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EVALUATION OF SUB-ZERO AND RESIDENCE TIMES AFTER CONTINUOUS VERSUS MULTIPLE INTERMITTENT CRYOGEN SPRAY COOLING EXPOSURE ON HUMAN SKIN PHANTOM

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ABSTRACT

Cryogen spray cooling (CSC) is used to minimize the risk of epidermal damage during various laser dermatologic surgeries. However, as the application of single or multiple cryogen spurts becomes available on some commercial lasers devices, it is necessary to determine the optimal CSC parameters for different laser surgeries. The objective of this study was to measure the time the sprayed surface of a human skin phantom (HSP) remains below water freezing temperature 0°C, referred to as subzero time (t_s), and below the cryogen boiling temperature -26°C, referred to as residence time (t_r), as well as the minimum surface temperature (T_{min}) and the time at which T_{min} occurs (t_{Tmin}) for two HSP-initial temperatures (20 °C and 70 °C) during and after the application of single (SCS) and multiple cryogen spurts (MCS). For this propose, a HSP was used to measure t_s, t_r, T_{min}, and t_{Tmin} for nine sequences: one SCS of Δt_T = TCT = 40 ms; four MCS sequences, all adding to a Δt_T of 40 ms but with different TCT up to 110 ms and, finally; four SCS that matched the TCT of the four MCS sequences, but lead to different Δt_T. Our results show that the differences between SCS and MCS sequences with the same TCT are negligible for all variables measured (t_s, t_r, T_{min}, t_{Tmin}). Moreover, in this interval (40 ms≤ TCT ≤ 110 ms), this variables show a remarkable linear dependence with the TCT.

Keywords: dynamic cooling, cooling selectivity, cryo-injury, port wine stain.

INTRODUCTION

CSC is particularly necessary for treatment of superficial vascular lesions, since it permits [1]: (1) accurate control of the cryogen application time (typically 5-100 milliseconds) and, consequently, cooling time and; (2) high heat transfer rates as cryogen is deposited onto the skin and evaporates at the sprayed surface. These two characteristics are instrumental to achieve efficient and spatially selective epidermal cooling.

Despite these advantages, some authors have expressed concerns that CSC may induce cryo-injury [2]. With this in mind, different studies of CSC have been developed employing computational models [3], epoxy phantoms [4], and more recently an In-Vitro Skin Model (RAFT) [5] to study the effect of short cryogens spurts on HSP.

In this work, we investigate systematically the thermal response of skin phantoms by measuring the time (t_{Tmin}) and magnitude at which the minimum surface temperature (T_{min}) is reached, as well as the time the sprayed surface remains below 0 °C (subzero time, t_s) and -26 °C (residence time, t_r), and examine the differences between SCS and MCS sequences.

EXPERIMENTAL SETUP

The human skin phantom (HSP) consisted of a thin (90 μm) rectangular (3.42 × 3.50 mm) silver foil placed on top of an epoxy resin and a type-K thermocouple (≈50 μm bead diameter) positioned in between. Thermal paste was applied around the bead to ensure good thermal contact. The foil is thin to ensure fast response [4]. The purpose of this HSP is to provide skin-like thermal properties. In order to simulate the heat generated by the laser pulses, the HSP was placed on a copper plate, which was heated by a couple of thermo-electric coolers (TEC) controlled by a power-source until the HSP reached 70 °C (this temperature has been defined as the threshold temperature for instantaneous skin-damage [6]).

The only FDA-approved cryogen compound currently used in dermatology is 1,1,1,2 tetrafluoroethane, also known as R134a, with boiling temperature T_b ≈-26 °C at atmospheric pressure. A commercial cryogen spray nozzle used for laser treatment of vascular lesions and hair removal was employed: GentleLASE™ (by Candela, Wayland, MA), with approximate inner diameter of 0.5 mm. The cryogen was delivered through a standard high-pressure hose connecting the container to the control valve.

In this study we employed electronic controlled SCS and MCS sequences. T_{min}, t_{Tmin}, t_s, and t_r, were systematically measured for nine sequences: (a) one SCS of TCT = 40 ms; (b) four MCS sequences with identical Δt_T of 40 ms, but with a constant time interval between consecutive spurts (10 ms) which resulted in a variation of the total cooling time (TCT) from 50 to 110 ms; (c) four SCS sequences that matched the TCT of the MCS sequences described before (50, 70, 80 and 110 ms).

The nozzle-to-surface distance, *z*, was 31 mm for all cases, which corresponds to that used by most commercial devices. A schematic of the experimental setup is shown in Fig. 1.

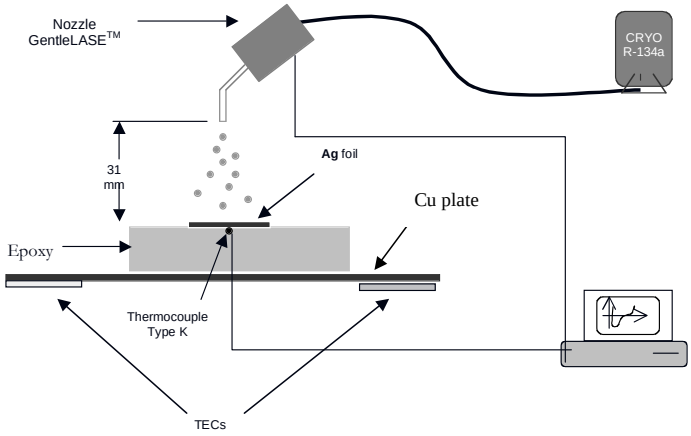

Fig. 1 Experimental setup employed to measure the sprayed surface temperature of the human skin model during the application of SCS and MCS, for two different initials HSP temperatures.

RESULTS AND DISCUSSION

Figure 2 shows a typical surface temperature measurement of the HSP in response to a MCS sequence, as well as the notation employed to describe the features of the temperature evolution with time. As spray droplets impinge on the surface, a very fast heat-extraction is generated on the cryogen-HSP interface. A rapid decrease in surface temperature (quantitatively similar to that expected to occur on human skin) is noted. A minimum surface temperature (T_{min}) is reached at a certain time (t_{Tmin}) that depends on the TCT employed in each sequence. Sometimes the interface can reach and maintain for several milliseconds a local constant temperature near T_b. This may be attributed to the presence of a thin residual cryogen layer, which evaporates during and after spurt termination. Aguilar et al [1] defined the residence time (t_r) as the period when the surface temperature is lower than the cryogen boiling point (T_b≈-26 °C). The increase in temperature from T_b up to the freezing temperature of water (T_m) is very gradual and relatively linear. Sometimes, a plateau is noted at T_m, which may be attributed to condensation, freezing and subsequent melting of the ambient water on the surface. The period the surface temperature remains below 0 ° is known as sub-zero time (t_s).

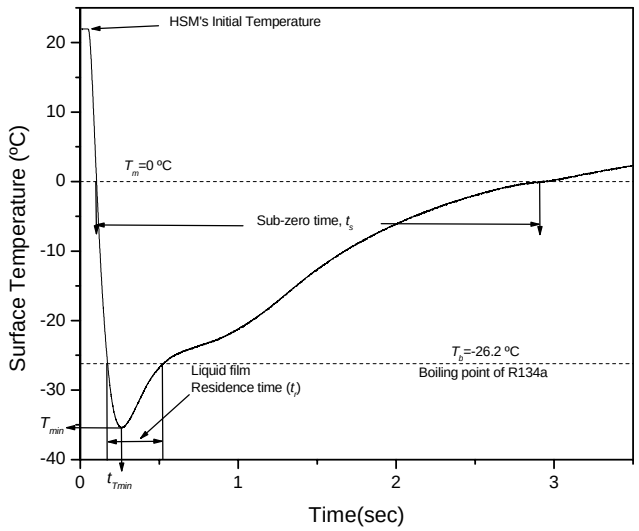

Fig. 2 Schematic of a typical temperature curve vs. time for MCS at spray distance (z) = 31 mm and a relative humidity of 39%. Characteristics features are minimum temperature (T_{min}); time at which T_{min} is reached (t_{Tmin}); sub-zero time (t_s), liquid cryogen residence time (t_r); boiling temperature of R134a (T_b) and, freezing temperature of water (T_m).

Figures 3 and 4 show, respectively, T_{min} and t_{Tmin} as a function of TCT for the nine sequences described above and for two different initial HSP temperatures (20°C and 70°C). For T_{min}, the differences between SCS and MCS sequences with the same TCT are negligible. Note, however, that T_{min} has a strong dependence on the initial HSP temperature. In Fig. 3, T_{min} shows an interestingly linear dependence with TCT. From Fig. 4 it is also possible to observe a remarkable linear dependence of t_{Tmin} with TCT. Interestingly, the slope of this linear behavior is ~1, which means that T_{min} is always reached upon spurt termination for both SCS and MCS and for the two initial HSP temperatures.

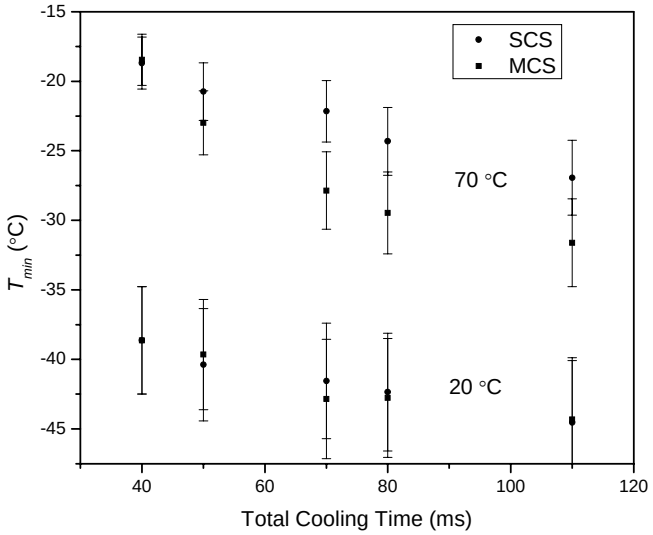

Fig. 3 T_{min} vs. TCT for SCS and MCS at two different HSP's initial temperatures. Notice the similarity between SCS and MCS with the same TCT. Interestingly T_{min} decrease linearly with TCT.

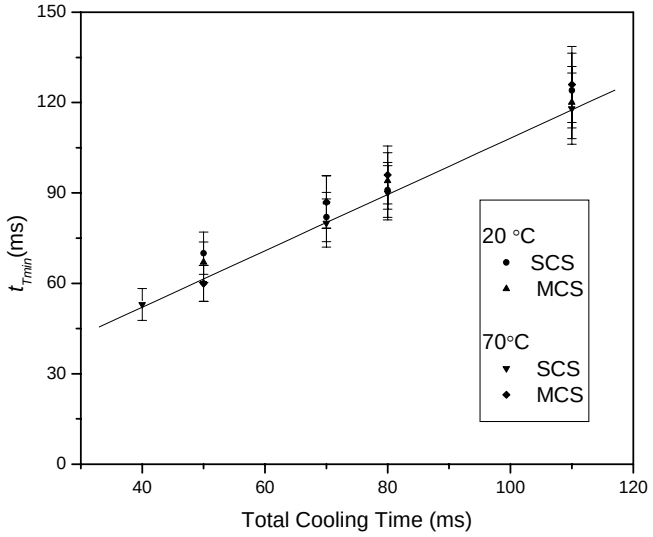

Fig. 4 t_{Tmin} vs TCT, for MCS and SCS sequences at two different initial temperatures. Interestingly, t_{Tmin} keeps the same linear behavior for all sequences and for the two initial HSP' temperatures.

Fig. 5 shows t_s vs. TCT for all sequences at the two initial HSP temperatures. Similar to T_{min} and t_{Tmin}, the difference between SCS and MCS is negligible.

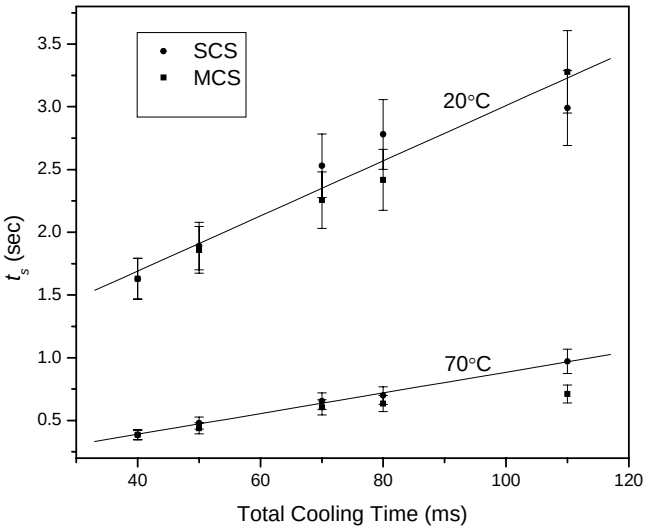

Fig. 5 Sub-zero (t_s) time as a function of the TCT. As well as T_{min} the differences between SCS and MCS sequences for t_s are negligible.

Note, however, that not only the magnitude but also the slope of this linear dependence is determined by the initial HSP temperature. Actually, the slope for the case of 20°C increases by a factor of two compared to that of 70°C. A qualitatively similar situation is seen in Figure 6, where the t_r is plotted as a function of TCT.

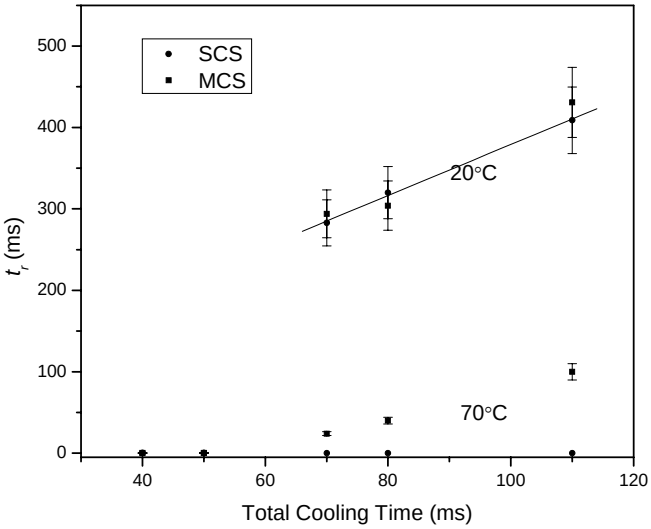

Fig. 6 Residence time (t_r) vs Total cooling time (TCT). Notice the high similitude between SCS and MCS for all sequences, and the dangerous linear increase of t_s for the case at 20°C.

The behavior of the surface temperature with time for the two type of sequences studied (SCS and MCS) suggests that three of the parameters studied: T_{min}, t_s, and t_r, are insensitive to

the spray sequence and are solely dependent on the initial HSP temperature and TCT, while t_{Tmin} is only dependent on TCT.

t_s depends mainly: on the time the surface temperature remains almost constant near T_b (which may be attributed to the presence and linear evaporation of a residual cryogen layer), as well as on the rate of growth (Fig. 7) from T_b to T_m (actually, the temperature in this range grows ~100% faster for the shortest sequence than the longest sequence in the interval TCT ≤ 110 ms). The linear superposition of these two linear processes, gives origin to the linear dependency of t_s on TCT.

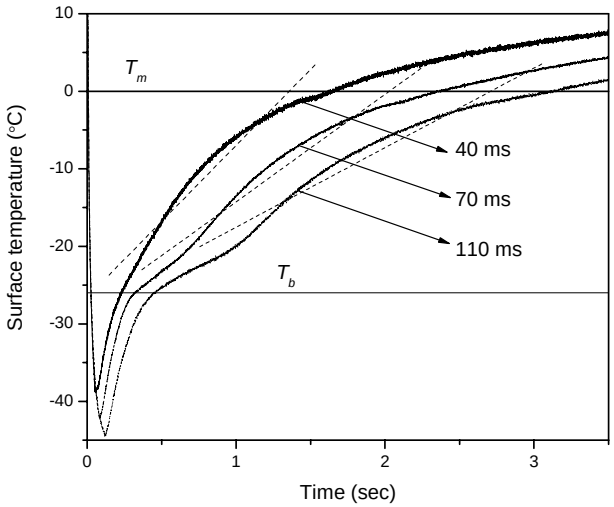

Fig. 7 Surface temperature vs Time for three SCS of different Δt_{total}

CONCLUSIONS

A HSP was built and used to measure the dynamic cooling effect during SCS and MCS. The temporal distribution of temperature for a specific sequence (continuous or multiple) is strongly dependent on the initial temperature difference between the HSP and the cryogen layer. Our results show that the differences between SCS and MCS sequences with the same TCT are negligible for all variables measured (T_{min}, t_{Tmin}, t_s, t_r). Interestingly, these parameters show a linear dependence with TCT. The longer TCT the longer t_{Tmin}, t_s, t_r, and lower T_{min}, this behavior is maintained for the two initial temperatures studied herein. These results suggest that in the interval 0≤ TCT ≤110 ms, similar epidermal protection may be attained with SCS and MCS.

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