α ALPHA 126

southern TRAVERSE

Jim Cotter

the ROYAL SOCIETY of NEW ZEALAND

UNIVERSITY of OTAGO
Te Whare Wānanga o Otāgo

Introduction

“Use it or lose it!” – a favourite line about maintaining the health of your body. There’s little doubt that regular physical activity and general well-being go hand-in-hand. But can you have too much of this good thing “physical activity”? Exercise scientists at the University of Otago were curious to know how we respond when pushed to exercise continuously for several days – 100 hours of exercise with minimal sleep! 100 hours – 6000 minutes. That’s equivalent to 75 rugby games one after another or 100 games of netball, or 4 days 4 hours of non-stop dancing! Sound impossible? For most of us it’s only as real as a dream but for some, like environmental physiologist Dr Jim Cotter, it’s the goal of months of multidisciplinary training culminating in one of the great international adventure races – the Southern Traverse. For almost 100 hours Dr Cotter and his three team mates run, cycle, swim, paddle, climb, bush-bash and navigate their way between checkpoints covering about 400 kilometres of coastal, tussock, alpine and forested New Zealand during the Southern Traverse Adventure Race. How does the human body respond to this challenge?

Normally, multiple body systems work in harmony, usually without our being aware of their actions. But the Southern Traverse doesn’t fit the normal domain of physical activity. As scientists, we wanted to find out how the body systems coped. What happens to the muscles and mind? What about the immune system? What happens to critical homeostatic markers like core-temperature, blood glucose and blood volume? How much food and drink is required? What happens to body weight and body composition? How does the brain cope with decision making and navigation under severe sleep deprivation and other stress in new and novel terrains while all the time recognising the demand for optimal speed, for you and your team to reach the finish line?

It’s almost impossible to simulate race conditions in the controlled environment of a research laboratory: No one would volunteer to run and or cycle to near their limits on a treadmill for 100 hours without leaving the room. The only acceptable alternative is to measure performance in the field. The challenge for the research team was to design a comprehensive investigation involving three teams (12 athletes) in the 2003 Southern Traverse in such a way that comprehensive and insightful data could be captured in minimal intervention and interference in the athletes’ race participation.

The investigation became a huge team effort with local, national and international researchers working together. At the University of Otago scientists were recruited from the School of Physical Education, School of Medicine, and Departments of Human Nutrition and Chemistry; at the national level HortResearch and the Academy of Sport were involved, and internationally the resources of The University of Copenhagen provided advanced assays of samples of muscle tissue from the athletes. The investigation focused on three significant data collection periods; before, during and immediately following the 2003 Southern Traverse adventure race that fortuitously started and ended in Dunedin, close to the University of Otago and home-base for most of the research team. The before and after data collection periods provided anchor points or bench-marks for the changes in body system and behavioural functions that might be associated with 100 hours of exercise. High technology opened testing opportunities not previously available: Tiny thermistor pills to measure core temperature, doubly-labelled water to measure energy use, subcutaneous sensors to track blood glucose levels, lap-top delivered cognitive function tests; GPS to track metre by metre location of the athletes; before and after muscle biopsies to assess structural and chemical change in the muscle, and questionnaires to identify changes in mood state. All of this while minimally delaying the athletes in their pursuit of the fastest time over the 400 km journey – whew!! So how did their bodies cope? Did athletes really see pink elephants in the trees?

So how do body functions alter under exercise stress?

We measured heart rate, body core temperature, stress hormones, immune status, movement velocities, and mood state either continuously (e.g. heart rate) or periodically (e.g. hormones, mood) before, during and after the race.

Core body temperature

Why is core body temperature important? If athletes' core body temperature is even slightly too hot or too cold they would use more of their precious stores of carbohydrates, their mood and immune status would likely be affected, and their exercise capacity would suffer. Our body core temperature usually stays within a very narrow band, called a null zone, which rises slightly during each day, and drops back at night. The heat produced in exercise can raise body temperature well above the null zone, to critical levels, whereas swimming in the cold sea and trekking through wet and chilly nights could potentially drop it to critically low levels. Some studies have also found that sleep deprivation and exercise widen the null zone, which means that an athlete's thermoregulatory system might not be called upon early enough or strongly enough to defend against excessive body warming or cooling.

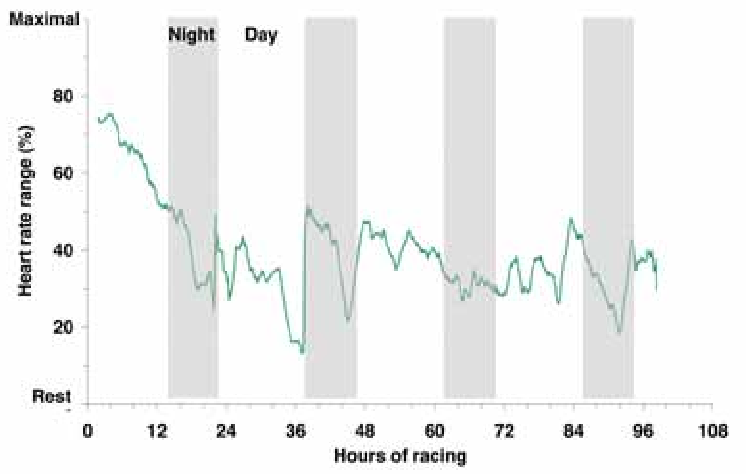
During the Southern Traverse, body core temperature was measured using miniature pills containing a quartz-crystal oscillator and transmitter. Oscillation frequency changes with temperature, and frequency is detected and stored using a portable logger worn by the athlete. We were a bit surprised to find that core body temperature oscillated within the normal range, and remained well below the critically high (~40 °C) and above the low (~35.5 °C) limits, despite the thermal stressors of this race (cold ocean swims, running in wetsuits, trekking and cycling in snow and hailstorms). But, perhaps this shouldn't be a surprise after all: Humans have powerful built-in behaviours to protect body temperature, and it clearly takes more than a few nights with virtually no sleep to knock out these abilities.

Heart rate

The heart rate for the three science teams was monitored every minute throughout the race. – that's over 7000 minutes for some athletes! Heart rate gives an indication of the relative intensity of exercise for each person; the highest level of exercise that we can maintain is partly determined by how much our heart's rate of pumping can increase. If we want to use heart rate to figure out how hard a person is exercising, we need to know what their personal heart rate range is, between resting and exercising as hard as they can. Regular exercise lowers a person's heart rate at rest and during exercise at any given intensity because they have more blood and a larger, more powerful heart. Note however, that aging lowers the maximal heart rate, almost irrespective of fitness.

So how did participating in the Southern traverse affect heart rate?

All three teams started the race at a moderate intensity, and dropped their intensity fairly consistently throughout the first 24 hours illustrated here as the average heart rate across athletes in Team A. Interestingly, the heart rates are very similar among the three teams despite one of them leading for this 24 hours and one coming along at the tail of the field. This indicates that the athletes were racing at similar intensities relative to their own maximum effort. So, one take-home message is that when comparing individuals, speed is not an accurate indicator as to how hard they're exercising.



If you look at the heart rates across the remainder of the race, you can see that once teams had settled into their own pace, they essentially stayed near that intensity level throughout the race – another 75 hours or more! The heart rate spikes reflect periods of harder exercise, such as climbing up onto the Lammamore Mountains and mountain biking up hills in the Berwick forest. The large dips reflect activity transitions and just maybe, the odd forty winks. Because we checked heart rate before and after the race under standardised exercise intensities in the laboratory we could determine whether heart rates across the days of racing remained a valid indicator of racing exercise intensity. This information was useful for measurements related to stress, work rate and energy expenditure estimations within the race.

Hormone levels and immune function

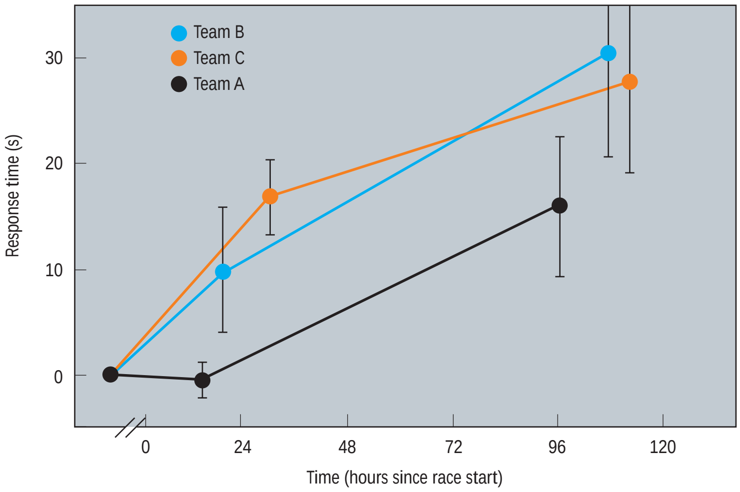
Hormone levels during exercise can indicate athletes' internal stress levels, and provide an indication of many things, including whether they may be deriving energy by literally breaking down their own muscles; how much their normal sleep rhythm control is altered, and how much their immune system is being affected. A strong immune system is important in an adventure race, yet immune function might be affected by the stress of racing. We already know that the stress and high body temperatures of endurance exercise affect the immune system in a similar way to mild infection and trauma. There are raised blood levels of the most common white blood cells (neutrophils), which scavenge foreign particles, whereas there is often a drop in blood levels of white blood cells involved in fighting specific infections (lymphocytes), and also in the level of antibodies that they produce to fight infections. These responses seem to be due at least partly to increase of some concentrations of the major stress hormone cortisol. Cortisol levels rise with increased duration and intensity of physical and psychological stress, and also with elevated body temperature. So, we expected that cortisol levels would rise and lose their daily rhythmicity, and numbers of neutrophils would rise but lymphocytes would drop.

Some of the results were obtained using normal blood sampling, with analyses performed by Southern Community Laboratories in Dunedin. Some of the results required blood components to be sampled many times, before, during, and after the race. Because it is really difficult – and unfair on the athletes – to repeatedly get blood samples from athletes in the environment, we used leading-edge technology, developed by HortResearch, to draw blood components – including hormones – directly through the skin. The technique, known as electrosonophoresis, works by generating an electric potential between the skin and a specialised probe, which draws molecules literally through the skin from the underlying fluid. Small molecules including hormones, glucose and immune chemical messengers can be sampled this way to reflect their levels in the blood. Sampling athletes' saliva also allows measurement of some hormones (steroid hormones) and antibodies.

An interesting observation was that before the race, hormones designed to help us cope with physical stress were already above normal levels. This was possibly an anticipatory or preparatory mechanism – the body getting ready for the big race ahead. The stress hormone cortisol increased, and stayed high, as expected, as did the numbers of leukocytes in the blood. Of most interest, lymphocyte levels didn't fall, and neither did the antibody levels in saliva fall substantially; both indicating that specific immune function may not have suffered much. This unexpected result will be the subject of further study.

Blood volume

Blood consists mostly of two things. Red blood cells make up almost half of the blood and nearly 1/3 of all the cells in our body. They carry oxygen to the other cells, including neurons in the brain and myofibrils in exercising muscle. Just over half of blood is fluid, called plasma, which transports the blood cells, nutrients, waste, heat, and various chemicals, such as hormones. We already know that plasma volume usually drops during exercise, but is elevated in endurance athletes and can even increase by about 7% during the 24 hours following a single bout of exercise, and as much as 25% following prolonged exercise on multiple, successive days. Sleep deprivation affects plasma volume too, expanding it. Hmmm! So how would plasma volume be affected by 100+ hours of exercise combined with prolonged sleep deprivation? We didn't know the answer, since an adventure race like the Traverse isn't really a single bout of exercise, nor is it 5 days of normal training. Although we couldn't measure it directly in the race situation, we estimated the change in plasma volume using an indirect technique that uses the changes in concentration of red blood cells in plasma and the concentrations of the oxygen-carrying molecules packed inside them.



Plasma volume – the first 24 hours

In the first 24 hours Team B – in blue – and team C – in red – increased their plasma volumes a great deal, whereas, no-one in team A showed any increase. We certainly didn't expect to see any increase early in the race. The differences between teams may be due to differences in speed, hydration, and the time in the event at which the samples were taken.

Between days 2 and 5, plasma volume rose in all athletes. Again, we hadn't really expected this, although in hindsight it may not be so surprising. The athletes were basically upright most of the time for nearly 100 hours, and therefore under continual postural stress.

Increased plasma volume is good!

Increased plasma volume has a number of health benefits – although it is not recommended that you achieve this by standing up for over 100 hours! However, having more of the transport medium for red blood cells makes it easier for oxygen to get around the body to where it's most needed, and reduces the competition between organs and muscles for blood supply during exercise. Plasma is also the highway for hormones, immune cells and immune messenger chemicals, and for high-energy molecules such as glucose and free fatty acids. And having a better distribution of blood means your heart doesn't have to work so hard; the beats can be further apart. Imagine if you only had a limited number of heart beats for your whole life: the further apart they are, the longer your life would be! People sometimes think that daily exercise would "use up" heart beats faster, but in reality the saved heart beats at other times of the day and night more than make up for the extra heart beats during exercise.

How hard are you REALLY working?

How hard is your body working? How do we measure that? Should we check heart rate? Speed of travel? We've already seen that both heart rate and speed vary from one athlete to another. Heart rate will give a good indication of how hard one athlete is working, by showing where their heart rate sits within their range. But sometimes an athlete will "feel" exhausted when the physical indicators show that the exercise level is well within their achievable levels. To get a better idea of how hard the work was, we used GPS – to see exactly how far each athlete was travelling – and we asked individuals to rate their perception of how hard they were working. Under more standardised conditions, we also asked athletes to rate their exertion during the exercise tests in the laboratory before and after the race.

We found that the physical indicator – the heart rate – suggested a lower level of exertion to that perceived by the athlete. Does that mean that the exercise wasn't as hard as they thought it was? Probably not; most likely other, non-metabolic or cardiovascular exercise factors were contributing to the mix of factors that collectively cause fatigue. These factors have been identified in controlled laboratory experiments on humans, laboratory animals and isolated muscle sections. They can include neuro-transmittors and immune mediators; electrolytes and their balances across cell membranes; and accumulated metabolites.

How do energy systems cope with 100 hours of exercise?

It takes an awful lot of Weetbix! We estimated that each athlete would use 160-200 megaJoules of energy (that's equivalent to about 600 to 900 Weetbix) within the 4-5 days of racing. During the first morning (4 or 5 hours) we expected the energy to be obtained mainly from the precious stores of carbohydrate in the muscle and liver, and from fat stored in the muscles and fat tissue. Later, energy would be expected to come mainly from the food that each athlete ate, from fat cells, and possibly even from breakdown of their own muscle tissue.

Many aspects of energy use were measured on athletes before, during and after the race:

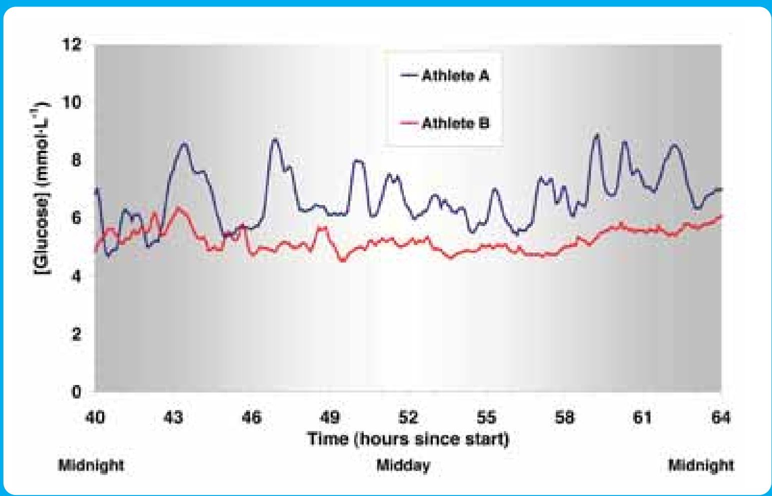
1. Blood glucose was measured constantly during the race for two athletes.
2. Fat mass was measured using the usual skin-fold tests, and also by electrical bioimpedance.
3. Respiratory gases were measured at rest and at different exercise intensities before and after the race to find out how much fat versus carbohydrate is used to power exercise, and how much this balance is altered by the race.
4. Samples (biopsies) of muscle tissue were collected before and immediately after the race, to see what happened to the stores of carbohydrate and fat in the muscle, and to the enzymes that break them down.
5. Doubly-labelled water was used to check how much energy athletes used during the race.

Where does the energy come from?

Glucose is the form of carbohydrate most readily used by our cells, and is essential for brain function. It is transported in the blood from our digestive tract and our liver to various tissues – which either use it immediately or store it. There's only about 3 tspns of glucose in blood, yet our muscles could use this much in 1-2 minutes of hard exercise. So it's not surprising that we have intricate and effective systems to keep the concentration of glucose in the bloodstream fairly stable. If the stability systems fail, what happens? High concentrations contribute to some diseases if they occur frequently (e.g., the common form of diabetes), whereas low concentrations can cause fatigue. Normally your concentration would remain around 5 mmol/l during normal daily activities. A fall to 2.5 mmol/l is often associated with poor mental and physical performance. Regular exercise training improves our body's ability to keep blood glucose stable. However, we expected that this much exercise in one go, with little rest, would deplete stores of carbohydrate in the muscles and the liver, and that perhaps the overall blood sugar levels would then become less stable, contributing to fatigue.

What happened to Blood Glucose levels?

The graph below shows the change in concentration (mmol/l) of blood glucose across a 24-hour period of the Southern Traverse (in this case the 3rd day). This result is typical of the whole race. Surprisingly, blood glucose levels didn't drop very far and remained relatively stable. The periodic increases (spikes) are usual following eating, and the differences between individuals are normal. But glucose was seldom low, even in one case following several hours without eating due to illness (Athlete B).



Fat versus Carbohydrate?

The levels of fatty acids (fat fragments) were measured before and after racing, and found to be several times higher after the race. This probably reflected a high breakdown of fat from adipose tissue and its transport to energy-demanding muscles. We think that the muscles were using fats more, to power exercise. We measured this before and after racing, from respiratory gases (see below), and also measured the fat mass loss.

Where did the fat go?

Skinfold thickness usually gives a more accurate measure of body fat mass than is obtained from bathroom scales. But when you've been upright, awake and constantly under physical stress for all but a few of 100+ hours, the skinfolds can be unreliable, because water builds up in tissue and blood, and folds may be thick for reasons other than fat! To overcome this limitation we used a new method, called bio-impedance analysis, to measure fat. This involved passing electrical current at four frequencies, through eight-electrodes, connected to both hands and feet. Fat is more resistant to electrical current, so the ease with which the current passes from one electrode to another can indicate how much of the tissue in between was fat. The tests were done with athletes fasted, rested, and well hydrated, one day before the race, and again one day after the race. The results indicated a marked drop in the amount of fat stored by the athletes – about 1.4 kg or 11%. This fat usage wasn't evident from either of the tests that are usually used to measure people's fat mass or its change (skinfolds and weight), but was consistent with the high blood fat levels and was supported by another set of measurements to determine the fuel mix in exercise.

By measuring how quickly people use oxygen and produce carbon dioxide under stable exercise conditions we can determine how quickly they're using energy and how much of this energy they're getting from fats versus carbohydrates. This technique has revealed not only the obvious - harder exercise uses more energy – but also that harder exercise causes proportionally more reliance on carbohydrates to provide that energy. (This doesn't mean that less fat is actually used in exercise. In reality more fat is used but it makes up a smaller proportion of total energy, until exercise becomes very intense. The exact exercise intensity at which fat usage starts to drop is debated among exercise scientists.) A major response to endurance training is that your body becomes better at using fats to supply its energy. This is important in a race like the Southern Traverse, where the supply of carbohydrates is so small compared with both the energy demands of the race and the supply of fat. Nine athletes in this race had their energy usage measured at rest and at two relevant levels of exercise before, then immediately after racing, to see how participation in the race modified their fuel use.

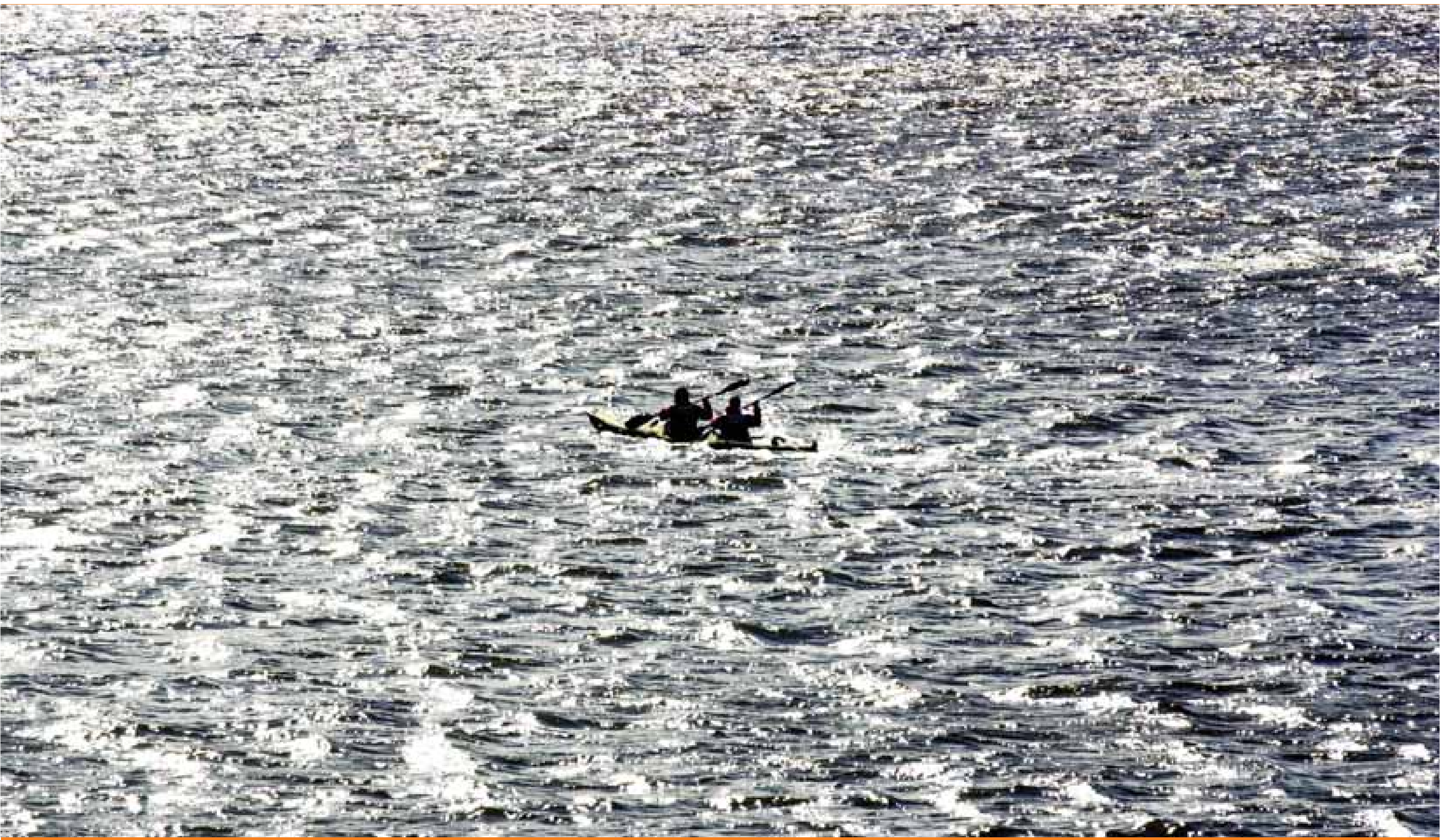
Table: Proportion of energy from fats versus carbohydrates before and after racing.

	Before race % CHO: % Fat	After race % CHO: % Fat
Rest	1:1	1:3
Light exercise	11:9	1:19
Moderate exercise	3:1	1:1

(Note: Fat and CHO fuel only ~90% of the total energy needs, with the rest coming from protein).

What can you find out from the table? Increasing exercise intensity increases the proportion of energy obtained from carbohydrate. Second, the race had a dramatic effect on fat usage, so much so that light exercise had become almost entirely fueled by fat. Third, even moderately hard exercise had become equally fueled by fat.

The end-of-race findings show that athletes became more reliant on fat to fuel their exercise by the end of the race. This is in agreement with the drop in body fat mass and the high blood levels of fat reported earlier. This shift in energy usage could be due to several things: The amount of carbohydrate and fat available in the muscle; the concentration and effectiveness of the enzymes which break them down; or the blood concentration of enzymes that break down fat from fat tissue. To find out which of these explanations was most likely to be true, we turned our attention to samples of muscle tissue taken from the athletes (with their permission!)



What do Muscle Biopsies tell us about Ultra Endurance exercise?

Small samples of muscle tissue were taken from a thigh muscle 2-5 weeks before the race, and then again within 3 hours of completing the race (before athletes were allowed to eat anything). These samples were sent to the Department of Medical Physiology in the University of Copenhagen, in Denmark for analysis by Dr Jörn Helge. We expected to find that the glycogen – which is the form of sugar/carbohydrate stored in muscles – would be extremely low after the race. Surprisingly, the biopsies showed that glucose was only depleted by about half, so athletes' high fat usage wasn't due to them lacking carbohydrate in their muscles. There was no increase in the concentration or effectiveness of some of the important enzymes that break down fatty acids or sugars in muscle, and not much change in the amount of genetic material (mRNA) that drives production of more of these enzymes. One factor that does help account for it was an increase in levels of the stress hormone cortisol, which helps break down and release the fat stored in our fat cells.

Doubly-labelled water

The daily energy usage and intake of 12 athletes was measured by scientists from the Departments of Human Nutrition and Chemistry.

Daily energy use was measured by what we call doubly-labelled water. Each athlete consumes a dose of about 100 ml water (hydrogen + oxygen) which has heavier-than-normal hydrogen and oxygen molecules, on the day before the race begins. They had already provided urine samples, so the scientists could work out the background levels of these heavy molecules before the race. A sample of urine was taken just before race start, and at approximately 24 hour intervals thereafter. The concept of this measurement is clever but reasonably simple. Over long periods (many hours), all our breakdown of stored food energy is done using oxygen (O_2), which forms carbon dioxide (CO_2) and water (H_2O). The heavy oxygen can therefore leave the body in both CO_2 and H_2O, whereas the heavy hydrogen can only leave in water. When people use energy faster, more heavy oxygen leaves as CO_2, which means that there's a faster decay and bigger difference in the heavy oxygen versus heavy hydrogen in water leaving the body (such as in urine).

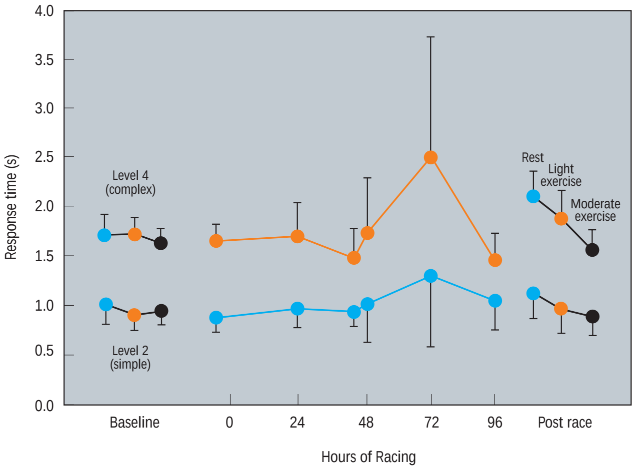
Analysis of the heavy oxygen and hydrogen levels in urine, once corrected for background levels in athletes' bodies, revealed that there was literally about 600-900 Weetbix worth of energy being used across athletes during the 4-5 days of racing. Fortunately they didn't have to eat it as Weetbix!

What's happening in your head?

Does prolonged exercise and sleep deprivation affect team members' ability to think? It's well-known that even moderately intense exercise improves brain function, while sleep deprivation lowers it especially for new tasks. During the race, competitors have to navigate through challenging environments – day and night – to complete the course in the shortest possible time. Successful performance is often dependent on making decisions as quickly and accurately as possible. Mental performance of competitors in the science teams was assessed before, during and immediately following the event using a modified brain function test, first developed by J Ridley Stroop in 1935. Using the Stroop test to measure cognitive performance in the field has been done before, for example during an Everest expedition, to test the effects of altitude on brain function. You can check it out here: http://www.pbs.org/wgbh/nova/everest/exposure/stroopintro.html

In addition to measuring cognitive function, we recorded electrical activity from the competitors' brains while they did the Stroop test before and after the Southern Traverse.

The "Stroop Test" measures the speed and accuracy of reading the names of colours presented in a different colour. It works like this: If the word "red" is presented in yellow letters, the correct response is to say "yellow!" as fast as possible. This is surprisingly hard to do, and it tests both attention and identification abilities. Because our brains have so much experience and practice reading we seem to recognize the "word" more easily than the colour in which the word is presented. **To try the Stroop test yourself, run the test on the DVD that goes with this ALPHA.** The results from the tests before the Southern Traverse provided a baseline against which the results from tests during and immediately following the event were compared. We were also interested in how changes in mental performance might relate to other factors like deep body temperature, energy expenditure, sleep deprivation, and exercise.



With the Stroop test, the two things we were testing for were response speed (time) and error rate (accuracy or correctness).

Focusing on Team A, we can see that response times to both the Simple and Complex tasks remained essentially at pre-race levels during the first two days of the race, but then showed more variability (lack of consistency). The most variable responses occurred at the end of the long trek, and were largely due to one athlete repeatedly falling asleep on task. One quite surprising observation from these data is that as long as a person can stay awake, speed and accuracy at both simple and complex tasks isn't dramatically affected by prolonged exercise and sleep deprivation. This was true for both measures – speed and accuracy – across the whole event.

So what has this initial research shown?

Some findings were unexpected:

It was no surprise that exercise intensity dropped from the high levels on day one, or that fats become the main source of fuel;

But, the extent to which fats were used without carbohydrate stores (at least in muscle) being severely depleted was surprising;

We were surprised that performance on the strength and power tasks wasn't greatly affected, but this may be due partly to the still ample carbohydrate in the muscles;

Indicators of the body's immune functions showed surprisingly little change, and this is something we're continuing to examine;

We expected that after 100 hours with virtually no sleep and so much physical exertion, the brain's decision making abilities would be impaired, but again, test results indicated otherwise. This is another area for continued investigation.

The overall picture is equally fascinating: just how does the mind – at some subliminal level - manage all the information received from multiple body systems, plus the navigational inputs from maps and environment, plus recognition and evaluation of team-mates' condition – and decide just what pace is sustainable?

We realise that the human body is a complex and wonderful thing: that understanding how it works is one of the great frontiers of scientific discovery.

Increasingly, activity in our day to day lives is far removed from this kind of extreme physical challenge. But our bodies are designed to cope with something between these ends of the spectrum. Regular moderate exercise is good for us: It's good for the brain, it's good for many of the body systems, and it's good for health. Many people think that extreme sports are too extreme to be healthy, but the science you've just been reading about hasn't shown that it's any worse than a week of inactivity. We believe that physical challenge is good for us although few take it to such lengths!

Why do people engage in 100 hours of exercise anyway?

There are many reasons. The challenges of it create an exciting feeling of being truly alive, even if sometimes the athletes also feel dead on their feet! Dr Jim Cotter, who was part of this research team and a competitor in the Southern Traverse, says the memories of the weeks he's spent doing Southern Traverse and other extreme adventure races, are incredibly clear. He feels this is because it's a period of being intensely alive and the feeling of pushing the limits of human performance. As our lives get further and further removed from physical challenges for survival, at least some people, an increasing number by popular accounts, seek physical challenge with adventure, train for it, and push themselves through it. We've all read or heard about amazing survival, where people have dragged themselves through ice and snow, or survived being adrift at sea, pushing themselves way beyond what they thought humanly possible. Humanly possible – the sky's the limit!

What can we say at the end?

We are left with a paradox. At first glance, our conclusion is different from what might have been logically predicted. We predicted that the feelings associated with exhaustion (fatigue?), sleep deprivation, and visions of pink elephants would be reflected in a disruption of the normal harmony of body systems working together. After all, the physical activity accompanying the Southern Traverse is hardly "normal" and surely the competitive drive to finish would impose huge strain on the body's systems. Yet, while nearly every competitor was totally "stuffed" at the end, our records indicated that pretty much every measure was within "normal" limits. The challenge for future research is to find out what's happening: what keeps people's need for speed balanced so well against their bodies' ability to cope.

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