Energy demands in competitive soccer

JENS BANGSBO

Laboratory for Human Physiology, August Krogh Institute, Universitetsparken 13, 2100 Copenhagen, Denmark

In elite outfield players, the average work rate during a soccer match, as estimated from variables such as heart rate, is approximately 70% of maximal oxygen uptake ($\dot{V}O_2$ max). This corresponds to an energy production of $\sim 5700$ kJ (1360 kcal) for a person weighing 75 kg with a $\dot{V}O_2$ max of 60 ml kg$^{-1}$ min$^{-1}$. Aerobic energy production appears to account for more than 90% of total energy consumption. Nevertheless, anaerobic energy production plays an essential role during soccer matches. During intensive exercise periods of a game, creatine phosphate, and to a lesser extent the stored adenosine triphosphate, are utilized. Both compounds are partly restored during a subsequent prolonged rest period. In blood samples taken after top-class soccer matches, the lactate concentration averages 3–9 mm, and individual values frequently exceed 10 mm during match-play. Furthermore, the adenosine diphosphate degradation products -- ammonia/ammonium, hypoxanthine and uric acid -- are elevated in the blood during soccer matches. Thus, the anaerobic energy systems are heavily taxed during periods of match-play. Glycogen in the working muscle seems to be the most important substrate for energy production during soccer matches. However, muscle triglycerides, blood free fatty acids and glucose are also used as substrates for oxidative metabolism in the muscles.

Keywords: Ammonia, anaerobic metabolism, lactate, glucose, glycerol, hypoxanthine, muscle glycogen.

Introduction

Analysis of activities during soccer matches has shown that a top-class male soccer player covers an average distance of approximately 11 km during a match. This distance is only to a limited extent a measure of the physiological demands placed on a player during a match, since in addition to running, a player is engaged in many other energy-demanding activities, such as tackling, jumping, accelerating and turning. A more precise evaluation of the total energy demand during a soccer match can be achieved by performing physiological measurements in connection with soccer matches. In this brief review, the physiological demands in soccer based on such measurements are evaluated. For a more extensive review, the reader is referred to Bangsbo (1994).

Aerobic energy production

There have been several attempts to determine the aerobic contribution to metabolism during soccer by measuring oxygen uptake ($\dot{V}O_2$) during match-play, and values of 1–2 l min$^{-1}$ have been obtained (Covell et al., 1965; Durnin and Passmore, 1967; Ogushi et al., 1993). These values are probably not representative of $\dot{V}O_2$ during match-play, since the procedure for collecting expired air interferes with normal play and only minor parts of a match have been analysed. The former problem has been minimized by the development of a lightweight (800 g) portable telemetry system (K2) to measure $\dot{V}O_2$. With this system, $\dot{V}O_2$ was measured during various soccer-related activities, the highest value of 41 l min$^{-1}$ being obtained during dribbling, whereas values of between 2 and 41 l min$^{-1}$ were obtained for drills such as 1 vs 1 and 3 vs 1 (Kawakami et al., 1992).

Information about the aerobic energy expenditure during soccer can also be obtained from continuous measurement of heart rate (HR) during a match. Based on individual relationships between HR and $\dot{V}O_2$ obtained during a standardized exercise protocol in the laboratory, the HR determinations for each player during match-play can be transformed to oxygen uptake (Fig. 1). As HR determinations can be performed without any restrictions on the player, this procedure may provide a more accurate picture of the contribution of the aerobic system in soccer. By such estimations, mean values of about 75% $\dot{V}O_2$ max have been obtained.
Figure 1 (a) Heart rate (HR) during a soccer match and (b) the relationship between HR and oxygen uptake (\(\dot{V}O_2\)) obtained during treadmill running for a male elite player. The mean HR of 171 and 163 beats min\(^{-1}\) for the first and second half, respectively, are converted to a \(\dot{V}O_2\) of 51.1 and 46.2 ml kg\(^{-1}\) min\(^{-1}\), corresponding to 78% (first half) and 72% (second half) \(\dot{V}O_2\) max (65.3 ml kg\(^{-1}\) min\(^{-1}\)).

(Reilly and Thomas, 1979; Ekblom, 1986; Bangsbo, 1994). It has to be emphasized that HR determinations provide an indirect measure of aerobic energy production, and thus inaccuracies related to the estimation of \(\dot{V}O_2\) from HR have to be taken into account. The \(\dot{V}O_2\) determined from HR measurements during soccer is probably somewhat overestimated, as under certain conditions – such as static muscle contractions, heat and emotional stress – HR does not reflect the actual \(\dot{V}O_2\) (Bangsbo, 1994). However, it is probably only during short periods during match-play that the HR and \(\dot{V}O_2\) relation is different from that obtained in the laboratory. Thus, it appears reasonable to suggest that the mean relative work rate in soccer is around 70% \(\dot{V}O_2\) max, corresponding to an energy production of \(~5700\) kJ (1360 kcal) for a person weighing 75 kg with a maximum oxygen uptake of 60 ml kg\(^{-1}\) min\(^{-1}\).

This suggestion is in accordance with the estimation of energy expenditure based on determinations of rectal temperature after soccer matches. The rectal temperature of Swedish elite players after matches averaged 39.5°C, with none of the players having values lower than 39°C at the end of the match (Andersson et al., 1983). Similar values were reported by Smolikka (1978). These temperatures are consistent with a relative work rate of 70–80% \(\dot{V}O_2\) max, when it is taken into account that fluid loss during match-play also elevates body temperature without a concomitant increase in energy consumption (Saltin and Hermansen, 1966; Ekblom et al., 1970; Noakes et al., 1991). Under normal weather conditions, the decrease in body mass during a match is approximately 2 kg, which also suggests that the demands placed on the aerobic energy system are high (Bangsbo, 1994).

There is little information available concerning the HR of female players during match-play. In general, determinations of HR during match-play for female and youth male players show the same level and pattern of changes as observed for male adult players (B. Ekblom, pers. comm.; Bangsbo, 1994).

A relative work rate of 70% \(\dot{V}O_2\) max may appear high, since it has been observed that a player stands or walks for almost half of the game, and the total distance covered of about 11 km corresponds to a mean speed of 7.2 km h\(^{-1}\) (Bangsbo et al., 1991). However, the latter value only in part reflects the physical activities of the players. Players perform many energy-demanding activities, which are not detected by an analysis of distance covered, e.g. accelerations, changes in direction, decelerations, jumps, and getting up from the ground.

### Anaerobic energy production

For elite male players, the total duration of high-intensity exercise during a soccer match is about 7 min. This includes about 19 sprints with a mean duration of 2.0 s (Bangsbo et al., 1991).

### ATP and creatine phosphate utilization

Degradation of creatine phosphate (CP), and to a lesser extent the stored ATP, provides a considerable amount of energy during periods of high intensity in a match. As CP is rapidly resynthesized during periods of rest and

[Figure showing heart rate and oxygen uptake during soccer match]
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Swedish first division players were 9.5 and 7.2 mm after the first and second half, respectively, while the corresponding values for fourth division players were 4.0 and 3.9 mm (Ekblom, 1986). Players from the second and third divisions had BLa values in between these (Table 1). Mean BLa concentrations of 3–7 mm have been reported for German amateur, Danish elite and English college players (Table 1).

The relevance of BLa as an indicator of lactate production has to be questioned. Lactate is metabolized within the active muscles after high-intensity exercise (Brooks, 1987; Nordheim and Vallesstad, 1990; Bangsbo, 1994), and the rate is elevated if low-intensity activities are performed in between periods of intense exercise during a match (Bangsbo, 1994). Thus, not all of the lactate produced will appear in the blood. In addition, the duration of intense exercise may be too short to provide a considerable increase in blood lactate. For example, Boobis (1987) observed that the muscle lactate concentration increased to 10 mm during a 6 s sprint, whereas BLa concentration only rose to 1.8 mm and did not exceed 5 mm in the following recovery period. Similarly, BLa was only slightly elevated during repeated 5 min periods of intermittent exercise (including a 5 s sprint), roughly corresponding to those that occur in soccer (Bangsbo et al., 1992). Furthermore, lactate released from the active muscles to the blood is taken up at a high rate by various tissues such as the heart, liver, kidney and inactive muscles (Brooks, 1987). Since BLa represents the balance of release from muscle and removal of lactate from the blood, BLa levels inevitably underestimate lactate production. In line with this are findings of significantly higher lactate concentrations in muscle compared with blood, both during submaximal and maximal exercise (Knuttgen and Saltin, 1972; Jacobs and Kajser, 1982; Tesch et al., 1982; Chwalbinska-Moneta et al., 1989).

In most studies where BLa has been determined during match-play, a large variation has been observed and peak values higher than 10 mm have frequently been reported (Table 1). In addition, determinations of BLa from the same player several times during a match have shown pronounced differences (Ekblom, 1986; Bangsbo et al., 1991). These findings are likely to be the result of differences in the activities undertaken before sampling, since it has been demonstrated that BLa measurements are related to the incidence of high-intensity running prior to blood sampling (Bangsbo et al., 1991).

As a consequence of the factors discussed above, single BLa determinations cannot be considered to be representative of lactate production during an entire match. Lactate in the blood taken during match-play may reflect, but underestimate, lactate production in a short period prior to sampling. Therefore, based on findings of high BLa concentrations, it can be concluded

Figure 2 Creatine phosphate (CP) concentration in the M. gastrocnemius determined by NMR (upper panel) during isometric contractions with the calf muscles at alternating work loads (lower panel). The exercise consisted of three identical 2 min periods of contraction, each including a maximal contraction.

low-intensity exercise, the CP concentration probably alternates continuously as a result of the intermittent nature of the game. Figure 2 shows an example of the fluctuations of CP determined by nuclear magnetic resonance (NMR) during three 2 min intermittent exercise periods, each of which included short maximal contractions, low-intensity contractions and rest, similar to activities in soccer. A pronounced decrease in CP was observed during the maximal contractions, but it almost reached the pre-exercise value at the end of each 2 min intermittent contraction period. Although the net utilization of CP is quantitatively small during a soccer match, CP has a very important function as an energy buffer, providing phosphate for the resynthesis of ATP through the creatine kinase reaction during rapid elevations in exercise intensity (Fig. 2).

Lactate production

The concentration of lactate in the blood is often used as an indicator of anaerobic lactic acid energy production in soccer. The blood lactate (BLa) concentrations of
Table 1  Blood lactate concentration (mM) taken from a fingertip or an arm vein during or after a soccer matcha

<table>
<thead>
<tr>
<th>Study</th>
<th>Players</th>
<th>First half</th>
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<th>Second half</th>
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<tr>
<td>Agnewik (1970)</td>
<td>First division (Sweden)</td>
<td>4.9±1.9</td>
<td>4.1±1.3</td>
<td>10.0</td>
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<tr>
<td>Smaros (1980)</td>
<td>Second division (Finland)</td>
<td>9.5</td>
<td>7.2</td>
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<tr>
<td>Ekbloom (1986)</td>
<td>First division (Sweden)</td>
<td>(6.9–14.3)</td>
<td>(4.5–10.8)</td>
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<td></td>
<td>Second division (Sweden)</td>
<td>8.0</td>
<td>6.6</td>
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<td></td>
<td>Third division (Sweden)</td>
<td>(5.1–11.5)</td>
<td>(3.1–11.0)</td>
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<td></td>
<td>Fourth division (Sweden)</td>
<td>5.5</td>
<td>4.2</td>
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<td></td>
<td></td>
<td>(3.0–12.6)</td>
<td>(3.2–8.0)</td>
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<tr>
<td>Rhode and Espersen (1988)</td>
<td>First and second divisions (Denmark)</td>
<td>4.0</td>
<td>3.9</td>
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<td>Gerisch et al. (1988)</td>
<td>Top amateur league (Germany)</td>
<td>5.1±1.6</td>
<td>3.9±1.6</td>
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<td></td>
<td>University match (Germany)</td>
<td>5.6±2.0</td>
<td>4.7±2.2</td>
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<tr>
<td>Smith et al. (1993)</td>
<td>College matches (England)</td>
<td>6.8±1.0</td>
<td>5.9±2.0</td>
<td>5.1±1.6</td>
<td>4.9±1.7</td>
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<td>Bangsbo et al. (1991)</td>
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<td>4.9</td>
<td>3.7</td>
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<td>Bangsbo (1994)</td>
<td>League match (Denmark)</td>
<td>(2.1–10.3)</td>
<td>(1.8–5.2)</td>
<td>(2.1–6.9)</td>
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<tr>
<td></td>
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<td>4.1</td>
<td>2.6</td>
<td>2.4</td>
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<td></td>
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<td></td>
<td>League match (Denmark)a</td>
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<td>(2.8–5.4)</td>
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aData presented as means ± S.D. or range (in brackets).

bLactate analysis was performed using whole blood except in this case, where plasma was used.

that lactate production may be very high at certain times during a match.

It is difficult to quantify the energy production related to the activity of the lactate-producing system during a soccer match, but the contribution to the total turnover is probably small (<10%; Bangsbo, 1994). Nevertheless, anaerobic energy production is extremely important, as it provides energy at a very high rate during periods of intense exercise in a match.

Ammonia, hypoxanthine and uric acid production in soccer

The concentration of ammonia/ammonium (NH₃) in blood was elevated during a soccer match, indicating that the muscles produce NH₃ (Fig. 3). Thus, both the adenyate kinase and the adenine monophosphate (AMP) deaminase reaction appear to be activated in soccer (Fig. 4; Löwenstein, 1990). This is supported by the finding of an elevated concentration of the inosine monophosphate (IMP) degradation product, hypoxanthine (HX), in the blood during match-play (Fig. 5). In addition, the concentration of uric acid (UA) in the blood was higher during match-play than at rest, which suggests that a proportion of the HX formed is further oxidized to UA.

Figure 3  Venous blood ammonia/ammonium (NH₃) concentration for six players before, during and after a competitive soccer match. The match was stopped for 1 min twice in each half in order to collect the samples. The data are presented as x±S.E.M.

Substrate utilization

The high levels of aerobic energy production in soccer and the pronounced anaerobic energy turnover during periods of match-play are associated with the consumption of large amounts of substrates. During a match, the blood glucose concentration is often found to be higher than at rest and hypoglycaemia occurs only in very rare cases (Smaros, 1980; Ekbloom, 1986; Bangsbo, 1994).
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**Figure 4** Metabolic pathways associated with ammonia/ammonium (NH₃), hypoxanthine (HX) and uric acid (UA) production. Production of NH₃ and HX occur within the muscle cell, whereas uric acid is produced outside the cell. ATP, adenosine triphosphate; ADP, adenosine diphosphate; AMP, adenosine monophosphate; IMP, inosine monophosphate.

**Figure 5** Venous plasma uric acid (□) and hypoxanthine (■) concentration for six players before, during and after a competitive soccer match. The players and the match are the same as those referred to in Fig. 3. The data are presented as \( \bar{x} \pm S.E.M. \)

Thus, it appears that the liver releases enough glucose to maintain and even elevate blood glucose during a match.

There is a pronounced utilization of glycogen in the leg muscles during a match. In a Swedish study, the average thigh muscle glycogen concentrations of five players were 96, 32 and 9 mmol kg⁻¹ (w.w.) before, at half-time and after a non-competitive match, respectively (Saltin, 1973). Four other players started the same match with low muscle glycogen levels (45 mmol kg⁻¹ w.w.) as a result of extensive physical exercise the day prior to the game. For these players, the stores of muscle glycogen were almost depleted by half-time. In a Finnish study, glycogen in the quadriceps muscle was observed to be 84 mmol kg⁻¹ (w.w.) before a match, and it was reduced to 63 and 43 mmol kg⁻¹ (w.w.) at half-time and after the match, respectively (Smaros, 1980). Thus, muscle glycogen stores are not always totally depleted during soccer matches. Similarly, for 15 Swedish players, the glycogen concentration in the quadriceps muscle was found to be 46 mmol kg⁻¹ (w.w.) at the end of a match (Jacobs et al., 1982). Unfortunately, the change in muscle glycogen could not be determined in the latter study, since no samples were taken before the match. The difference in muscle glycogen content represents the net utilization of muscle glycogen. The total glycogen turnover is probably considerably higher, since resynthesis of glycogen may occur during periods of rest and low-intensity exercise in a match (Nordheim and Völlestad, 1990).

It was observed that the free fatty acid (FFA) concentration in the blood increased during a competitive soccer match, and more so during the second half of the match (Bangsbo, 1994). Only a minor increase in glyceral was found, suggesting a high uptake of glyceral in various tissues. The most important tissue is likely to be the liver, which presumably has a larger uptake of glyceral during a match than observed during continuous exercise at the same relative intensity, due to the high splanchnic blood flow in periods of rest during match-play (Ahlborg and Felig, 1982). Thus, glyceral
might represent a significant gluconeogenic precursor during soccer play. The uptake of FFA and the amount of fat oxidized during a soccer match cannot be determined from blood FFA and glycerol concentrations. Intramuscular lipolysis probably also takes place in soccer, which further complicates the evaluation of fat metabolism (Essén, 1978; Hurley et al., 1986). Furthermore, ketone bodies may function as a fat source in soccer, but these appear to be of quantitatively minor importance during exercise (Wahren et al., 1984; Hargreaves et al., 1991). The role of protein in metabolism in soccer is unclear. Studies with continuous exercise at a mean work rate and duration similar to soccer have shown that oxidation of proteins may contribute less than 10% of total energy production (Wagenmakers et al., 1989, 1990).

**General discussion**

Soccer is a complex game in which the physiological demands are multifactorial and vary markedly during match-play. The high BLA concentrations and elevated NH₃ concentrations during periods of match-play indicate that major muscle metabolic and ionic changes occur. The demands during a soccer match may become so high that they lead to fatigue, with impairments of the physical performance potential and the technical performance even at submaximal exercise intensities. An experienced player will probably avoid repeated prolonged intense exercise periods that require a long period of recovery. On the other hand, it is not always possible for a player to rest and regain normal function.

An example is the case of a defender marking a forward who makes long runs at high speed.

Towards the end of a soccer match, a decrease in performance may not only be associated with periods of intense exercise, but also with general fatigue as a result of the total length of play. This type of fatigue may be related to a depletion of muscle glycogen stores. The findings of low muscle glycogen concentrations at the end of a soccer match (Saltin, 1973; Smaros, 1980; Jacobs et al., 1982), and a more pronounced use of glycogen in the first compared with the second half (Saltin, 1973), indicate that the level of muscle glycogen prior to a match influences performance towards the end of a game. This is supported by the observation that players with initially low glycogen covered a shorter distance and sprinted significantly less, particularly in the second half, than players who had normal muscle glycogen levels prior to the match (Saltin, 1973). A scenario might be that the fast-twitch (FT) muscle fibres during a match become progressively more involved in the development of force as the slow-twitch (ST) muscle fibres fatigue. The FT fibres may not recover completely during periods of rest in a match, which leads to the gradual exhaustion of these fibres. Combined with a reduced capacity of the ST fibres, the fatigue of some FT fibres could result in an impaired ability to perform towards the end of a match. A reduction in performance occurs only when the compensatory functions are not sufficient, that is, if too many muscle fibres are fatigued.

An example of the relative energy contributions of the aerobic and anaerobic energy systems, and the substrates used, is given in Fig. 6. It has to be emphasized that large inter-individual differences exist in aerobic and anaerobic energy production during match-play due to the variety of factors which influence exercise intensity, for example motivation, physical capacity and tactical strategy. The influence of positional role on the field was reflected in a study by Van Gool (1987), who observed that the mean HR of central defenders and full-backs was about 155 beats min⁻¹, whereas it was ~170 beats min⁻¹ for midfield players and forwards. The effect of tactics used is also illustrated by the higher BLA values of players when teams used ‘man-to-man’ marking compared with ‘zone-cover’ (Gerisch et al., 1988).

This review has concerned the energy demands of match-play. However, there are also energy considerations that apply to training. Energy expenditure during training among English professional players has been estimated to be ~6100 kJ (1500 kcal) (Reilly, 1979). It should be acknowledged that this value varies from day to day, the training usually building up to a midweek peak and subsequent sessions of less activity as a taper for the weekend match. The typical values may be
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Exceeded when players train twice a day. Furthermore, the pattern of energy expenditure will be altered when extra matches are played in midweek. There will also be variations in daily energy expenditure with the phases of the competitive season and with individual players recovering from injury unable to participate fully in training.

In summary, the mean rate of aerobic energy production for elite players was estimated to be ~70% \( \dot{V}O_2 \) max during match-play. Such a high work rate for 90 min, preceded by a 15–30 min warm-up period, suggests that there is a great demand placed on the energy-producing systems during a soccer match. In support of this is the finding that body temperature after a match is high, that the loss of body fluid is considerable during a match and that some players have almost depleted glycogen stores in the quadriceps muscle.

Further research is required to examine how various environmental conditions such as high temperatures and altitude, and different styles of play, influence the physiological demands during a game.

References


Reilly, T. and Thomas, V. (1979). Estimated daily energy

**Bangsbo**

**Cyclically uranium atoms:**


**Key facts:**

- Blood lactate levels increase during intense exercise.
- Oxygen consumption increases during prolonged aerobic exercise.
- Exercise-induced activation of the branched-chain 2-oxo acid dehydrogenase occurs in human muscle.
- Turnover and splanchnic metabolism of free fatty acids and ketones in insulin-dependent diabetics at rest and in response to exercise.

**Introduction:**

During exercise, the body impairs the impact of the carbohydrates in providing energy. Notably, during intense exercise, the body empowers the use of carbohydrates before relying on fat as a source. Hargreaves, in *Carbohydrates in Lipid Metabolism*, discusses the increased use of carbohydrates.

The body during exercise consumes and conserves glucose, which is the primary source of energy. Factors that influence glucose during exercise include oxygen delivery, heart rate, increase in muscle blood flow, and sources of oxygen. *International Journal of Sports Medicine*, 10, 101–113.

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