol* **599**, 737–767.

Wasserman K, Whipp BJ, Koyl SN & Beaver WL (1973). Anaerobic threshold and respiratory gas exchange during exercise. *J Appl Physiol* **35**, 236–243.

Additional information

Competing interests

No competing interests declared.

Author contributions

Sole author.

Funding

No funding was received for this work.

Acknowledgements

I would like to thank Prof. Hermann Heck and Prof. Andrew Jones for useful comments.

Open access funding enabled and organized by Projekt DEAL.

Keywords

anaerobic threshold, exercise, lactate