

Correlation between Tourniquet Duration and Reactive Hyperemia in the Upper Limb

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Abstract: The physiological reaction of postocclusive local reactive hyperemia is regulated by neurovascular mechanisms and it reflects the function of microcirculation. Thermoregulatory changes occur first, in the form of increased skin surface temperature, which is usually followed by an increase in local blood flow. This study investigated a correlation between tourniquet duration on the upper arm, and the appearance of reactive hyperemia in the distal parts of the upper limb. Changes were registered with infrared thermometer and infrared thermography, which provided us a highly precise view of distribution of reactive hyperemia. Changes of oxygen saturation of peripheral arterial blood and blood pressure were also recorded. Our research has shown that longer duration of tourniquet leads to more intense and longer lasting reactive hyperemia in the palmar region, followed by higher temperatures of the skin surface, without any changes in postocclusive values of SpO₂.

Keywords: Infrared thermography, Microcirculation, Postocclusive hyperemia, Skin temperature, Tourniquet, Thermoregulatory changes.

1. INTRODUCTION

Postocclusive reactive hyperemia is a sudden increase in blood flow within organs or extremities due to the previous period of ischemia, caused by temporary arterial occlusion, [1] a phenomenon that usually occurs with the use of pneumatic tourniquet during bloodless field operations on extremities. The target pressure to which the pneumatic tourniquet cuff should be inflated depends on a large number of variables, including patient's age, skin characteristics, and blood pressure, shape and size of the extremity, as well as the size of the cuff itself. Many surgeons use the empirically obtained pressure value or systolic pressure value of a patient added to a value of standard deviations of pressure, which are obtained based on variations during the surgical procedure [2,3]. The duration of postocclusive reactive hyperemia is important in surgical procedures due to the fact that exact haemostasis is very difficult to achieve during that period. and most surgeons prefer to wait for this reactive hyperemia to subside before attempting to perform haemostasis. This period of waiting is usually empirically set at 5 minutes, but in reality the hyperemia can last longer or shorter.

The main objective of this study was to examine the correlation between the different duration of tourniquet and duration of local reactive hyperemia assessed by recording differences in skin temperature. Skin temperature is influenced not only by blood flow, but also by thermal characteristics of the tissue, transfer of heat within the tissue, skin and environment interaction, as well as metabolic production of heat. Small nerve fibers (myelinated A δ and unmyelinated C fibers), regulate the local blood flow through the skin with the purpose of skin temperature regulation [4]. Oscillations of skin temperature appear with delay of 10-20 seconds compared to blood flow oscillations. This latency of temperature waves can be used to determine the effective thickness of the tissue layer, which separates the blood vessels and skin surface [5].

Previous studies have shown that changes in skin temperature are in correlation with blood flow changes only on the area of fingers, palms, and feet [6]. Such observation is most likely related to local anatomical differences of skin vasculature. Arterio-venous anastomoses (AVA) are present in large number in the skin of face, hands, and feet, areas known as thermoregulatory windows. On these areas, blood vessels are arranged into 3 skin layers, with AVA regulated via the autonomic nervous system. When AVA is opened, there is an increase in blood flow due

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to redirecting part of the blood directly into the venous plexus, which facilitates the release of heat. Contrary to that, in more proximal parts, such as forearm, the blood flow is mainly nutritious and not thermoregulatory, so in such places we can find only a few AVAs [7]. The body's heat loss depends on the environmental factors and it is a result of the conduction, convection, infrared radiation, and evaporation from the skin surface, also of minor part which is lost by breathing. According to Planck's law, dry human skin is almost perfect black body that emits infrared waves of large wavelength, whose maximum is $9.3\mu\text{m}$ [8]. Bilateral symmetry is one of the most important characteristics of heating pattern on the surface of human body [9,10]. Any significant temperature asymmetry $>0.7\text{ }^{\circ}\text{C}$ is defined as abnormal and can indicate the physiological or anatomical variation [11].

Infrared thermography has been shown as a reliable, indirect measurement method of skin perfusion, which provides results in real time, based on the assumption that skin temperature changes reflect concurrent changes in blood flow, especially in the area of the peripheral parts of the extremity. Infrared thermography is used for measuring and analysis of physiological functions and pathology associated with thermal homeostasis of the body. It is a noninvasive diagnostic method whose results can not be compared directly with those obtained by structural methods of visualization [12,13]. The advantages of this method are noninvasive and contactless usage, also absence of using any harmful radiation, accompanied with detailed, colored thermal images, simple for understanding to every patient, with the disadvantage of being highly sensitive due to exogenous factors (the evaporation of body heat, external sources of heat, etc.), which can cause confusion or lessen the quality images and in that way reduce the diagnostic reliability [14].

2. MATERIALS AND METHODS

The study included 28 healthy volunteers, 14 female and 14 male, with exclusion criteria being: age <18 years or >35 years, vasoactive medications, current presence of neurological, vascular, or systemic disease, or acute skin conditions and injuries. Approval for research has been obtained by the institution's ethics committee and informed consents were obtained from the study subjects. All the jewelry and similar accessories (such as ring, bracelet, watch, nail polish), which could affect measurements during the research, were removed.

All measurements were obtained under controlled experimental conditions of the environment, at room temperature ($26.84\text{ }^{\circ}\text{C} \pm 4.81\text{ SD}$) and humidity of 22 %, according to the usual recommendations for such a kind of testing [15]. Measuring procedures were based on the previous research and modified with additional steps needed because of longer tourniquet duration. The subjects spent 15 minutes before the start of testing in the examination room in order to achieve adequate adaptation to the environmental conditions. During testing procedure, they were in a sitting position, with palms facing up, which were placed on EPS (expanded polystyrene) board that was on a wooden table. EPS material was used with purpose of a thermal insulator, to minimize direct contact with wood which supported the arms and to achieve minimum heat loss during measuring. Throughout testing procedure, subjects were not allowed to change their starting position nor to move the upper limbs.

Tourniquet was randomly applied for 5 minutes or 10 minutes to the left or right arm. There was a "washout" period between the two applications of tourniquet lasting about 20-25 minutes, to avoid possible influence of the first tourniquet application to the next one. Tourniquet cuff was placed over the upper arm of the examined arm, just above the cubital fossa. The following parameters were measured in all subjects before tourniquet application: blood pressure on both hands, pulse and oxygen saturation of peripheral arterial blood (measured on thumb), as well as temperature of skin surface in the middle of the palms of both hands. Just before tourniquet application, images of both hands were taken with thermal and digital camera, at a distance of 1 meter, to note the initial condition. Both hands were elevated for 30 seconds at 90° , at the head level, after which the cuff was inflated to the values of the supra-systolic pressure (180-250 mmHg), according to formula: supra-systolic pressure = systolic pressure (measured value) + 100 mmHg, for each examinee. In this way, complete occlusion of the brachial artery and temporarily interruption of blood flow were achieved. During the entire research, hands were in a supine position, placed at the heart level and on the EPS board, whose average temperature was $22.03\text{ }^{\circ}\text{C}$.

Measurements for each of three parameters: SpO_2 , skin thermography and skin temperature were made for each subject before placement of tourniquet, at 2 and 4 minutes in the 5-minute tourniquet study and at 2, 4 and 8 minutes in the 10-minute tourniquet study, as well as at 1, 2, 4, 6, 8 and 10 minutes after release of tourniquet.

Measurements were done with infrared thermographic camera, Keysight U5855A TrueIR camera (Keysight Technologies, Santa Rosa, USA) with a sensitivity of 0.07 °C for detection of skin temperature and transcutaneous blood flow, defined by spot and line analysis in the middle of the palm. The obtained thermographic images were analyzed using the Keysight TrueIR Analysis and Reporting Tool 2.0 software. Average values of all obtained temperatures were calculated, of each given time period, which were then compared to "zero" temperature (skin temperature just before cuff release). We used standard fingertip pulse oximeter for measuring oxygen saturation of peripheral arterial blood and peripheral pulse, a non-contact infrared thermometer (with laser targeting and LCD display), for measurement of skin surface temperature, analogue blood pressure meter for blood pressure measurement, and pneumatic tourniquet required to achieve occlusion.

Collected measured results were analyzed using SPSS v23, version 23.0.0.2 (CIPH license). The Kolmogorov-Smirnov test showed that almost none of temperature variables (by thermometer or thermography), followed the normal distribution. Therefore, the nonparametric test, related samples Wilcoxon signed-rank test, was used to test the statistical significance of differences in paired measurements. Statistical significance is accepted when $p < 0.05$. The final results have been shown by absolute numbers and percentages, and in a form of diagrams and tables.

3. RESULTS

Observation of temperature difference between the examined (tourniquet) and the control hand measured by non contact IR thermometer revealed statistically significant increase of temperature difference after tourniquet release (ΔT) at both 5 minute ($p=0,029$) and 10 minute ($p=0,0001$) tourniquet studies. The highest temperature difference (considering temperature measured just before the releasing of tourniquet) was noted in second minute of postocclusive measuring (Figure 1). There was a statistically significant temperature difference ($p < 0.05$), at all time periods, during and after tourniquet (except for basal temperature of examined: control hand, at 5 min and 10 min).

Temperature difference between the examined (tourniquet) and control hand measured by thermography revealed statistically significant increase of temperature difference (ΔT) following tourniquet release at 10 minute tourniquet study ($p=0,008$). Skin temperature increase was significantly higher for 6 minutes after tourniquet release in the 10-minute tourniquet study. The highest temperature difference (considering temperature measured just before the releasing of tourniquet) was noted 1 minute after tourniquet release in the 5-minute tourniquet study and 2 minutes after release in the 10-minute tourniquet study (Figure 2).

According to results obtained by visual detection of duration of reactive hyperemia (as visible redness on

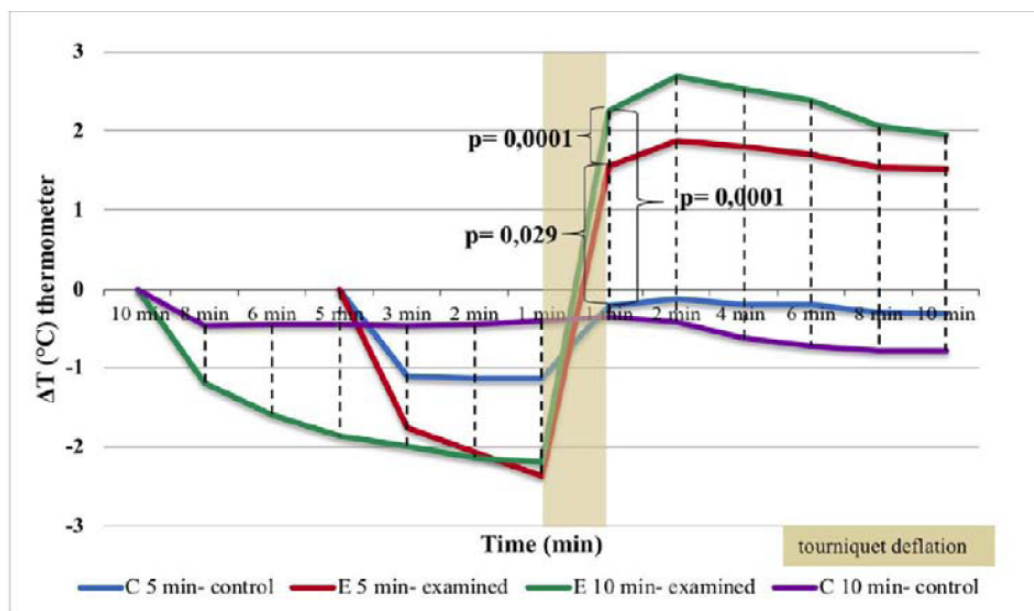


Figure 1: Temperature differences (ΔT), on both hands, of five-minute and ten-minute tourniquet, during and after tourniquet application (C- control hand, E- examined hand), measured by non-contact infrared thermometer.

palms), five-minute tourniquet causes shorter duration of reactive hyperemia, mostly present in periods: 2-4 min (39 %, n=11) and 4-6 min (54 %, n=15). Accordingly, ten-minute tourniquet causes longer duration of reactive hyperemia, with a distribution of 4-6 min (64 %, n=18) and 6-8 min (32 %, n=9) (Figure 3).

After deflation of five-minute tourniquet, SpO₂ values on the examined hand were lower (mean 97.5 %) compared to the control hand (mean 97.8 %), in

each measurement period, although they weren't statistically significant (p>0.05) (Figure 4).

After ten-minute tourniquet, SpO₂ was showing irregular curve movement on both hands, with the same mean value (98.1 %). From 1st to 4th min, mean value of SpO₂ was lower on the examined hand compared to the control hand, while from 6th to 10th min, it was almost equated on both hands. Obtained differences in saturation weren't statistically significant (p>0.05) (Figure 5).

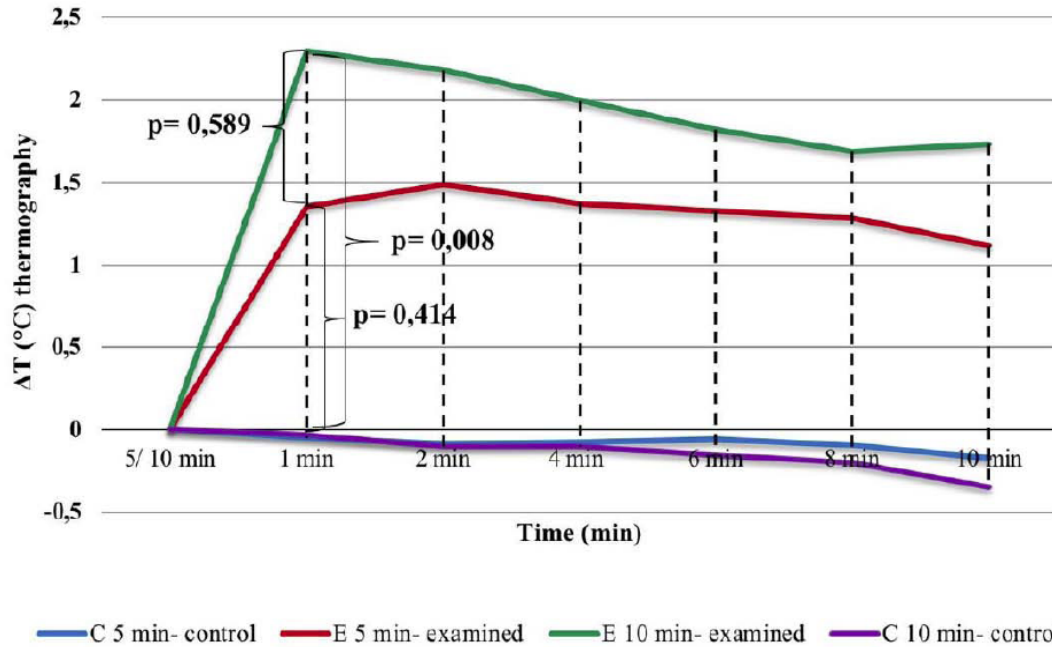


Figure 2. Temperature differences (ΔT), on both hands, of five-minute and ten-minute tourniquet, during after tourniquet application (C- control hand, E- examined hand), measured by infrared thermography.

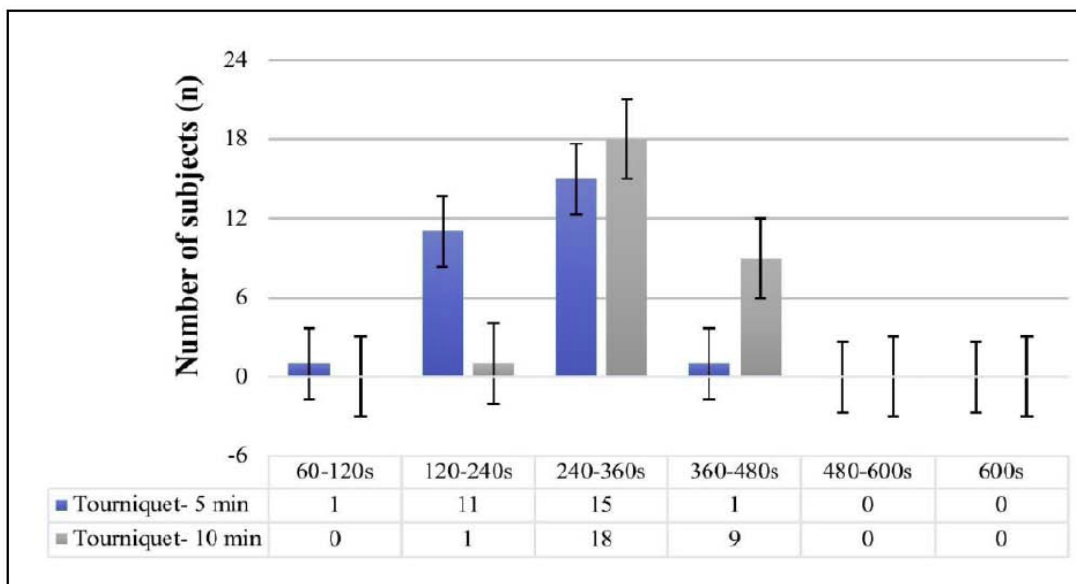


Figure 3: Duration of reactive hyperemia in subjects, according to visual estimation, for examined hand (number (n) refers to number of subjects).

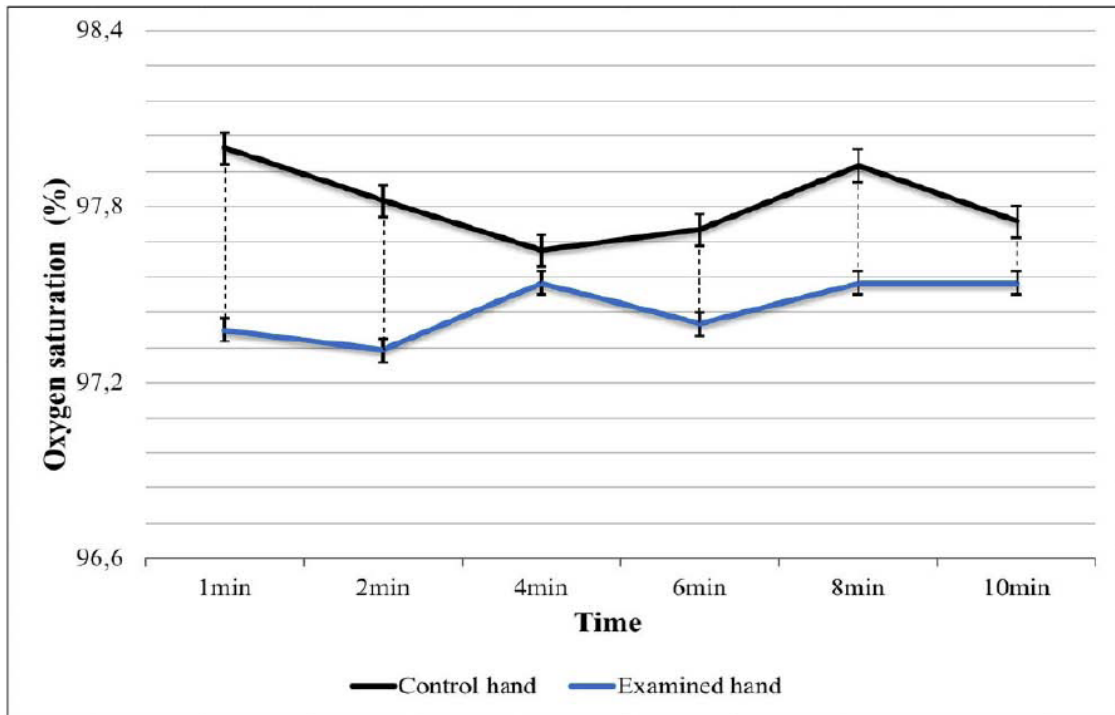


Figure 4: SpO₂ after five-minute tourniquet.

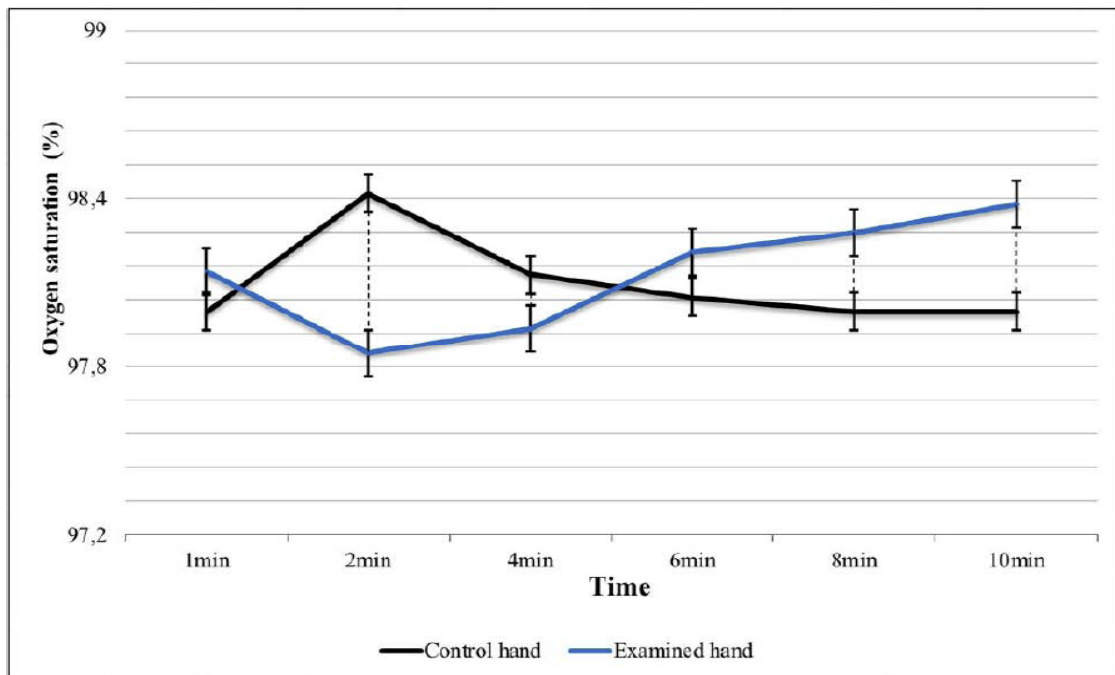


Figure 5: SpO₂ after ten-minute tourniquet.

Reactive hyperemia after five-minute tourniquet (Figure 6) and after ten-minute tourniquet (Figure 7). The first thermographic image shows palmar regions of both hands, in the period of 8-10 min, just before tourniquet deflation. The middle of the palm represents reference point for temperature measurement, with the examined hand being 31 °C, compared to the control

hand where it is 33.9 °C. Further images show progressive temperature rise (examined hand-palmar) at 11th, 12th, 14th, 16th, 18 and 20th minute, with the highest temperature (34 °C) being achieved. At the same time, temperature of the control hand (palmar), has minimally changed from 32.8-33.7 °C (Figure 8).



Figure 6: ΔT - palmar 0,9 °C.

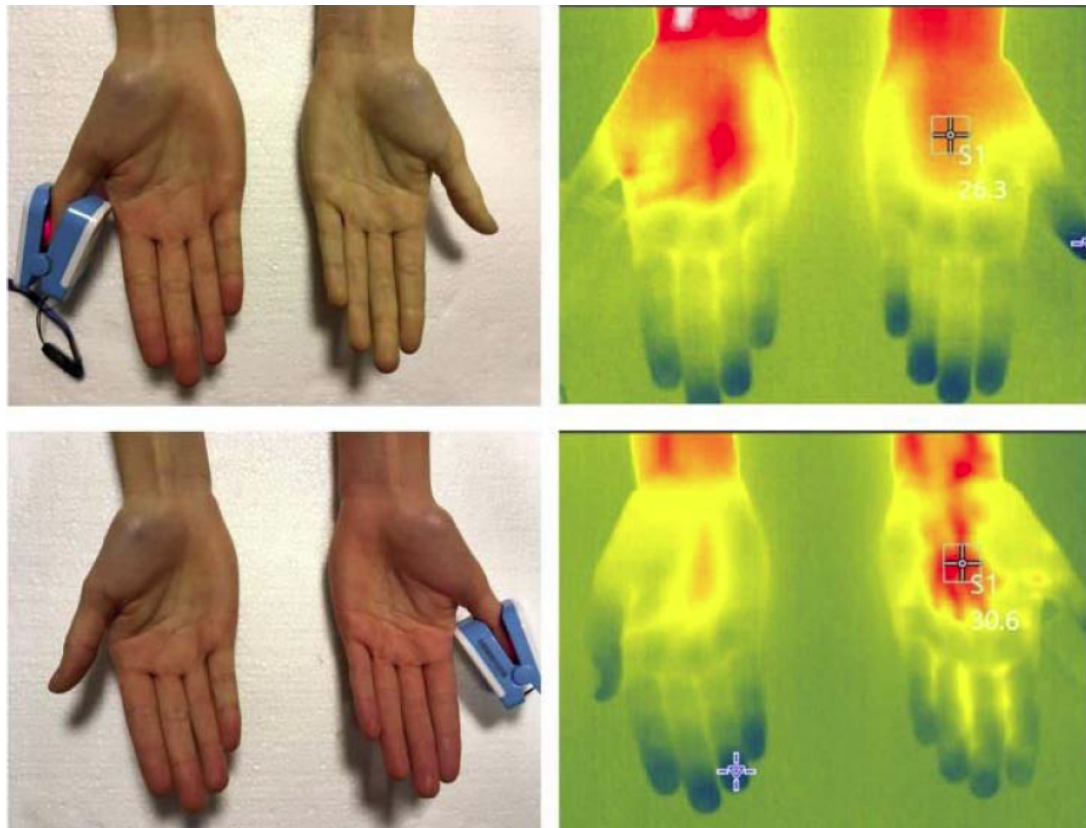


Figure 7: ΔT - palmar 4,2 °C.

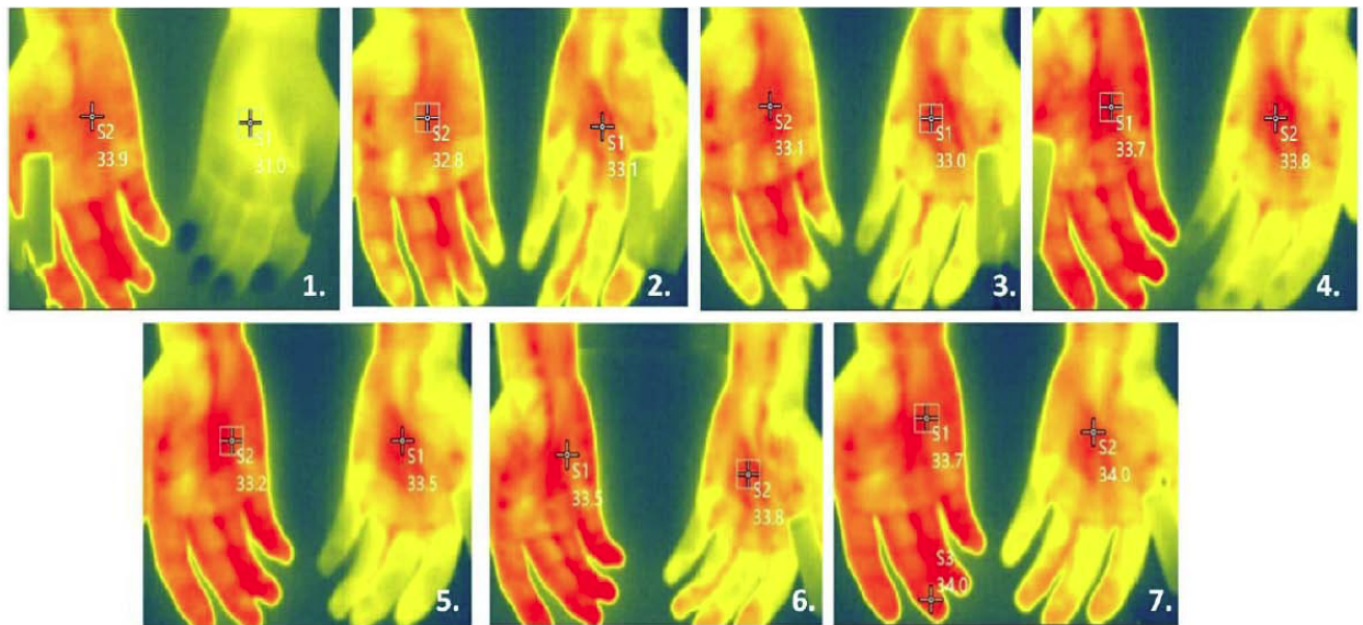


Figure 8: Dynamics of skin temperature and blood flow changes, during and after ten-minute tourniquet presented by thermal camera.

4. DISCUSSION

Infrared thermography has proven to be a useful tool for detecting changes before and after arterial occlusion in the upper arm and for estimating the physiological and pathophysiological functions of the skin circulation [12]. Although, absolute temperatures obtained by thermography depend on a large number of factors, the relative temperature differences measured at the same point, at the same surface, have been shown reliable [16]. Among several suggested methods, special attention was given to occlusion by tourniquet, which was proposed as a valuable method for evaluating of skin blood flow, at sudden changes in perfusion condition [15]. Previous studies have shown, that vascular occlusion in the upper arm, established by 3-minute tourniquet, leads to reactive hyperemia on the palms and fingertips. This involved reducing of skin temperature during vascular occlusion and resulting in temperature increase and skin erythema during reactive hyperemia [17]. Such association may have implications for various areas of surgery, such as orthopedics, plastic and reconstructive, and vascular surgery, in which the use of tourniquet is unavoidable and extremely important for achieving bloodless surgical field. As in the field of anesthesiology, where venodilation induced by reactive hyperemia may facilitate placement of venous needle, especially in patients with otherwise difficult venous access [18].

The main objective of this research is to investigate the existence of correlation between tourniquet duration and temperatures achieved by reactive

hyperemia in the palmar region. To achieve this, 2 noninvasive methods of blood flow measurement were used, infrared thermometer and infrared thermography. None of these methods allows direct measuring of blood flow, but previous studies have demonstrated their reliability in measuring the projected skin temperature, which is an adequate blood flow indicator [19]. Furthermore, duration of reactive hyperemia considering different tourniquet duration, was also measured by visual estimation of time necessary for reducing of skin erythema which is a result of reactive blood flow.

Our research has shown that longer duration of tourniquet leads to more intense and longer reactive hyperemia in the palmar region. The intensity of reactive hyperemia is based on the size of temperature rise considering basal temperature before tourniquet establishment. Results obtained by infrared thermometer have shown statistically significant correlation in all performed comparisons, between the examined and control hand. Those obtained by infrared thermography have shown significance only between the examined and control hand at ten-minute tourniquet and between the examined hands on 5 and 10 minutes, only in the first measuring. Possible explanation of such results is in differences between techniques used for measurement. That is why is necessary, for results obtained by thermography, to take into account distance from which it is measured, the emissivity of palmar surface, temperature and humidity of room, and the fact that was performed after

the measurement by thermometer. Differences of obtained results can also be explained by method of line analysis of thermographic images where mean temperature values were used, to minimize temperature differences that physiologically exist between two points [16].

SpO₂ detection by pulse oximeter, didn't show statistically significant differences at different tourniquet duration nor at comparison of the initial and postocclusive values of SpO₂. There are two main reasons for explaining such a result: low sensitivity of pulse oximeter, and a short time of measuring. It is known that during vascular occlusion, distal parts of the extremity retain residual volume of erythrocytes, whose release of oxygen from hemoglobin is extremely slow [18]. Potential local complications include tourniquet failure causing inadequate hemostasis, without achieving of adequate bloodless field, neuro-vascular and muscular injuries, skin trauma, limb edema and more difficult complications such as compartment syndrome. Systemic complications are also possible after longer tourniquet duration and include arterial hypertension, by increasing peripheral vascular resistance, volume overload, rhabdomyolysis, metabolic and electrolyte disturbances as well as thromboembolism which can be manifested through pulmonary embolism or cerebral infarction.

Finally, results obtained in this research should be interpreted with caution because of small sample of subjects and possible physiological differences considering gender. In addition, attention should be given to research conditions such as time of day, temperature and humidity of the room, and other limiting factors; such as consumption of alcohol, caffeine and/or cigarettes, presence of physical activity and number of hours of sleep, which can have indirect effect. It should be noted, that there is clearly correlation between duration of vascular occlusion at the upper limb and the intensity and duration of reactive hyperemia in the palmar region, which has made base for future research in this area.

5. CONCLUSION

In conclusion, this study provides an inception of probable correlation between duration of tourniquet and distal reactive hyperemia, along with showing potential methods for their registration. To our knowledge so far, there haven't been similar studies for possible comparison, which would consider different tourniquet duration and lasting of reactive hyperemia, using

infrared thermography as a main method. Thermoregulatory difference, as a response to various duration of occlusion, manifests through intensity and lasting of reactive hyperemia. That's why after longer occlusion, there is more intensive and longer duration of increased blood flow, which primary function is to stabilize circulation and to recover it from accumulated metabolites. It can also give us information on the critical period for development of complications, the one in which reactive hyperemia is the most active. Also reactive hyperemia induces quicker venodilation, by increasing of forearm vein area, which can have valuable clinical implications for placement of peripheral *iv* catheters, when there is difficult venous access, as well as sufficient metabolic recovery on the upper limb, after ischemia caused by tourniquet. Although, we have to have in mind that all followed advantages as well as tourniquet-induced bloodless field, which is facilitating operative procedure and reducing blood loss, are very relative and dependent. Therefore postischemic reactive hyperemia can be saveable but it also can induce further hemostatic problems, if we have not obtain exact duration of tourniquet-induced ischemia period.

It is very interesting, that even minor changes in occlusion duration produce significant variations in thermal regulation, which lead us to conclusion that there is an existence of circulatory protective mechanism. At the same time, it opens up space for further research of the most optimal and most effective duration of tourniquet, to establish maximal and most effective postischemic venodilation, with as less as possible repercussions per patient.

DISCLOSURE STATEMENT

The authors declare no conflicts of interest.

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