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Skin Blood Flow in the Forearms during Simulation of a Tennis Match: Implications for the Thermoregulatory Role of Dynamic Exercise.

Nikiforos Galanis MD, PhD[1], Dimitrios Farmakiotis MD[1], Evdoxia Valavani MD[1], John Sarris, MD, PhD[1], Eleftherios Tsiridis, MD, PhD[1], Fares Sayegh MD, PhD[1] , Dimitrios Christopoulos MD, PhD[2], Dimitrios Papadimitriou MD, PhD[2], John Kirkos MD, PhD[1]

1 Division of Sports Medicine, Department of Orthopaedics, Papageorgiou General Hospital, School of Medicine, Aristotle University of Thessaloniki, Greece

2 Division of Vascular Surgery, Department of General Surgery, Gennimatas General Hospital, School of Medicine, Aristotle University of Thessaloniki, Greece

Abstract

BACKGROUND: Control of skin blood flow (SkBF) during exercise involves three phases: 1. an initial vasoconstriction response, 2. a thermoregulatory vasodilator phase, and 3. a plateau phase. This study was designed to investigate the above mechanisms in the forearms of tennis players during simulation of a tennis match. SUBJECTS & METHODS: Thirty-two healthy, right-handed, non-professional, male tennis players underwent simulation of a tennis match. SkBF in both forearms was measured by Laser Doppler Flowmetry (LDF) at baseline and after specific time intervals (t=6΄, 19΄30΄΄, 33΄, 46΄30΄΄, 60΄).

RESULTS: We found that SkBF initially increased in both forearms, then, after t=19΄30΄΄, declined reaching a plateau after t=33΄ in the non-dominant and after 46΄30΄΄ in the dominant forearm. The time course of changes in heart rate was similar. In the beginning (t=6΄, 19΄30΄΄), SkBF values were significantly higher in the non-dominant forearm, compared to the dominant one. After approximately 25΄ this difference was reversed, and remained so.

CONCLUSIONS: Our results show that, similar to what has been shown in other models of dynamic exercise, SkBF in the forearms of tennis players has three phases. An important implication of our data is that the warm-up of tennis players should last at least half an hour. These results could be used towards designing better training programs and reducing overload injuries and burnout syndromes.

Keywords: tennis, skin blood flow, Laser Doppler, exercise physiology

✷ *Corresponding author: e-mail: ngalanismed@gmail.com*

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CONCLUSIONS: Our results show that, similar to what has been shown in other models of dynamic exercise, SkBF in the forearms of tennis players has three phases. An important implication of our data is that the warm-up of tennis players should last at least half an hour. These results could be used towards designing better training programs and reducing overload injuries and burnout syndromes.

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1 INTRODUCTION

Regulation of skin blood flow (SkBF) during exercise is essential for the athlete, in order to achieve a high level of performance (Sawka et al., 2011). It is controlled by a complex balance between local vasoconstrictor and vasodilator, but also central, influences.

An important first parameter of exercise in the regulation of SkBF is thermoregulation (Kenney & Johnson, 1992; González-Alonso, Crandall & Johnson, 2007; Simmons et al., 2011; Périard, Racinais & Sawka 2015). The energy expended by contracting muscle is a major source of heat, and the regulation of body temperature must invoke powerful vasomotor and sudomotor mechanisms of heat loss, to balance those of heat production.

SkBF accommodates the dissipation of most of that heat (Simmons et al., 2011; Hayashi et al., 2014). In other words, during exercise, muscle and skin circulations must compete, but also collaborate for blood flow distribution, due to the increased metabolic production of heat (Andersen & Saltin, 1985; Laughin, 1987; González-Alonso, 2012; Joyner & Casey, 2015).

Despite the importance of thermoregulation, at the onset of dynamic exercise, a non-thermoregulatory cutaneous vasoconstriction in the finger and forearm has been observed (Bevegard & Shepherd, 1966; Johnson & Park, 1982; Kellogg et al., 1991a; Wilson et al. 2002; González-Alonso et al. 2007; Kondo et al. 2010; Nielsen 2015). Measurement of SkBF by a relatively new technique, Laser Doppler Flowmetry (LDF), has confirmed this initial vasoconstrictor response of cutaneous vasculature (Kellogg, Johnson & Kosiba, 1991a). This non-thermoregulatory mechanism, apparently serves in increasing active muscle blood flow (Taylor et al. 1988; Taylor, Johnson & Kosiba, 1989; Shibasaki et al., 2005; Joyner & Casey, 2015), and is primarily mediated by the adrenergic vasoconstrictor system common to all regional circulations (Kellogg, Johnson & Kosiba, 1991a; Kenney & Johnson, 1992; Kellogg, 2006; Nielsen, 2015).

As exercise continues, the core temperature rises, which is a result of increased metabolic heat production. In order to protect the nervous system, excess heat must be transferred to the skin, and cutaneous vasoconstriction comes into conflict with the thermoregulatory demands for increased blood flow. Therefore, at this time, a cutaneous vasodilation occurs, in order to increase SkBF and regulate body temperature (Rowell et al., 1966; Crandall & González-Alonso, 2010; Simmons et al., 2011). Notably, though, dynamic exercise results in an elevated temperature threshold for cutaneous vasodilation and sweating (Johnson and Park, 1981; Kellogg, Johnson & Kosiba, 1991b; Smolander, Saalo & Korhonen, 1991; Johnson, 1992; Kenney & Johnson, 1992; González-Alonso, Crandall & Johnson, 2007). This elevation has been found to be due primarily to a delay in the activation of the sympathetic vasodilator system (Kellogg, Johnson & Kosiba, 1991b).

The increase in SkBF ends typically, after prolonged exercise, when the core temperature reaches approximately 38oC, since, under these conditions, the competition between skin and working muscle becomes formidable (Kenney & Johnson, 1992; González-Alonso et al., 1999). This attenuation of cutaneous vasodilation is thought to arise from a decrease in central filling pressure, sensed by cardiopulmonary baroreceptors, rather than vasomotor reflexes, since cardiac output is also stabilized at this point (Nadel, Fortney & Wenger, 1979; Nose et al., 1990).

The present study was designed in order to evaluate whether the above mechanisms take place in the forearms of tennis players, and correlate the magnitude and time course of SkBF between the dominant and non- dominant forearms of the athletes.

2 METHODS

2.1 Subjects

Thirty-two right-handed, male tennis players, 30-40 years old, were voluntarily recruited for the study. None of the subjects reported any chronic health problems, admission to a hospital or use of any medication over the past six months. All subjects had been playing tennis for over 10 years and exercised regularly over three times per week. Their ranking in the U.S. national ranking program ranged from 5.0 to 6.0. For the ground strokes (forehand and backhand), they used one hand. Informed consent was obtained from all men, and the study was approved by the institutional review board.

2.2 Procedures

The required equipment was placed inside a 4-person, sun-proof tent alongside the tennis court. We used a sun-proof tent in order to avoid any possible interference from the environment such as solar radiation. We used a tennis ball machine (Tutor Model 4 Plus, Burbank, CA, USA) to simulate the conditions of a tennis match. By using such a machine we could set the direction, timing, speed, height and spin of the ball. In that way we could control as much as possible the work of the athletes and ensure that the conditions of the match were similar for all of them. The balls used were yellow, Nassau (Nassau Co, Ltd, Korea) and were replenished after every measurement.

We made an effort to keep the timing as close as possible to the timing of a real tennis match including the breaks. This timing was based on the regulations of the International Tennis Federation (ITF) and on previously published studies regarding the work demands of a tennis match (Kellogg, Johnson & Kosiba, 1991a; Taylor, Johnson & Kosiba, 1989). The conditions we chose were similar to those of a high quality game. The courts we used were those of the Salonica Country Tennis Club (Thessaloniki, Greece), which have a hard surface with a quick bounce of the ball. In this type of court, games are shorter than in other courts (e.g., clay). The ball machine was programmed to send two balls to the right of the athlete, one ball to the left, between the service line and the baseline with a speed of 110 km/hr. The speed of the ball was verified using a speed radar (Tribar Industries, Inc., CA, USA)

SkBF was measured at rest and at regular time intervals as shown in table 1, using LDF, which measures perfusion of surface vessels, free from blood flow to underlying tissues (Johnson, 1990; Braverman, 2000). To the best of our knowledge, this is the first study to examine SkBF by this relatively new technique in the forearms of tennis athletes. We used a LaserFlo BMP2 Laser Doppler Flowmeter (Vasamedics, MN, USA), which measures SkBF in real time in mlLD/min/100 gr of tissue. During the measurement the athlete rested his right forearm and then his left forearm inside the tent. All measurements were taken from the same point (which was previously marked) on the right and left forearms, at the level of the largest diameter, in the middle of the ventral surface. Every measurement lasted ten seconds, which was sufficient to allow the machine to record ten different measurements of blood flow.

In addition to SkBF we recorded the athlete's heart rate using a heart rate (HR) monitor (Polar, NY, USA).

The temperature during the matches was between 20 and 25 degrees Celsius. Overall, every match including the breaks lasted one hour. The players had a light meal one hour before the match and a regular meal three hours before the match. They were allowed to replenish the loss of fluids and electrolytes throughout the duration of the match.

2.3 Statistical Analysis

All statistical analyses were performed with the SPSS statistical package. Normality of distribution was tested with the one-sample Kolmogorov- Smirnoff test. Means were compared with the paired t-test. Statistical significance was set at 5%. Bivariate correlations were assessed by calculation of the Spearman coefficient.

3 RESULTS

The time courses of SkBF in the right and left forearms, as well as the heart rate, are shown in table 2 and in figure 1.

In both forearms, SkBF increased significantly ($p<0.05$) after the first game, reaching its maximal value after games 2 and 3 (measurement no 3, t=17:30). Shortly afterwards, SkBF began to decline, and its values in both forearms were significantly lower, compared to the previous ones ($p<0.05$), until measurement no 4 (t=33:00) for the non-dominant forearm, and measurement no 5 (t=46:30) for the dominant forearm. After this point, SkBF reached a plateau (figure 1).

The time course of changes in HR was similar; HR was significantly ($p<0.05$) increased until game 3 (measurement no 3, t=17:30). After that point it declined ($p<0.05$), reaching a plateau after measurement no 4 (t=33:00) (table1, figure 1).

At baseline (measurement no 1, t=0), SkBF was significantly higher in the non-dominant forearm, compared to the dominant one ($p<0.005$). This difference remained significant after the first game (measurement no 2, t=6:00), but was reversed soon afterwards, and SkBF in the right forearm remained significantly higher than SkBF in the left forearm ($p<0.005$), until the end of the match (table1, figure 1).

Calculation of the Spearman coefficient showed that SkBF means in both forearms was positively correlated with HR means (dominant forearm: $r=0.960$, $p<0.001$; non-dominant: $r=0.980$, $p<0.001$), (figure 2).

Table 1. Simulated tennis match using a tennis ball machine

TIME	LASER DOPPLER MEASUREMENT no 1. (BASELINE)						GAME
00:00	√	√	√	√	√	√	1st
06:00	**BREAK: LASER DOPPLER MEASUREMENT no 2.**						
07:30	√	√	√	√	√	√	2nd
13:30	√	√	√	√	√	√	3rd
19:30	**BREAK: LASER DOPPLER MEASUREMENT no 3.**						
21:00	√	√	√	√	√	√	4th
27:00	√	√	√	√	√	√	5th
33:00	**BREAK: LASER DOPPLER MEASUREMENT no 4.**						
34:30	√	√	√	√	√	√	6th
40:30	√	√	√	√	√	√	7th
46:30	**BREAK: LASER DOPPLER MEASUREMENT no 5.**						
48:00	√	√	√	√	√	√	8th
54:00	√	√	√	√	√	√	9th
60:00	**BREAK: LASER DOPPLER MEASUREMENT no 6.**						

* Every √ represents a point and a time interval of 40 seconds. Between points (√) there was a 20 seconds pause

Table 2. SkBF and heart rate measurements in the dominant and non-dominant forearms of non-professional tennis players during simulation of a match.

Laser doppler measurement no (time)	Right forearm SkBF (ml/min/100gr)	Left forearm SkBF (ml/min/100gr)	Heart rate (pulses/min)
1. (00:00)	3.77±0.57 #	4.56±0.6	71±8
2. (06:00)	6.15±1.03 ‡ #	8.59±1.11 ‡	142±5 ‡
3. (19:30)	14.64±3.1 ‡ #	10.06±1.38 ‡	165±5 ‡
4. (33:00)	12.23±2.0 ‡ #	9.1±0.88 ‡	156±6 ‡
5. (46:30)	10.60±1.2 ‡ #	8.61±1.27	155±7
6. (60:00)	10.73±1.05 #	8.94±0.94	155±2

‡ : p<0.05 vs. previous measurement. # : p<0.005 between dominant and non- dominant forearms.

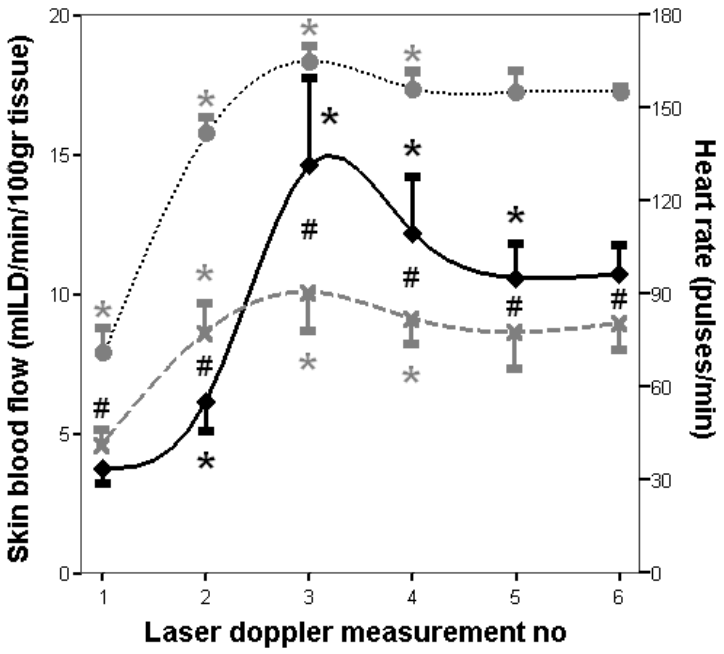


Figure 1. Skin blood flow (mean ± S.D, statistical significance) in the dominant (black ribbon) and non-dominant (gray-"X") forearms and heart rate (grey circles) of non-professional tennis players, during simulation of a match. Asterisk: p<0.05 vs. previous measurement. #: p<0.005 between dominant and non-dominant forearms.

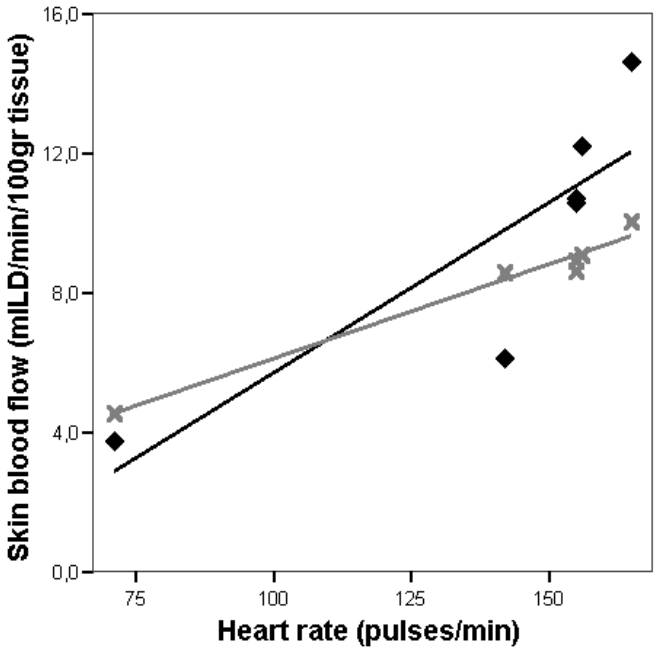


Figure 2. Correlation between heart rate and Skin blood flow means in the dominant (black ribbon) and non-dominant (gray-"X") forearms of non-professional tennis players, during simulation of a match.

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4 DISCUSSION

In our study, SkBF was measured by means of LDF in the forearms of tennis players during the intervals between simulated games of a tennis match. This relatively new technology measures in real time blood flow to the surface, but not to underlying tissues (Johnson, 1990; Braverman, 2000).

We chose to perform the measurements during the breaks because: 1. The sport itself includes breaks between the periods of maximal effort (games), therefore, e could better assess real-time hemodynamic changes (Chandler, 1995; Reilly & Palmer, 1994), 2. Laser Doppler signal during exercise would not be reliable (Eriksen et al., 1990), and 3. maximal vasodilation and perfusion of muscle occurs at rest, between games, since muscle contraction during exercise limits vascular dilation (Radegran & Saltin, 1998).

Control of SkBF during dynamic exercise undergoes three phases (Kenney & Johnson, 1992; González-Alonso, Crandall & Johnson, 2007; Périard, Racinais & Sawka, 2015): 1. a non-thermoregulatory vasoconstriction response, which helps redistribute blood flow from the inactive skin to working skeletal muscles, 2. a thermoregulatory vasodilator phase, after a temperature threshold (Tc) is reached, and 3. a plateau phase that is thought to result from baroreceptor-mediated cardiac reflexes.

In our experiments, the initial decrease in cutaneous blood flow was not recorded, although it is implied by the fit curve for the dominant forearm (figure 1). Interestingly, the SkBF was significantly increased in the non-dominant forearm, both at baseline, and until after game 1, i.e., between 6΄30΄΄ and 19΄30΄΄ (tables 1 & 2, figure 1). This novel finding is probably due to the same mechanism that mediates the initial vasoconstrictor response, i.e., a vasoconstrictor drive from the cutaneous adrenergic system (Johnson, 1986; Kellogg, Johnson & Kosiba, 1991a; Kenney & Johnson, 1992; Kellogg, 2006; Nielsen, 2015). Thus, active muscle blood flow is increased in the more active dominant forearm, resulting in decreased SkBF, compared to the non-dominant, both at rest and at the onset of dynamic exercise.

As exercise continued, the difference between the two forearms was reversed, and SkBF in the right forearm became significantly higher than that in the left forearm, at approximately t=25΄ (figure 1). This is apparently due to increased cutaneous vasodilation in the dominant forearm, in order to dissipate the greater amount of metabolically produced heat. Peak SkBF was recorded in both forearms at t=19:30. This effect is probably mediated by the cutaneous sympathetic vasodilator system (Roddie, Sheperd & Whelan, 1957), the activation of which in the dominant muscle groups was relatively delayed. Indeed, exercise has been shown to result in an elevation of Tc for cutaneous thermoregulatory responses to occur (Johnson & Park, 1981; Kellogg, Johnson & Kosiba, 1991b; Smolander, Saalo & Korhonen, 1991; Johnson, 1992; Kenney & Johnson, 1992; González-Alonso, Crandall & Johnson, 2007).After measurement no 3 (t=19:30), SkBF began to decrease in both forearms, and was stabilized in the dominant forearm after t=46:30 and the non-dominant at t=33:00 (table 2, figure 1). The plateau phase is currently regarded as an adaptation to the delicate competition for blood flow between muscle and skin, once core temperature reaches a threshold of 38oC, although maximal vasodilation has not yet been achieved (Brengelmann et al., 1977). This is thought to result from decreased preload (Nose et al. 1990), and excess perspiration (Nadel, Fortney & Wenger, 1980). In our study, it is interesting that HR also reached a plateau, after measurement no 4 (t=33:00, game 7), and was significantly correlated with SkBF in both forearms (figure 2). These findings suggest that SkBF stabilization occurs

after thirty minutes, and attenuation of the processes of vasodilation is mediated via a decrease in cardiac output. It might indicates that the warm-up of tennis players, before the match or the training session, should last at least half an hour, since hemodynamic stabilization appears to occur after this time although further investigation is needed.

Instructors should keep in mind that during the first half hour of tennis exercise, the metabolism of the dominant forearm depends primarily on local factors. Cardiovascular fitness is important, however, for the needs of a tennis match, specialized training of the upper limb is also required for a high performance of the athletes.

In conclusion, we show that during a simulated tennis match the SkBF in the forearms of tennis players has three phases consistent with previously published data regarding SkBF adaptations to dynamic exercise. Our study has important implications that could help towards the design of advanced and specialized training programs. This could help towards the performance, reduction of overload injuries and burnout syndromes.

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