

## IN MEMORIAM

**Bengt Saltin (1935–2014)**

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The death of Bengt Saltin is an enormous loss. With his exceptional contribution at so many levels, he has, like no one else in the world, been at the forefront of the development of exercise and sports physiology, primarily within research but also in education.

Research within the area of exercise and sports physiology in Scandinavia is internationally renowned. It was initiated by pioneers such as Johannes Lindhard and August Krogh, who at the beginning of the last century created a unique foundation, which their pupils, the three musketeers Erling Asmussen, Marius Nielsen and Erik Howtö-Christensen, built upon (Hellsten & Saltin, 2010). It was in their footsteps that Bengt Saltin, with Professor Erik Hohwü-Christensen as his mentor, from the 1960 s continued the tradition of exercise physiology, first in Stockholm, Sweden and then in Copenhagen, Denmark.



Bengt Saltin grew up in the vicinity of Stockholm, Sweden. His parents were school teachers, and although the original plan of Bengt Saltin was to become a forester in the woods of Sweden, his mother convinced him to become a medical doctor. Bengt Saltin received his Medical degree from the Karolinska Institute in Stockholm in 1962. Already during his medical studies he performed research together with Hohwü-Christensen and published his first

research article in 1960 in the journal *Acta Physiologica Scandinavica*. The title of his work was 'Intermittent and continuous running' (Christensen *et al.* 1960); a theme that today, more than 50 years later, is still in focus in exercise physiology. In 1964, he defended his doctoral thesis with the title 'Aerobic work capacity and circulation at exercise in man'. He received a position as Associate Professor at the Karolinska Institute, where he became professor in 1968. Encouraged by Hohwü-Christensen, Bengt Saltin moved to Copenhagen in 1973 to become professor at the physical education department at the August Krogh Institute. He rapidly developed a strong research environment and established a vast international network within exercise and sports physiology.

In 1990, Bengt Saltin felt compelled to return to the research environment at the Karolinska Institute in Stockholm. He remained in Stockholm until 1993, at which time he accepted an offer from The Danish National Research Foundation to become head of the Copenhagen Muscle Research Centre (CMRC). In the subsequent 10 year period, Bengt was the driving force behind the major success of the CMRC, a research center focusing on many aspects within exercise physiology and health that involved extensive interactions between researchers from the August Krogh Institute, the Panum Institute, Bispebjerg Hospital and the Capitol Hospital of Copenhagen, as well as a broad interaction with many distinguished international research groups. The period at CMRC resulted in the development of many young talented researchers within the area of exercise physiology who today constitute the foundation of the high level of research in Copenhagen within this area. Those of us who have been part of the development will always be grateful for his enormous efforts to develop and promote the area of exercise physiology and health.

Bengt Saltin was internationally a well-renowned man within many areas of physiology. His outstanding position in exercise physiology is evidenced by his many accomplishments; he has published more than 600 research papers and reviews/book chapters, of which more than 50 of his original articles were published in *The Journal of Physiology*, which he always considered to be one of the finest places

to publish. He has been awarded a large number of prizes, including the prestigious Novo Nordic Prize in 1999, the August Krogh Prize in 2001, and the International Olympic committee's 'Olympic Prize on Sport Sciences' in 2002, which is the finest recognition a scientist can receive from the international sports world. In 2011, the Ministry of Culture in Denmark awarded him a prize for his efforts to promote sports and a healthy, active lifestyle for the Danish population. Bengt Saltin held many prestigious lectures, including the first American College of Sport Medicine 'Wolffe Memorial Lecture' in 1973, 'The A.D. Adolph Inauguration Lecture' at the American Physiological Society Congress in 1994, and 'The August Krogh Lecture' at the International Union of Physiological Sciences Conference in 2001. Bengt Saltin was honorary doctorate at 12 universities in Europe and North America, and he has received a degree of honour from both the Danish Queen and the Swedish King.

Bengt Saltin was active and well known in many areas outside of research. He was the co-founder of the European College of Sport Medicine. He was president for the International Orienteering Federation (1982–1988) and later the medical expert for the International Cross Country Skiing Federation. He was highly active in the battle against doping and was the first chair of the Danish agency 'Anti-doping Denmark' and member of the world doping agency, WADA.

Throughout his life, the scientific interest and curiosity of Bengt Saltin was without limit, and he wanted to understand the mechanisms underlying his observations. His area of expertise was very broad and ranged from molecular pathways to the intact organism, with a particular strength in human integrative exercise physiology. One of his specific focuses was on skeletal muscle, and he was one of the first in the 1960 s to make use of the method of obtaining skeletal muscle biopsies using the Bergström technique (Bergström *et al.* 1967). The method allowed for detailed studies of human muscle that had not previously been possible. Together with his Scandinavian colleagues Erik Hultman, Jonas Bergström and Lars Hermansen and American visitors including David Costill and Phil Gollnick, he conducted

a large number of studies examining muscle glycogen utilization and metabolism (Bergström *et al.* 1967; Hermansen *et al.* 1967; Costill *et al.* 1974; Gollnick *et al.* 1974). He maintained a close collaboration and friendship with Phil Gollnick, with whom he wrote the famous chapter 'Skeletal muscle adaptability: significance for metabolism and performance' published in *Handbook of Physiology* in 1983. The chapter has been cited more than 1000 times and has been standard literature for many university students within exercise physiology all over the world.

Bengt Saltin was also one of the leading researchers within the area of cardiovascular physiology during exercise. One of his most well-known studies was a bed-rest study examining the effect of inactivity and activity on cardiovascular alterations in humans. He conducted the study together with his good friend Jere Mitchell and other American colleagues. In the study, healthy young subjects were exposed to 3 weeks of bed rest followed by a period of endurance training (Saltin *et al.* 1968). In accordance with the thorough mindset and never-ending curiosity of Bengt Saltin, the subjects and researchers of the bed-rest study were assembled 30 years later to conduct a follow-up study. Interestingly, they found that the maximal oxygen uptake declined over the 30 year study interval, primarily because of reduced maximal peripheral oxygen extraction (McGuire *et al.* 2004a,b). Maximal cardiac output was maintained, with a reduction in maximal heart rate compensated for by an increased maximal stroke volume. In comparing the studies, they made the remarkable observation that the reduction in maximal oxygen uptake was greater with 3 weeks of bed rest in the young subjects than after 30 years of ageing.

In his search to obtain a better understanding of central *versus* peripheral limitations in the cardiovascular system, Bengt Saltin developed the knee-extensor exercise model, basing it on the highly accurate cycle ergometer of August Krogh (Andersen *et al.* 1985). In the model, exercise was performed with one leg only, with the active muscle being confined to the quadriceps muscle, for which a rather precise estimation of the active muscle mass could be made. In addition, he introduced the thermodilution technique for assessment of leg blood flow through infusion of ice-cold saline into the femoral vein and measurement of the temperature

changes with a thermistor. These methods allowed for measurements of blood flow to the muscle during exercise without the systemic cardiovascular limitation inherent to cycling and other types of exercise involving a large muscle mass. The studies of Bengt Saltin made it clear that the perfusion capacity of skeletal muscle was much higher than previously assumed, and provided some of the first indications that the heart and not the muscle tissue was setting the limitation for maximal oxygen uptake, an issue that has been extensively discussed since (Saltin & Calbet, 2006; Wagner, 2006). The one-leg knee-extensor model and the thermodilution technique provided a major advancement in the understanding of cardiovascular regulation during exercise in man. The impact of this research is exemplified by the fact that the article on perfusion of skeletal muscle that Bengt Saltin published together with his PhD student Per Andersen in *The Journal of Physiology* (Andersen & Saltin, 1985) has to date been cited more than 750 times, and it is the seventh most referenced article in *The Journal of Physiology* ever. The experimental set-up was also combined with measurements of blood gases and compounds in blood drawn from catheters inserted in the femoral artery and femoral vein and with infusion of pharmacological compounds to inhibit or stimulate specific systems. He successfully used such highly invasive and technically advanced methods to gain valuable insight into different cardiovascular aspects, including how the distribution of cardiac output was altered during maximal exercise when the requirement for oxygen supply may increase up to 30-fold (Strange *et al.* 1993; Frandsen *et al.* 2001; Mortensen *et al.* 2007). Distribution of cardiac output was an interest he maintained to his last years, as evidenced by his recent reviews on this topic (Saltin, 2007; Saltin & Mortensen, 2012).

Since his first studies on the effect of muscle glycogen on metabolism and work capacity during exercise in the 1960s and 1970s, he conducted a number of studies within metabolism and energy production using the knee-extensor model (Kiens *et al.* 1993; Bangsbo *et al.* 1990, 1992). Since the 1960s, he had held a basic interest in understanding whether oxygen deficit could be used as a measure of the anaerobic energy production (Karlsson & Saltin, 1971), and by use of the knee-extensor model, he provided evidence for that the oxygen

deficit could indeed be used to represent anaerobic energy production (Bangsbo *et al.* 1990). However, a major assumption in this original study was that the energy production was constant during exercise at a given intensity, which he later could demonstrate, through measurements of heat accumulation and heat release in the muscle, was not the case (Krustrup *et al.* 2001).

The research of Bengt Saltin was not limited to basic science. He was himself a successful orienteer and he had a vivid interest in understanding the limitations of human performance. Even at the beginning of his career, he participated in the preparation of the Swedish athletes for the Olympic Games in Mexico in 1968. A classical photograph found in various textbooks is one of Bengt Saltin cycling on a bicycle, with a local helper sitting behind him holding a Douglas bag to collect expired air from a Swedish top-class runner in order to determine oxygen uptake. Later, he thoroughly studied the world-best Kenyan runners to understand the mechanisms underlying their superiority. From his investigations, he concluded that it is the physical activity during childhood, combined with intense training as teenagers that bring about the high maximal oxygen uptake, and it is the high maximal oxygen uptake that, together with their good running economy, makes them such remarkable runners (Saltin *et al.* 1995). Bengt Saltin also conducted studies with Swedish elite cross-country skiers, and in a highly impressive study published in *The Journal of Physiology*, he had Swedish elite cross-country skiers conducting different skiing techniques on a treadmill with highly invasive measures, and convincingly demonstrated that skeletal muscle vascular conductance is restrained during whole-body exercise in the upright position to avoid hypotension (Calbet *et al.* 2004).

Bengt Saltin also followed up on the long-standing tradition of the earlier researchers at the August Krogh Institute of conducting high-altitude and hypoxia studies, by organizing and participating in several high-altitude expeditions to Kenya, the Himalayas and the Andes (Saltin, 1967; Blomqvist *et al.* 1969; Savard *et al.* 1995). He cherished conducting difficult and sophisticated research in challenging conditions. One of the high-altitude questions he addressed was why heart rate is lower during exercise at altitude, and

he was able to show that the underlying mechanism is an enhanced parasympathetic neural activity (Boushel *et al.* 2001).

Bengt Saltin was known for his kindness and willingness to help. He would share his knowledge and insight with anyone who showed an interest, regardless of their background and possibilities. Bengt Saltin has been an inspiration for several generations of physiologists all over the world. Words cannot express the vast impact a man like Bengt Saltin has had on the area of integrative exercise physiology and, importantly, on the people who have had the privilege to meet him. Few people in science have had or are likely to have such an impact on so many people as Bengt Saltin. We will truly miss him, but we will never forget him; his spirit will keep on living for many, many years ahead.

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## Additional information

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