

STUDY OF RAYNAUD'S PHENOMENON BY MEANS OF INFRARED FUNCTIONAL IMAGING

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Abstract – Infrared Functional Imaging was applied to the study of Raynaud's Phenomenon obtaining a simultaneous assessment of the thermal properties of all five fingers of both hands of a group of patients with respect of a control group. The method is based on the use of high-resolution telethermography imaging and allows identification of objective parameters from the re-warming curves of finger immediately after a 2 min cold stress. The evaluation of the area under the temperature versus time curve, namely the temperature integral INT, provides a figure particularly effective in describing the thermal properties of the finger. 18 healthy volunteers, 20 Secondary Scleroderma and 20 Primary Raynaud's Phenomenon patients were studied subsequently to clinical evaluation and nailfold capillaroscopy. This new approach highlighted a quite different behaviour between patients with Primary Raynaud's Phenomenon and those with early diagnosed Systemic Sclerosis. This new method, compared with other existing techniques, seems to be useful tool to discriminate between PRP and RP secondary to SSc.

Keywords – Raynaud's Phenomenon, Infrared Imaging

I. INTRODUCTION

Raynaud's phenomenon is usually defined as an episodic vasoconstriction, in response to cold or emotion, of small arteries and arterioles of fingers, toes and, sometimes of nose's tip and earlobes. In PRP, episodic ischaemia in response to cold exposure or to emotional stimuli is usually completely reversible: absence of tissue damage is the typical feature [1], but also mild structural changes are demonstrated [2]. On the contrary, sclerodermic RP shows irreversible tissue damage and severe structural changes in the finger vascular organisation [3]. Moreover, among a certain group of patients it is not so clear if RP is benign or if it represents the first symptom of SSc disease. Only the evaluation of the disease severity and degree of digital vascular disease will permit to distinguish between PRP and RP secondary to connective tissue diseases, especially Systemic Sclerosis.

None of the physiological measurement techniques currently in use are completely exhaustive in focusing primary or secondary RP [4]. Moreover, these techniques -as nailfold capillary microscopy, cutaneous laser-Doppler flowmetry,

and plethysmography- can proceed just into a partial investigation, usually assessing only one finger for each measurement. Only infrared functional imaging (IRFI) can assess more fingers of both hands, simultaneously giving a pictorial representation of surface temperature. Thermography protocols [5-11] usually include dynamic testing, such as cold stress, in order to evaluate the capability of the patient hands to re-warm. This capability is, in some way, depicted by the pattern of the re-warming curve that also gives some information on the underlying structural diseases. Several studies have shown how the analysis of re-warming curves could differentiate between healthy subjects and RP patients [5- 11]. The direct or indirect dependence of the parameters considered in those studies on finger thermophysical properties and on blood perfusion has not been thoroughly investigated so that they may appear somewhat empirical and lacking a proper physiological meaning.

Aim of this pilot study is to verify the capability of IRFI to identify objective parameters useful for discriminating PRP from SSc patients, starting from a physiological basis, and by means of a simple thermophysical model.

II. THEORY

The first mechanism activated by the finger to exposure to a cold environment is vasoconstriction, which induces a rapid and consistent decrease of blood flow into distal districts, particularly in fingers. Following cold environmental temperatures, fingers blood flow drops to nutritional levels [12 - 16]. During the re-warming period following a cold stress, thermal energy is transported and exchanged at the finger level by means of different factors: 1) exchange with the environment; 2) transport by the incoming blood flow; 3) conduction from adjacent tissue layers; 4) metabolic processes. The net balance of the energy input/output determines the increase/decrease of the finger temperature. The analysis of the relative contributions of the re-warming factors suggests that the energy conducted from adjacent tissues and the metabolic processes are negligible compared to the other two [17-18]. Therefore, it may be assumed that finger temperature reflects the balance between the input power due to blood perfusion and the power lost to the environment:

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$$\frac{dQ_{\text{tot}}}{dt} = \frac{dQ_{\text{env}}}{dt} + \frac{dQ_{\text{ctr}}}{dt}$$

In normal subjects, immediately after a cold stress, the finger temperature increases exhibiting the typical re-warming pattern shown in Fig. 1.

In absence of thermoregulatory control, fingers exchange heat only with the environment and, in this case, their temperature (T_{exp}) follows an exponential pattern with time constant $\tau = (\rho cV)/(hA)$, – where ρ is the mass density, c the specific heat, V the finger volume, h is the combined heat transfer coefficient between the finger and the environment and A is the finger surface area.

The amount of heat exchanged with the environment during this exponential phase, within a time interval Δt , is directly proportional to the difference between T_{exp} and the ambient temperature T_0 .

$$\Delta Q_{\text{env}} = hA(T_0 - T_{\text{exp}}) \cdot \Delta t$$

and is represented in Fig. 1 by the area of the trapezoid CDEF multiplied by $h \cdot A$.

On the other hand, due to the presence of the thermoregulatory control, the finger maintains its temperature T greater than T_{exp} , thanks to an excess of heat provided by blood flow and quantified, for a Δt time, by the area of the trapezoid ABCF multiplied by $h \cdot A$, namely ΔQ_{ctrl} .

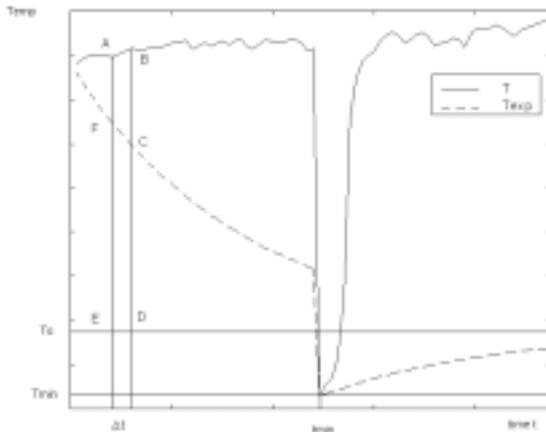


Fig. 1: Re-warming curves after cold stress in normal subjects. The continuous curve represents the recorded experimental temperature finger. The dot curve represents the exponential temperature pattern exhibited by the finger in absence of thermoregulatory control. In this case, the only heat source for the finger is the environment.

This amount summed to ΔQ_{env} yields the global amount of heat stored in the finger:

$$\Delta Q = \Delta Q_{\text{env}} + \Delta Q_{\text{ctrl}}$$

Then, the area of the trapezoid ABDE, divided by $h \cdot A$, represents the amount of heat in the finger during a Δt interval. The total amount of heat is then obtained calculating by integrating the area subtended by the temperature curve T and the constant straight line T_0 :

$$Q = - h \cdot A \int_{t_1}^{t_2} (T_0 - T(t)) d\eta$$

where the minus sign takes into account that the heat stored by the finger is counted as positive.

It should be noted that Q_{str} is intrinsically related to the finger heat capacity per unity volume ρc , according to the expression

$$\Delta Q = \rho cV \Delta T$$

Then the numerical integration of the temperature T is directly related to the thermoregulatory properties of the finger and, under the hypothesis of a constant T_0 , can be used to characterise the re-warming exhibited by a healthy- or a suffering finger since it represents a normalisation of the thermoregulatory properties. In particular, we can define

$$\text{INT} = \int_{t_{\text{min}}}^t T(t) d\eta \quad (1)$$

The integral defined by the expression (1) can be evaluated with reference to a (t_{min}, t) time interval, equal for each measurement, by numerical methods. The value obtained by means of (1), can be calculated for a single finger or for all of the fingers of both hands, individually and simultaneously.

MATERIALS AND METHODS

40 patients selected among those monitored at the Clinical Immunology Unit - Department of Clinical Medicine, University "La Sapienza", Rome were tested. 18 healthy volunteers were also enrolled to get a comparative normal group. 20 out of 40 were classified as the primary RP (PRP) group for the absence of any symptom or sign of connective tissue disorders; 20 out of the 40 patients had RP secondary to SSc, diagnosed within the last two years according to ARA criteria for this disease [8].

All patients had pharmacological washout during the two weeks preceding the measurement and no vasoactive drugs for 24 hours before the test.

A 15 minutes acclimation period preceded the study session carried out in a measurement room with constant temperature ($T_0 = 23 \pm 0.5$)°C.

The test consisted in recording 5 telethermographic images of hands at rest and other 40 during the re-warming period after the cold thermal stress. IRFI was performed using a 14 bit digital telethermographic camera AEG 256 PtSi, which spectral band is within 8-14 μm . The measurement noise was about 0.02. Black body correction was executed to avoid and correct instrumental artefacts, for each subject at the beginning and at the end of measurement session.

The cold stress consisted in a 2minute immersion of both gloved hands in a cold bath at 10°C.

Re-warming curves were recorded for each of the five finger of both hands at level of the nailbed.

The thermographic data were analysed by means of the ANOVA test, and the statistical significance level was fixed at $p < 0.001$.

All subjects gave informed consent to the study, which was approved by the local Ethical Committee

RESULTS

INT, which represents the normalised amount of heat in the finger following a cold stress during a (t-tmin) time interval, allows to clearly discriminate (Table 1) between patients with Primary Raynaud Phenomenon (PRP), Sclerodermic Raynaud patients (SSc) and healthy subjects.

The individual INT value, i.e. the value obtained for each finger of all patients, is reported in Fig. 2, at the end of the paper. Grouping of the two classes confirms the findings described above. In particular, the PRP group features low intra-individual and inter-individual variability whereas the SSc group displays a large variability between healthy and unhealthy fingers, as confirmed by the large standard deviation of the group mean.

The ANOVA test provided a value $p < 0.001$ that was considered as statistically significant.

Table 1: Group INT Values and Statistical Significance

Group	INT (° C·min)	Statistical Significance		
		vs PRP	vs SSc	vs Control
PRP	(380.5 ± 13)	-	P < 0.001	P < 0.001
SSc	(510.6 ± 92.1)	P < 0.001	-	P < 0.001
Control	(1022.0 ± 110.2)	P < 0.001	P < 0.001	-

In the normal subject and in the PRP patient all five fingers demonstrate a homogeneous behaviour, even if a pathological poor recovery characterises the PRP fingers; additionally, in the PRP patients the homogeneous behaviour is maintained also regarding the equilibrium temperature before the cold stress. On the contrary, for the SSc subjects, a quite different thermoregulatory response was observed in each finger, probably because of scleroderma, that modifies the thermal properties and blood flow organisation in different finger.

DISCUSSION AND CONCLUSIONS

In this paper, we present a novel approach to the estimation of Raynaud's phenomenon based on infrared functional imaging. The INT parameter seems to be particularly effective in order to describe the thermal recovery capabilities of the finger. Mean values of the temperature integral, taken during the re-warming process after a short time cold stress, clearly highlight the difference between PRP and SSc patients and provide useful information about the abnormalities of their thermophysical and thermoregulatory finger properties.

This pilot study, simultaneously assessing all the five fingers of both patients, highlighted the difference between a quite homogeneous behaviour of all fingers in all fingers of PRP patients, in contrast with a quite variable behaviour of fingers in SSc patients.

PRP fingers behaviour is due to equal, low and constant blood perfusion of all fingers and to differences in heat lost to the environment, both processes being related to the finger surface-to-volume ratio. Analogous behaviour can also be traced at the equilibrium state, in absence of thermal shock. In

fact, the general lower equilibrium temperatures of the "PRP" fingers with respect to the "SSc" ones could be explained in terms of reduced efficiency of the thermoregulatory system of the finger.

Moreover, the "shared" weak thermoregulatory response can also explain the remarkable intra and inter individual homogeneity observed in the PRP group.

Conversely, no common behaviour was found for the SSc patients, since their disease determines - for each finger - very different thermophysical and blood perfusion properties.

The presence of scleroderma seems to increase the thermal capacity with a reduced ability to exchange heat; the altered capillaroscopic frame seems to lead to an improper local thermoregulatory control, with an increased blood flow for the larger vessels and a reduced one in the distal areas.

These typical SSc damages can produce different regional thermoregulatory behaviours among the same finger, together with the possible presence of the scleroderma spots.

In conclusion IRFI allows determining a numerical parameter closely associated with the thermophysical properties and thermoregulatory capabilities of fingers. By the use of simple physiological energy balance principles, infrared functional imaging allows a non-invasive measurement to control, simultaneously and quickly, all fingers response.

In conclusion, the method presented, when compared with other existing techniques, seems to be a useful tool to discriminate between PRP patients and patients affected by RP secondary to SSc.

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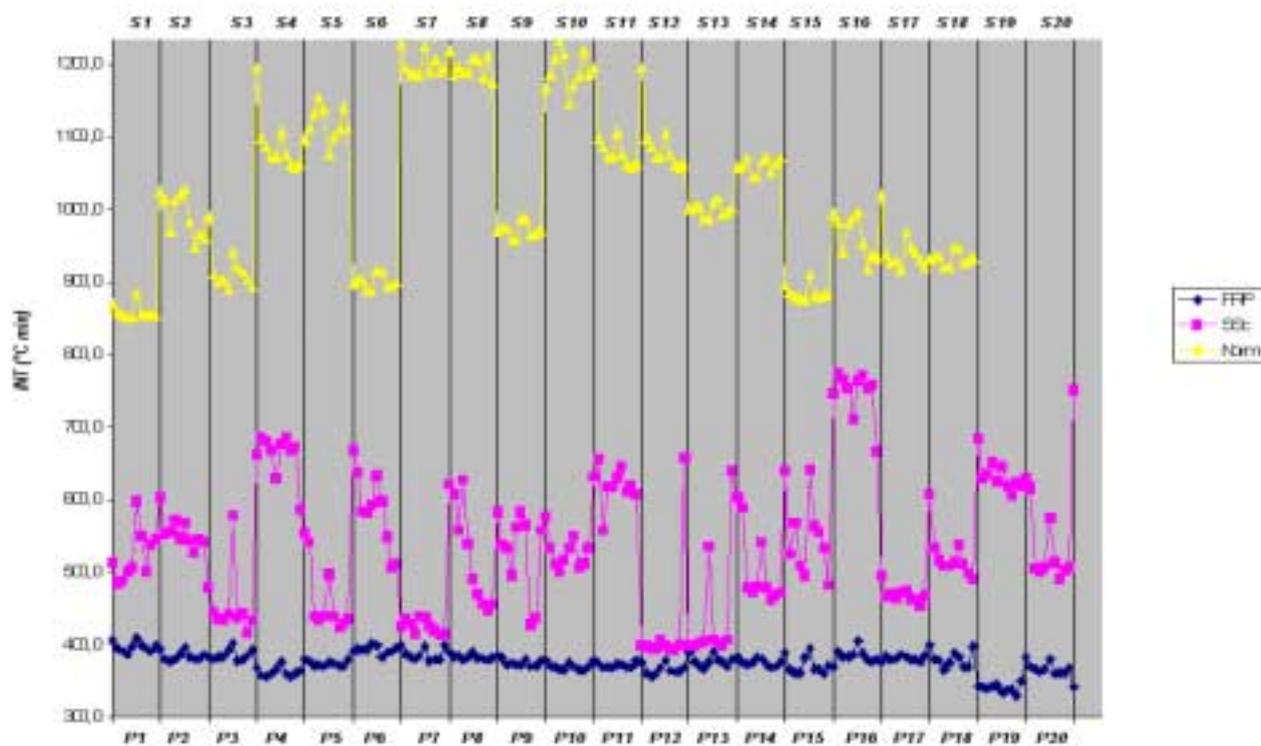


Fig. 2: INT values calculated for each finger of each patient. SSc patient codes are reported on the upper x-axis, while the lower one reports the PRP patient codes.