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Title: Elevating Physiology: Griffith Pugh on the limits of human performance and survival

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Title: Elevating Physiology; Griffith Pugh on the limits of human performance and survival

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As *The Journal of Physiology* celebrates the publication of the 600th volume, it is timely to reflect on the broad contribution made to the advancement of our scientific discipline, and the translation to real-world impact. Since its conception in 1878, *The Journal of Physiology* has featured the works of 42 Nobel laureates and published more than 50 articles with over 1000 citations. In contrast to these high profile publications, the relatively modest works of Dr Lewis Griffith Cresswell Evans Pugh published in *The Journal of Physiology* underpinned what is arguably one of the greatest feats of human endeavour; to reach the summit of Mt Everest. Pugh pioneered the acclimatisation strategies and technological advancements for the successful attempt at the world's highest peak in 1953 by Sir Edmund Hillary and Tenzing Norgay. Pugh's work serves as a reminder of the importance of synergy between mechanistic laboratory research and applied field research, and an important example of how true impact can only be appreciated over time.

Cho Yuo and the 1953 British Everest Expedition

The foundations for the successful ascent of Mt Everest in 1953 were laid in the two years prior, when a British party went to Nepal in the Autumn of 1951 and summited Cho Oyu (8153 m) in 1952. Here, Pugh determined that the biggest issues facing mountaineers at extreme altitudes were physiological in nature, and not necessarily related to climbing. He noted that adequate oxygen flow rates, daily fluid intake, suitable clothing and acclimatisation duration were the limiting factors, and set about determining the optimal strategies for the expedition team (Hunt, 1978). Indeed, the Swiss team that obtained the only licence to climb Everest in 1952 were thwarted just 300 m from the summit due the low flow rates of their oxygen sets (~2 L/min), and returned severely dehydrated. Pugh set about his field work with the same meticulous precision expected in the laboratory, and even devised new methodologies specifically for the expeditions (Pugh, 1953). To determine the oxygen flow rates required, Pugh had to first establish the oxygen cost of muscular work on mountain terrain at varying altitudes. These results were then compared to treadmill experiments conducted at sea level in his laboratory (Pugh, 1958). He established that, once acclimatised, climbers could comfortably perform physical work at an altitude of ~15,000-20,000 ft (4500-6000 m), and that this would be the "effective altitude" to be achieved via supplementary oxygen on the higher slopes of Everest. The level of physical work corresponded to a high rate of oxygen consumption, which focused the need for adequate supplies of oxygen cylinders and respirators that worked at high rates of ventilation. The result was an open-circuit system for oxygen delivery capable of delivering 4-5 L/min, with two specially designed masks for use during exercise and sleep to aid performance and recovery, respectively. Pugh's attention to detail extended well beyond the hypoxic challenge of high altitude, where he designed warm, comfortable and lightweight clothing and equipment, all tested in the laboratory and the field. Of particular importance to Pugh was the maintenance of hydration, and each climber was required to drink 2-3 L/day (Pugh, 2004). The above represents only a brief snapshot of the enormous body of work completed by Griffith Pugh, that supported the successful summit of the world's tallest peak in May 1953. Pugh's recommendations have stood the test of time, particularly in relation to a cautious ascent profile that allows for acclimatisation, and the necessity to remain well hydrated in the dry air of the mountains. It is notworthy that Pugh's recommendations for flow rates of supplementory oxygen are still commonly used today.

Figure 1. Left: Prof. John West and Prof. Mike Ward assembling the cycle ergometer on the Makalu Col (7440 m) with Mount Everest (8849 m) behind on the right and Lhotse (8516 m) on the left. Right panel: Four members of the Silverhut Expedition in London (1971); L. to R. Sukamy Lahiri, John West, Griffith Pugh, Jim Milledge. London in 1971. Photos courtsey of JB West and Breathing on the roof of the world (West, 2017).

<u>Summit to Sporting Success</u>

Over a decade later, Pugh had continued his work in the Himalayan as scientific lead on the Silver Hut Expedition (Gill *et al.*, 1962; Pugh, 1964). This 9 month expedition, where Pugh and his collegeues resided at 5800m for 5-6 months, remains one of the most comprehensive studies on the physiology of acclimatization in human lowlander volunteers at extreme altitude (Milledge, 2010). This first-of-kind programme of research included making mesures of maximal oxygen consumption at 7440 m (Figure 1). Because of his expertise in hypoxic exercise physiology, he was enlisted by the British Olympic Association (BOA). Pugh himself was selected for the 1936 Olympics in the cross-country skiing discipline, although had to withdraw due to injury (Ward & Milledge, 2002). The International Olympic Association had awarded the 1968 games to Mexico City, which sits at 2270 m above sea level, and the BOA wanted to reassure athletes that performing at high altitude was safe. Pugh was commissioned to investigate, and applied his tried and tested combination of laboratory and field research in six of the UK's best endurance athletes. His work reported an 8.5% drop in 3-mile time trial performance on the 4^{th} day in Mexico City compared to sea level, and that performance had recovered to a 5.7% decrease by day 29 (Pugh, 1967). Thus, Pugh was the first to report the decrease in elite sporting performance at high altitude, and the improvements in performance with adequate time for recovery. Similar to his philosophy for mountaineering, he recommended athletes spend as long as practicably possible acclimatising in preparation for competition, with a month the absolute minimum. Despite Pugh's scientific findings, debate around the benefits of acclimatisation simmered, driven by politics rather than science. This led to animosity between Pugh and the BOA and in turn the MRC, with him tendering resignation before being offer his own unit in 1967- paradoxically called the

“Laboratory for Field Research” (Tuckey, 2013). With his independence, Pugh embarked on a period of scientific discovery for athletic performance. He discovered that running economy could be improved via drafting whilst running, with wind resistance accounting for ~8% of total energy cost at 21.5km/hr (Pugh, 1970, 1971). Similar drafting techniques have been recently employed as part of the scientific and sporting efforts to break the 2-hour marathon barrier (Jones *et al.*, 2021).

Thermoregulation and hydration

Due to, in part, the appreciation of the adverse influence of cold on human performance at high altitude, Pugh extended his investigations to the common wet and windy enviroments encountered in the UK where fatal outcomes of accidential hypothermia are some of the highest in the world. This work was especially influential as it guided not only the treatment of such hypothermia, but also on the optimum prevention stratagies such as clothing and shelter (Pugh, 1966a; Pugh, 1966b) that were readily adapted by mountain rescue groups. This work and related recommendations in accidental hypothermia was also extended to many aspects of cold water immersion. Related to this research in hypothermia, Pugh was also interested in heat stress during marathon running and the interaction with hydration. Now a multi-billion pound drinks industry and one of the most researched areas of sport science, Pugh advocated for detailed hydration strategies and the abolishment of rules preventing runners from having access to drinking stations in the first 10 miles of a marathon (Tuckey, 2013). He discovered that even at relatively modest ambient temperatures, heat accumulation could have a detrimental impact on marathon performance (Pugh *et al.*, 1967), and explored new investigative techniques in thermal physiology (Clark *et al.*, 1977). Collectively, Pugh’s work were part of the beginnings of the sport science academic discipline that is now worth £3.9 billion per year to the UK economy alone (The Physiological Society, 2019).

Summary

Dr Lewis Griffith Cresswell Pugh was a pioneering physiologist whose knowledge of exercise and survival in environmental extremes facilitated one of our species greatest physical achievements. His originality, boldness and meticulous approach to both laboratory and field research in the pursuit of answers to real-world problems should be inspirational for current and future generations of physiologists.

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