Section 3 :

Physiology

The Need for Exercise

The need for exercise is quite simple and stems from the fact that changes in society take place at an incredible rate whereas the evolution of man is a much slower process. When compared to our predecessors, modern society requires less physical activity but we are subject to greater stress. Inactivity and stress form a lethal cocktail that is the major cause of heart disease, high blood pressure and certain forms of cancer which together account for the majority of deaths in Western society.

Stress is not all bad, we need a certain amount to stimulate us into action; too much stress is bad especially if the stress level cannot be relieved. Stress activates a mechanism in the body releasing chemicals that allow for a tremendous burst of energy. This is a vital survival mechanism know as "fight or flight", however, the stressors that trigger this mechanism in modern man often stem from frustration in traffic jams, train cancellations and computers crashing.

Unlike our predecessors we are unable to run freely or climb the nearest tree to restore the chemical balance of the body. We have to sit there whilst the chemicals released for action stagnate in our blood stream causing untold long-term damage.

The body is a truly magnificent machine with a capacity to correct a lot of these problems. Too often unaware of the consequences, we go until the situation becomes chronic. However, there are some indicators that all is not well and one of the more obvious signs is when we start to put on weight.

Recent surveys show that over 50% of the population of the UK are overweight and only the USA, with more than 60%, is in worse shape. Being overweight increases the risk of serious health problems and in most cases is unnecessary. Excessive weight gain will not happen overnight and a regular exercise routine along with a sensible diet will keep you in good shape.

In order to maintain a healthy lifestyle we must have an understanding of how our body works, how to train it to improve its efficiency and how to provide it with the nutrition that it requires.

If you want to know more about how your body works and how each energy system is trained, then read the rest of this section. If not, then you can go straight to the next section.

Your Body

Whatever you are doing, whether you are running a marathon or lying in bed you require energy. If you do nothing at all, then you only require a very small amount of energy to keep you alive. This is called the basal metabolic rate (BMR) and is the minimum amount of energy that your body can survive on. Anything that you do adds to your energy requirements. Any kind of exercise or movement requires energy so it follows that the body must be able to provide for these energy requirements. This section of the guide will explain how the systems that produce energy in the body work, the fuels that they require and the systems that supply those fuels and remove the waste products.

The Energy Systems

To produce movement the body must break down an energy store to release energy in a form that it can use. The energy store that the body requires to release this energy is called adenosine triphosphate (ATP). When the body breaks down the ATP the energy released is in a form that can be used to create movement.

The Anaerobic System

The anaerobic system has two energy pathways, the phosphocreatine, creatine phosphate or alactic system which provides very rapid release of ATP but only lasts for ten seconds, and the lactic acid system which is slightly less rapid but lasts for up to four minutes.

The alactic system relies on the substrate creatine phosphate that is stored in the muscles and because of its short duration is the main energy source used by 100m sprinters and weight lifters. After high intensity exercise your creatine phosphate levels will be depleted and can be resynthesised using energy from glycogen metabolism.

The lactic acid system breaks down glucose, or glycogen (stored sugar), to produce ATP. It comes into use immediately after the alactic system and can produce enough ATP for up to four minutes of high intensity exercise, but peaks at one minute. For this reason a 400m runner or 100m swimmer relies heavily on this system for their energy. Unlike the alactic system the lactic acid system leaves behind a by-product, lactic acid. Lactic acid causes the muscles to become more acidic, work less efficiently and causes the muscular pain that we associate with exercising hard. Therefore we try to minimise the production of lactic acid wherever possible.

The Aerobic System

The aerobic system is the slowest of the three systems to work but has the advantage of lasting indefinitely. This is the system that produces the energy required for the BMR and any non-sprinting movement that takes place throughout the day. Like the lactic acid system the aerobic system can use glucose or glycogen as its fuel but can also use fat, which produces much more ATP. The aerobic system is able to produce 19 times more ATP from each molecule of glucose than the lactic acid system can but has the disadvantage of requiring oxygen so takes as long to start as it takes the oxygen requirements of the cell to be catered for. For this reason the aerobic system does not take over from the lactic acid system for approximately three minutes. When fat is used as the fuel for the aerobic system it produces much more energy than glucose or glycogen but requires even more oxygen and so it can take between 20 and 40 minutes for fat to take over as the main fuel as it takes this long for the oxygen requirement to be met.

How Do the Fuels Get to the Muscles?

There are two body systems responsible for supplying the demand of fuels for the energy systems. These are the respiratory system and the circulatory or cardiovascular system.

The Respiratory System

The respiratory system consists of the lungs and respiratory muscles (the muscles of the chest wall, the abdomen and the diaphragm). The main job of the respiratory system is to inhale air, allowing the oxygen in the lungs to diffuse into the blood and the carbon dioxide in the blood to diffuse into the lungs to be exhaled. The oxygenated blood can then be transported around the body through the cardiovascular system.

The Cardiovascular System

The cardiovascular system consists of the heart and blood vessels. It is responsible for circulating the blood through two circuits. The first pumps the deoxygenated blood from the right side of the heart to the lungs where it becomes oxygenated as the oxygen bonds to the haemoglobin molecules in the red blood cells. The oxygenated blood then returns to the heart. The second circuit pumps the oxygenated blood from the left side of the heart around the body. Because the left side of the heart has to pump the blood further it is more muscular than the right side. The blood is pumped through the intestines and stomach where it collects nutrients and then to the muscles or organs. It then travels to the cells where it releases the nutrients and oxygen and collects the waste products and carbon dioxide and returns to the heart. The cycle then starts again.

During exercise the heart rate increases in response to demands for increased blood flow. This controls the body temperature and the supply of oxygen and nutrients to the working muscles. During heavy bouts of exercise the amount of blood flowing at any given time can increase by a factor of seven as a result of increased heart rate and stroke volume. Heart rate increase is initially linear and directly proportional to exercise intensity.

The blood plays a very important part in both supplying the fuels and removing the waste products of energy synthesis and in the maintenance of homeostasis (maintaining the body at balance). It is composed of 55% plasma of which 90% is water, 44% red blood cells (erythrocytes) and about 1% of white blood cells (leukocytes) and platelets (thrombocytes). The red blood cells have the haemoglobin molecules which bond with oxygen and allow the transportation of oxygen, the white blood cells fight infection, the platelets allow clotting in the case of a cut or abrasion and the plasma supplies water to the cells and helps to maintain the body temperature. If there is a shortage of any of the constituent parts of the blood the body is not able to function properly. If there is not enough haemoglobin or red blood cells the person may feel weak. This is called anaemia and is common both in pregnant women and in endurance athletes. It is caused by a lack of iron, the important part of the haemoglobin molecule, and can be easily cured with an iron supplement. If you think you might be anaemic then you should visit your doctor for professional advice.

VO_2 Max

When exercising the level that we can work at is normally limited not by the fuel stores in the muscle but by the maximum amount of oxygen that the body can take in and utilise in any one minute. This is called the VO_2 max. VO_2 max is limited by the amount of blood that can be pumped through the lungs and to the working muscles and by the efficiency of the lungs. The maximum value possible for a person's VO_2 max is capped by their genetic make up but the right training can help you achieve your potential. (A test to calculate your VO_2 max is given in Physiological Tools in Section 3 : Physiology).

The Effects of Training on the Body

The effects that training has on the body is dependent on whether the training undertaken is aerobic or anaerobic so these effects will be explained in two sections.

Aerobic Effects

By following an aerobic training programme for as little as 12 weeks you can make significant improvement in your VO_2 max. This is possible because you have made some physiological changes to the parts of the body that limit your VO_2 max. The heart responds to aerobic training like any muscle does to work: by getting bigger. This is called cardiac hypertrophy and results in an increase in the amount of blood that can be pumped out in each beat (the stroke volume) and hence an increase in the amount of blood that can be pumped in one minute (the cardiac output). This change to the heart means that the heart needs to beat fewer times to move the same amount of blood, therefore your resting heart rate will decrease. The lungs are also affected by aerobic training. They become more efficient and are able to take in more air per breath and take more breaths per minute. The final changes that occur due to aerobic training is that your blood volume increases due to an increase in blood plasma and red blood cell volume and the muscles become more efficient due to an increase in the ability to transport oxygen within the cell and to respire (resynthesise ATP).

Anaerobic Effects

The changes that take place in the body due to anaerobic training are limited in number compared to those that take place due to aerobic training. This is because many of the changes caused by aerobic training are an improvement in the ability to carry or utilise oxygen. In anaerobic training this system is not required so the adaptations are limited to four major points;

1. Muscle hypertrophy - the muscles used in high speed activities (the fast twitch muscle fibres) will increase in size.
2. Enzyme activity increases in the enzymes that are responsible for anaerobic energy production and recovery from anaerobic activity.
3. Energy stores of the anaerobic energy sources, ATP, phosphocreatine and glycogen increase in size.
4. Lactic tolerance - fast twitch muscle fibres become more tolerant to increased levels of lactic acid.

The changes outlined above show that it is very important to know what changes you wish to take place in the body before you start training so that you can ensure that you are doing the right sort of training to promote the improvements that you require.

Training Intensity

With improved knowledge of the energy systems that we use during exercise we can now move away from the "no pain, no gain" approach to training that has been prevalent, even recently, in some sports training. Exercise physiology has come a long way in the last fifty years and is now a much more exact science, capable of providing individuals with training programmes specific to their requirements. This section of the Training Guide aims to outline how varying the intensity of training can be used to bring about specific improvements in fitness with a much lower risk of illness or injury than the "no pain, no gain" philosophy. For all but the most experienced elite athletes the best way of monitoring training intensity is by ensuring that the heart rate is in the correct training zone. In order to do this we must have an understanding of resting heart rate, maximum heart rate and the difference between them - the heart rate range, the aerobic threshold and the anaerobic threshold, so that the correct training zones can be calculated.

Resting Heart Rate (RHR)

The heart, along with all of the other major organs in the body, is controlled directly by the autonomous nervous system; this means that we have limited conscious control over them. The heart responds directly to the demands placed upon it by the functions of the body. During rest the majority of blood flow is to the brain and major organs. To be able to identify the energy requirements of exercise and the correct training bands for heart rate we need to have a baseline; the resting heart rate. This can be measured by taking your heart rate as soon as you wake up, even before getting out of bed. Keeping a record of your resting heart rate can also help monitor your immune system thereby preventing over training and minimising the likelihood of getting ill. This is because your resting heart rate becomes elevated when your immune system is struggling to fight off infection. If you notice an unexplained rise in RHR of more than six to eight beats per minute then you should not train until it has returned to normal.

Maximum Heart Rate (MHR)

Maximum heart rate will vary depending on what you are doing to bring your heart rate up. Running will elicit a higher maximum heart rate than rowing which in turn will elicit a higher maximum than swimming. This is due in part to the fact that runners are upright and so the heart has to overcome the gravitational pull; rowers are seated and so the effects of gravity are reduced and swimmers are prone further reducing the gravitational pull. It is important to know what your maximum heart rate is as it enables you to calculate the correct training bands for heart rate. One method of calculating MHR is to use the equation MHR = 220 – age, but this can be very inaccurate, having an error of ±15/20 beats per minute (BPM). A more accurate method of finding your MHR is given in Physiological Tools in Section 3 : Physiology.

Heart Rate Range (HRR)

Heart rate range is determined by subtracting the resting heart rate from the maximum heart rate. When training bands are identified by percentages of heart rate, it is percentage of the HRR that is referred to. This value is then added to the RHR to give the training heart rate.

The Aerobic Threshold

Exercise brings about an increase in lactic acid in the blood, which at rest would be around 1mmol. The aerobic threshold is defined as a blood lactate concentration of 2mmols. This normally occurs at approximately 60% of maximum heart rate and is the lowest intensity that we regularly train at.

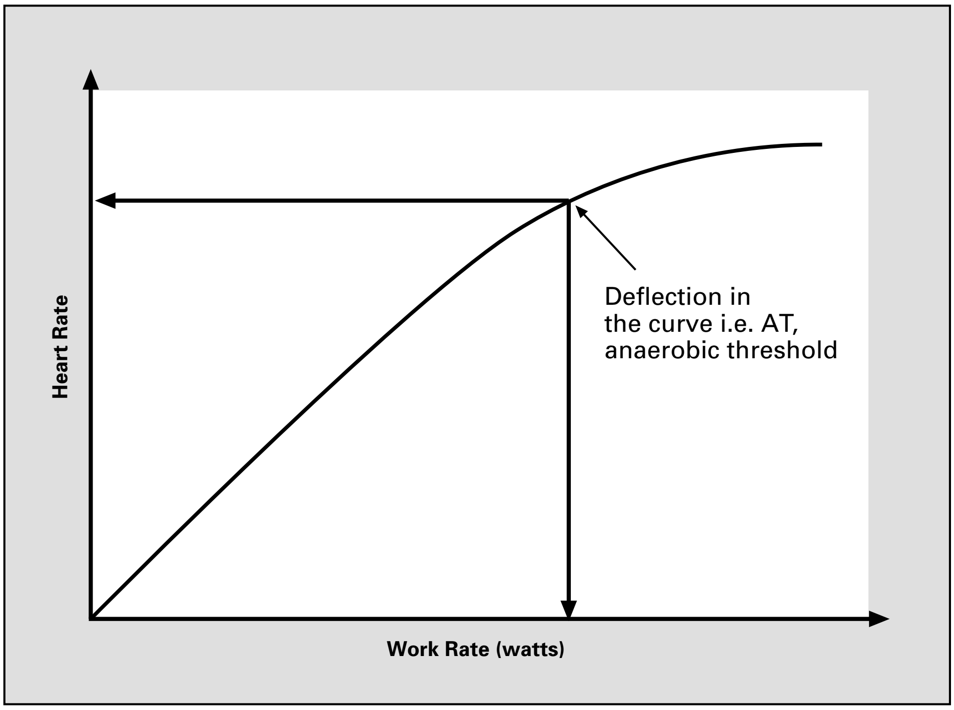
The Anaerobic Threshold (AT)

The anaerobic threshold is measured at 4mmols. At this point the lactic acid production is at the maximum level at which it can be metabolised and so it starts to accumulate in the working muscles, greatly reducing their efficiency. Anaerobic threshold is frequently measured as a percentage of aerobic capacity or VO_2 max and can be anywhere in the range of 50% to 85% of VO_2 max depending on fitness.

Because the heart has a limit on how fast it can beat there comes a stage where any further increase in demand for oxygen cannot be met. At this point there is a deflection in the heart rate/work rate graph (see below). The rate of increase slows down and eventually plateaus out at heart rate maximum. Many physiologists identify this point of deflection as the anaerobic threshold and exercise carried out above this level is anaerobic.

Training in this band has a greater effect on the development of the heart than training at a lower intensity. The development of muscular efficiency continues at a higher intensity but because training in this band is more physically demanding than aerobic training it cannot be sustained. Consequently although muscular efficiency is being trained at a higher rate it is for less overall time and therefore may not yield the same benefits.

For people with limited time to train, exercise within this band will have the greatest short-term effect.



Training Heart Rate

Training heart rates are divided into bands. These bands are determined by four key physiological points; resting heart rate, maximum heart rate, heart rate at aerobic threshold and heart rate at anaerobic threshold. In an unfit person the anaerobic threshold can occur as low as 50% of maximum heart rate but in a highly trained athlete this can be as high as 85% of maximum heart rate.

When starting out on a training regime, either from scratch or after several years of no regular exercise, then the simple method of determining your training heart rate can be used. This simply requires you to subtract your age from a nominal figure of 220, which represents maximum heart rate. You then apply the relevant percentage referred to in the training programmes to this figure. Any errors in this method will be on the safe side but as you get fitter you may want to use the heart rate range method.

If you have been exercising regularly you should calculate your maximum heart rate using the test in Physiological Tools in Section 3 : Physiology and then calculate your training bands accordingly.

Training Bands

Training heart rates are divided into five bands, determined by the RHR, MHR, aerobic threshold and anaerobic threshold. The five training bands can be divided into aerobic and anaerobic. The aerobic bands, utilisation training 2 (UT2) and utilisation training 1 (UT1), rely solely on the aerobic system and form the foundation of most training programmes. In these bands the main fuels are carbohydrate and fat, the percentage of each is dependant on the length of the exercise period. The anaerobic bands, anaerobic threshold (AT), oxygen transport (TR), and anaerobic (AN) combine the full output of the aerobic system with varying input from the anaerobic system. The fuel for these bands is carbohydrate.

The table below illustrates the relationship between the training bands and stroke rate. It describes how you may feel during the training and the training effect of working within each band.

Table 3.1

Training Bands					
Band	**Type of Work**	**% MHR**	**Rate (SPM)**	**What it is good for**	**How you feel**
UT2	Utilisation 2. Light aerobic, low intensity work. Sustain-able and fat burning.	55-70	18-20	General CV fitness.	Relaxed. Able to carry on a conversation.
UT1	Utilisation 1. Heavy aerobic work using more oxygen.	70-80	20-24	Higher level of CV fitness.	Working. Feel warmer. Heart rate and respiration up. May sweat.
AT	Anaerobic Threshold. Harder work. On the aerobic limit. Pushing into anaerobic area.	80-85	24-28	High level of CV fitness. Building mental and physical tolerance.	Hard work. Heart rate and respiration up. Carbon dioxide build up. Sweating. Breathing hard.
TR	Oxygen Transportation. Working hard. Unsustainable for long periods.	85-95	28-32	Developing oxygen transport to the muscles under stress. Increasing cardiac output.	Stressed. Panting. Sweating freely.
AN	Anaerobic (without oxygen). Short bursts of maximum effort. Unsustain-able. Burning carbohydrate.	95-100	32+	Anaerobic work. Increasing speed. Accustoming the body to work without oxygen.	Very stressful. Gasping. Sweating heavily.

Notes

SPM = strokes per minute

%MHR = percentage of maximum heart rate

CV = cardiovascular

The different training bands use differing amounts of carbohydrates and fats as their primary source of fuel. Table 3.2 below gives a rough indication of the fuel usage at different intensities of exercise. Remember that this is only a rough guide as the percentage of fat versus carbohydrates used during exercise is dependant on duration and fitness as well as intensity.

Table 3.2

Relationship between Exercise Intensity and Energy Source				
Exercise Intensity %MHR	**Heart Rate (bpm)**	**% Carbohydrate**	**% Fat**	**Length of time at required intensity**
65-70	130-140	40	60	60-90 mins
70-75	140-150	50	50	30-60 mins
75-80	150-160	65	35	15-30 mins
80-85	160-170	80	20	10-15 mins
85-90	170-180	90	10	4-6 mins
90-95	180-190	95	5	90 secs-4 mins
100	190-200	100	-	45-60 secs

Notes

Example 20 year old, MHR = 200

Physiological Tools

In order to achieve accurate results the same pre-test protocol should be carried out before the tests each time you undertake them. This should include:

- Being in good health.
- Being well rested with no heavy training sessions in the last 48 hours.
- No alcohol consumed within the last 24 hours.
- No strong coffee or tea in the previous three to four hours.

You will need a heart rate monitor and interface and where possible someone to record your results. The drag factor can be set to individual preference (see The Damper Lever and Drag Factor in Appendix).

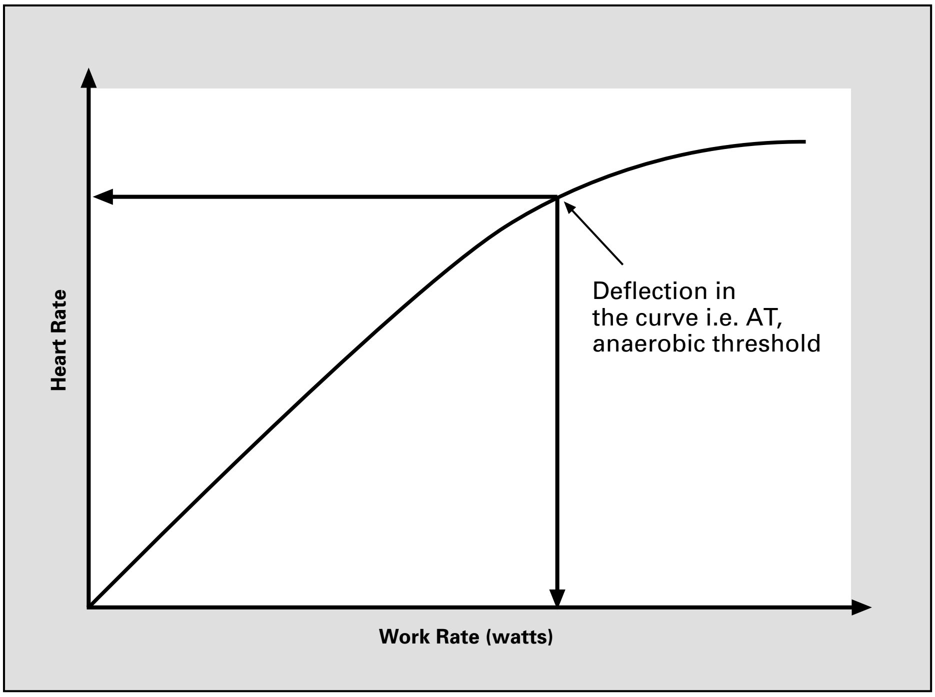
Row an eight to ten minute warm up followed by stretching as outlined in Stretching in Section 1 : Before and After Exercise. Then complete the warm up by rowing for five minutes with heart rate not exceeding 140 BPM and record the split time that corresponds to this heart rate.

Determining your MHR and Anaerobic Threshold

You will need someone to record your work rate and heart rate through this test.

Start the test by rowing at the split you recorded from the warm up. After every 90 seconds note the heart rate and increase the effort by 25 watts (see 500m Split Time to Watts Conversion in Appendix). Repeat this procedure until you reach exhaustion and record the maximum heart rate achieved.

In order to find your anaerobic threshold you will need to have someone to record your heart rate and work rate in watts every 15 seconds. This will enable you to plot a graph of your heart rate against work rate. You should then be able to find the point where there is a deflection in the curve. This corresponds to your anaerobic threshold. You can then find your heart rate and work rate at AT.



Finding an Estimate of Your Stroke Volume (ESV)

The following table gives an estimate of stroke volume based on a total blood volume of five litres.

Table 3.3

Estimated Stroke Volume in Millilitres					
Heart rate	**110 Watts**	**165 Watts**	**220 Watts**	**275 Watts**	**330 Watts**
110	162	188	233	258	303
105	155	179	221	245	288
110	148	170	211	234	275
115	141	163	202	224	263
120	131	156	196	215	252
125	130	150	186	206	242
130	125	144	179	198	233
135	120	139	172	191	224
140	116	134	166	184	216
145	112	129	160	178	209
150	108	125	155	172	202
155	105	121	150	166	195
160	102	117	145	161	189
165	98	114	141	156	183
170	96	110	137	151	178
175	93	107	133	147	173
180	90	104	129	143	168
185	88	101	126	139	164
190	86	99	122	136	159
195	83	96	119	132	155
200	81	94	116	129	151

To ascertain your estimated stroke volume from the above table, set the performance monitor to read watts and connect your heart rate interface. After a warm up, row at a constant watts setting as indicated in the boxes across the top of the table. Row at this intensity for four minutes.

After a while your heart rate will stabilise for a given workload. Using the column on the left hand side of the chart select the nearest heart rate to the one you observed in the test. Move across to the right until you arrive at the column that corresponds to your watts setting and read the stroke volume.

Example - A heart rate of 160 on a setting of 220 watts = ESV of 145ml/beat.

Estimation Your VO_2 max

The only precise way to determine your VO_2 max is through a laboratory test that involves measuring the difference in oxygen content between inspired and expired air.

However, as a result of gathering data over a number of years a formula has been developed by which you can approximate your VO_2 max. First you need to know your average power in watts for a 2,000m test. This figure is then multiplied by 14.4 and a constant of 65 added to give VO_2 max in millilitres.

For example, 2,000m time = 6:40 therefore, from the table in 500m Split Time to Watts Conversion in Appendix, the average watts are 350.

350 x 14.4 = 5,040

5,040 + 65 = 5,105 millilitres/min or 5.105 l/min.

This is an estimate within +/- 10%.

Frequently Asked Questions

answered by Terry O'Neill

I have been following the Concept 2 website advice for weight management. By taking 41 (my age) from 220 for my maximum heart rate I get 179 but recently achieved 185 bpm in my hill sprint training. My resting heart rate is 42 to 44.

Using the figure 179 I take 65% to get a work rate of 116 bpm. In order to achieve this I have to row at rate 28 to 30 instead of the 18 to 20 as recommended in the Training Guide. What am I doing wrong?

Your maximum heart rate will depend on what you are doing. Hill sprints will initiate a much higher maximum heart rate than indoor rowing. If you want to find your maximum heart rate on the Indoor Rower refer to the test in Physiological Tools in Section 3 : Physiology.

The percentage of heart rate that you should work at is with respect to your heart rate range. You determine this by subtracting your resting heart rate from your maximum heart rate. Multiply this by the percentage you require and add your resting heart rate on again. This will give you an accurate idea of the correct heart rate for that training zone.

You should not be too concerned about the stroke rate you use to achieve your training zones. This is a throwback to water rowing before heart rate monitors were common, when rowers controlled the intensity of training by using stroke rate. It is much more important to achieve the correct heart rate than the suggested stroke rate.

Why do we need to train in different training bands and why can't you just train as hard as you can for as long as you can?

When I first took up coaching the national team back in the late 70s we used three training bands. Then they were called steady state, tempo and interval training. For steady state read UT1, for tempo read anaerobic threshold. Interval training was based around a series of 500m pieces.

Following a programme based on these three bands the crew I coached in 1980 won the World Championships and set a world best time that stood for nine years. The athletes in the crew all had full time jobs and trained four evenings a week and twice on Saturday and Sunday.

It would be a brave coach that suggested turning back the clock to this type of programme to full time athletes that form the current national team. The nearest thing that I got to it was a couple of years ago when I helped a local club. The first thing I did was cut the number of sessions per week by removing all early morning weekday sessions. The reason was that these sessions were not focused because of the pressure to finish in time for work. The quality of the evening session was poor because the athletes were not getting enough sleep and arriving for training tired. When I suggested dropping the morning sessions I could see from the expression on their faces they were thinking "Who is this bloke?" However, they did as I asked and went on to win at Henley, which was their aim.

With full time athletes tiredness is not such an issue as they are able to rest between sessions. This is because they have more time to train so training fills up the time they have available. The rational used is that the training can be more specific and to achieve this the number of training bands are expanded to five or in some cases seven.

Identifying various bands isn't that different from training as hard as you can for as long as you can. Low intensity work is carried out over a longer period and if you went off too hard you would not be able to complete the session. But if you mean why don't you make each session flat out then the answer is you would only be training at one point on a continuum which ranges from low intensity aerobic work to high intensity anaerobic work.

The two extremes of training could also be called the endurance end and the strength end of the continuum. You will find that there will be some strength gains from endurance training and some endurance gains from strength training.

We identify bands by blood lactate levels and this is relevant to training programmes for rowing over 2,000m. Blood lactate levels may not be relevant to someone training for a marathon as marathon runners may not be able to create significant levels of lactate. It is relevant to rowers because there are two reasons why you will be unable to continue to exercise, one is you will run out of fuel and you can do this through aerobic work. This will happen to athletes involved in prolonged aerobic activities such as the ironman triathlon, if they fail to refuel as they go. The other reason is that through high intensity work you have an accumulation of lactate to a point where it changes the pH of blood from a normal alkaline 6.8 to an acidic 7.3. In this case calcium, which is the bonding agent in the actomyosin complex (part of the contractile unit of the muscle), is broken down and muscles can no longer function. This can be clearly seen in an event like the 400m hurdles where as the runners approach the finish line they appear to be running in treacle and stop immediately they cross the line. The total event lasts for less than a minute so there is no way the athlete has run out of fuel.

Lactate accumulation will also be the limiting factor in a 2,000m flat out row. The energy costs are about 400 calories, which in itself is not too high considering that a human has a capacity of around 10,000. However, this is the maximum consumption over a period of 24 hours and the rate of expenditure for a 2,000m piece is around ten times the sustainable rate which is why it is such a physical challenge.

The main objective of a training programme is to increase the amount of usable energy before the debilitating effects of lactate accumulation. Therefore you need to know at what training intensity this occurs (anaerobic threshold).

Because lactate is constantly present in the bloodstream, we also need to establish what amount is there as a result of the basal metabolism plus normal activity and what level we can expect from exercise that will bring about the desired training effect (aerobic threshold). These two points have been identified as 4 and 2mmols respectively. Then there are the training bands above the anaerobic threshold, the first at 6mmols and then above. We need to train in these bands to develop a tolerance to lactate and improve the metabolic resynthisis.

Recommended Reading

- **McKardle, Katch and Katch, *Exercise Physiology: Energy Nutrition and Human Performance***
  Lippincott Williams and Wilkins, 2001
  ISBN: 0781725445
- **Wilmore and Costill, *Physiology of Sport and Exercise***
  Human Kinetics Europe Ltd, 1999
  ISBN: 0736000844