Severe Local Hypothermia from Laparoscopic Gas Evaporative Jet Cooling: A Mechanism To Explain Clinical Observations

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ABSTRACT

Background and Objectives: Explanations for laparoscopic-induced hypothermia fail to explain clinical observations. It is possible that water evaporation occurs from the jet stream of gas inflation resulting in tissue surface super-cooling leading to tissue damage and drying.

Methods: Theoretical calculations based on thermal conductivity, mass transfer effects and heat flux considerations correlated closely with synthetic and tissue experiments. Thermocouple measurements at a rate of 15 data points per second were performed.

Results: Cooling rates of 10 to 25 degrees centigrade per second for high flow rates were found based on gas flow rate and effective size of gas delivery site. These rapid temperature drops extended beyond a 2 cm^2 diameter.

Conclusions: Evaporative cooling accounts for significant hypothermia. The cooling is dependent on the lack of water vapor in the gases currently used during laparoscopy. Cooling rates are independent of height from tissue and geometry of delivery port. Heating and hydrating the gas to a physiologic condition eliminates hypothermia and tissue dessication.

Key Words: Laparoscopy, Hypothermia, Evaporation, Pneumoperitoneum, Peritoneal fluid.

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INTRODUCTION

Past theoretical mechanisms have failed to explain the observed, postoperative hypothermia in laparoscopic patients. Mismatch of tissue and inflation gas thermal capacities rule out any substantial global tissue temperature reductions during laparoscopic procedures. Overlooked, however, is the possibility that severe hypothermia is due to local super-cooling of tissue caused by evaporation from tissue surfaces of peritoneal fluid water into the dry jet of insufflation gas. This mechanism is examined analytically and experimentally and is found to be real and significant.

Patient hypothermia during laparoscopic surgery is widely reported in recent literature.[1-6] While this clinical condition and its undesirable consequences to the patient are well understood, the exact cause of the additional hypothermia due to laparoscopy is not clear. It is reported that the heat capacity effects of the CO_2 insufflation gas are not sufficient to cause physiologically significant, bulk tissue cooling.[7,8] The question remains, therefore, What is the cause of a patient's additional hypothermic response observed during laparoscopic surgery?

At least one possible causative factor could be severe cooling of local tissue surfaces through the evaporation of peritoneal fluid by the jet of dry insufflation gas (usually CO_2) impinging on the epithelial surface while the gas is being introduced to the peritoneal cavity through a trocar or other device, such as a Veress needle. This study was designed to explore the possibility that such a mechanism could result in substantial cooling of surface tissue during the initial abdominal insufflation and/or subsequent insufflation during the laparoscopic procedure.

A theoretical analysis was completed of the evaporative cooling effects caused by the simultaneous tissue-conductive, and gas-convective, jet heat and mass transport that reasonably could be expected to occur during typical insufflation. Laboratory measurements of the temperature transient occurring when a dry CO_2 gas jet impinged on simulated and animal tissue material was obtained to verify the results of these theoretical calculations. The experimental studies included measurement

of the effects of procedure variables: insufflation gas flow rates; height's of the gas jet; tissue cooling-area size; type of gas entry port; tissue type; and, most importantly, the thermal/humidity condition of the insufflation gas stream. **Table 1** summarizes the range of these variables for which theoretical and experimental results were obtained in this work.

MATERIALS AND METHODS

Evaporation jet cooling of the epithelial tissue occurs when the end of a Veress needle or trocar is positioned close to a tissue surface, as shown in **Figure 1**. The insufflation gas exits from the end of the Veress needle or trocar (the "nozzle" of **Figure 1**) in a free vertical jet. When the gas jet reaches the epithelial surface (impingement surface of **Figure 1**), the gas flow is redirected horizontally and flows radially away from the centerline of the entry port on the impingement surface (the stagnation point). Because of a very rapid flow transition on the epithelial surface, high heat and mass transfer rates are generated in the area of the stagnation point with the maximum effect occurring at the stagnation point. When the insufflation gas is dry, as it is in all laparoscopic procedures, a large evaporation-driving force is generated in the resulting gas phase boundary layer, with velocity profile transitions, in very high evaporation rates around the stagnation point. The energy needed to evaporate fluid from peritoneal tissue surfaces is from jet evaporation

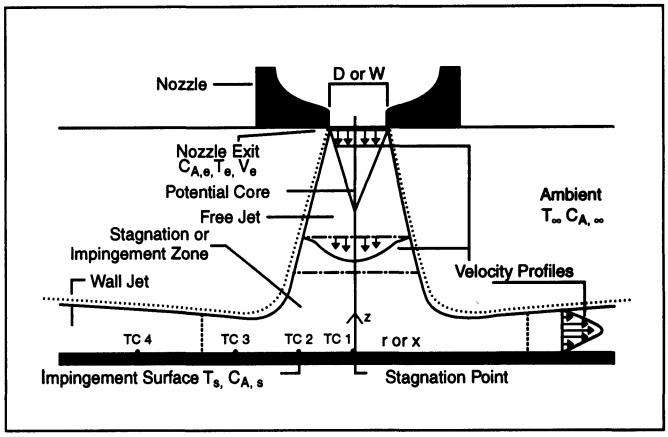

Figure 1. Surface impingement of a single round or slot gas jet.

and cools the surface at a rapid rate. How fast, how long, and how much tissue will be cooled and to what temperature is a complex function of the gas flow rate (F l/m), the height of the gas injection device above the tissue (H mm), the dimension of the gas injection device (D, the diameter of the circular entrance port, or W, the width of the annular jet from a trocar), the size of the cooled tissue area (measured by r, the distance from the stagnation point for the circular jet, or x, the distance from the center of slot width W of an annular jet), the magnitude of the tissue's thermal parameters of thermal conductivity and diffusivity and, most important, the relative humidity of the insufflation gas. The theoretical analysis and these results are the focus of this study.

Experimental verification of the theoretical results were obtained through *in vitro* measurements of jet cooling of synthetic and animal tissue surfaces at various flow and geometry conditions known to influence the cooling rates. The rapid tissue cooling rates were measured with single and four thermocouple (t/c) configurations that detected tissue surface temperature at the stagnation point and with the four t/c configuration, at progressively larger distances (r) from the stagnation point **(Figure 1)**. Temperatures were collected by computer data acquisition at rates of 5 to 15 points per second and stored for analysis and display. Great care was taken during the experimental measurements with the apparatus seen in **Figure 1** to assure that the surrounding conditions of temperature (T_∞) and humidity simulated conditions that are experienced in the human abdomen.

Table 1.
Summary of Studied Procedural Variables.

Insufflation gas flow rates	1 - 10 liters min
Height of gas jet	1 - 10 mm
Cooled tissue size	0.5 - 2.0 cm^2
Type of gas entry port	Veress needle
	10 mm trocar
"Tissue" types	Porous wet gauze
	Porous wet polyurethane foam
	Wet turkey
	Wet ham
	Wet corned beef
Gas temperature	22 – 37°C
Gas humidity	0 & 95+%

THEORY

Much theoretical and experimental work has been done on heat and mass transfer into and from circular and slot gas jet streams.[9-11] The mass transfer elements of these studies, however, have been limited to sublimation of a solid into a gas jet; and gas jet evaporative mass transfer of a liquid surface has been studied very little. For this study, we have used the well known and reliable heat-mass transfer analog for convective flow, making it relatively simple to circumvent this lack of direct experimental correlations.

Referring to **Figure 1**, the impingement surface of our model is wet with peritoneal fluid and is cooled by latent evaporative heat flux into the jet of dry CO_2 insufflation gas. The heat transfer flux due to this evaporative mass transfer is characterized by the equation,

$$J_{h,e} = h_e p_s (1-\phi) \quad (1)$$

where h_e is the evaporative heat transfer coefficient, p_s, the vapor pressure of the surface fluid (a function of surface temperature), and ø is the jet gas's relative humidity (assumed zero for this analysis).

As has been discussed, the heat and mass transfer coefficients needed in Equation 1 vary considerably from a maximum at the stagnation point to decreasingly lower values at positions r (or x for a slot jet) away from the circular jet center line. The integral mean values for the transfer coefficients in these regions in terms of r and x; the diameter, D, of the circular jet (or W, the width of the slot jet); and the height of the nozzle, H, from the impingement surface have previously been determined and is called the Martin's Nusselt number.[9] From the Martin's Nusselt number correlations we obtained mean (with r or x) heat transfer coefficients, h_e. The classic heat-mass transfer analog is in the form

$$Sh/Nu = (Sc/\mathrm{Pr})^n \quad (2)$$

where Sh is the Sherwood number, Nu = Nusselt number, Sc = Schmidt number, and Pr is the Prandtl number. The constant n is empirically determined from the specific flow configuration. For round and slot jet flows, Martin determined this constant to be n = 0.42. Equation 2, with Sc = 0.49, Pr = 0.75 for diffusion of water through CO_2, permitted the calculation of the mass transfer coefficients h_D.

The evaporative heat transfer coefficient, h_e of Equation 1, was determined by the simple conversion of the mass transfer coefficient, h_D, from concentration units to partial pressure units, with assumptions of ideal gases and the boundary layer mean temperatures and the known values of water's heat of vaporization. This led to the following simple relationship:

$$h_e = 0.543 h_D \quad (3)$$

Thus, with Martin's correlations for Nusselt number as a function of entry port type (gas jet stream), size, orientation, flow conditions, and height, H, above the impingement surface, and with Equations 1-3 described above, it is possible to determine the mean (between the stagnation point and the position r or x) heat flux due to evaporation for any set of flow and entry port configuration conditions. These values then become the critical boundary conditions for the unsteady state, tissue-conduction problem.

The speed that peritoneal tissue will be cooled by evaporative jet cooling is governed by the jet's evaporative surface heat flux, $J_{h,e}$, the size of the jet, and the conduction characteristics of the tissue. To simplify the analysis, it was assumed that the very high heat fluxes caused by the evaporative gas jet would completely dominate tissue internal heating due to metabolism and perfusion near the tissue surface. Additionally, it was assumed that the tissue dimensions would be large in comparison to that of the gas jet, for example, very large conduction pathways. Under these conditions, the general transient heat conduction differential equation reduces to

$$\frac{\partial \Theta}{\partial t} = a \frac{\partial^2 \Theta}{\partial x^2} \quad (4)$$

where, for our model, the reduced temperature, theta, is defined as

$$\Theta(x,t) = T(x,0) - \mathrm{T}(x,t)$$

and the boundary conditions for evaporative surface cooling, with $c = J_e/k$ where k is the surface tissue's thermal conductivity, are as follows:

$$\Theta(x,0) = 0$$
$$\frac{\partial\Theta(0,t)}{\partial x} = c$$
$$\Theta(\infty,t) = 0$$

This classic transient-conduction problem has been solved by many. The solution for the general case, as well as the special situation of x = 0, or the impingement surface temperature of our model can be expressed as[12]

$$T(0,t) = T(0,0) - 2c\sqrt{\frac{\alpha t}{k}} \quad (5)$$

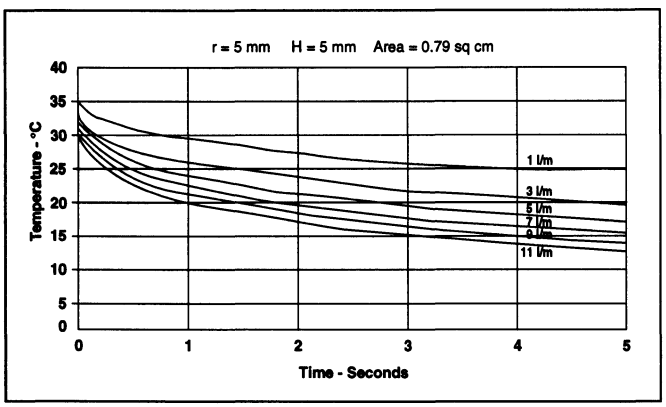

Figure 2. Surface temperature cooling – 1 mm circular jet.

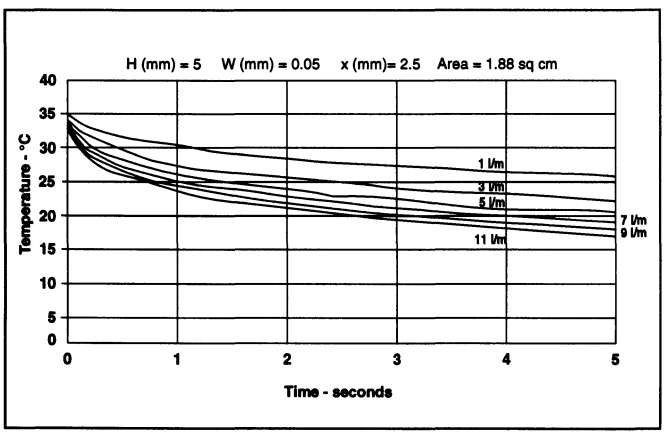

Figure 3. Surface temperature cooling – 10 mm trocar annulus.

where, for our jet evaporation system, $c = J_{h,e}/k$ and

α=*tissue thermal diffusivity*=$0.7x10^{-3}$ *cm*^{2}/sec
k=*tissue thermal conductivity*=$1.4x10^{-3}$ *cal/cm*.sec.°C

Solutions to Equation 5 are complicated by the fact that the value for $c = J_{h,e}/k$ is itself a nonlinear function of surface temperature, T, through $J_{h,e}$ and its dependence on the vapor pressure term p_s which, in turn, is a nonlinear function of surface temperature. This results in an Equation 5 that is transcendental in T and must be solved numerically by iterative, non-constant interval, finite-difference techniques.

THEORY RESULTS

Figure 2 shows the results of an Equation 5 calculation for the surface tissue temperature transient, caused by evaporative gas jet cooling of a circular area of 0.79 sq. cm around the impingement point. The data of this figure are calculated for a Veress needle height over the tissue of 5 mm and for insufflation gas flows of 1 to 11 liters per minute.

A typical set of surface temperature cooling curves for evaporative jet cooling via a trocar gas injection device is shown in **Figure 3**. As with the Veress needle theoretical results, the effect of insufflation gas flow rate is indicated parametrically for CO_2 flows from 1 to 11 liters per minute.

EXPERIMENTAL MEASUREMENTS

Experimental measurements have been made to verify the results of the theoretical analysis of laparoscopic evaporative gas jet cooling. These measurements were carried out in two phases. The first (Phase 1) was a series of tests using a single thermocouple (t/c) measurement, at the stagnation point = T1, of the temperature transient detected in 3 mm thick sections of synthetic materials; cellular polyurethane (cp) and woven rayon-polyester (wr). Data were collected at a rate of five points a second for Phase 1 measurements.

A second series of tests (Phase 2) consisted of measurements using cellular polyurethane and woven rayon, and ~3 mm sections of animal tissue consisting of turkey or ham. A four thermocouple array, with the first t/c (T1),

was located at the stagnation point, and the remaining t/cs (T2, T3, & T4) were spaced on a radial line 1, 2 and 4 mm from the first thermocouple, respectively. Phase 2 temperature data were collected simultaneously from each t/c at a rate of approximately 15 points per second

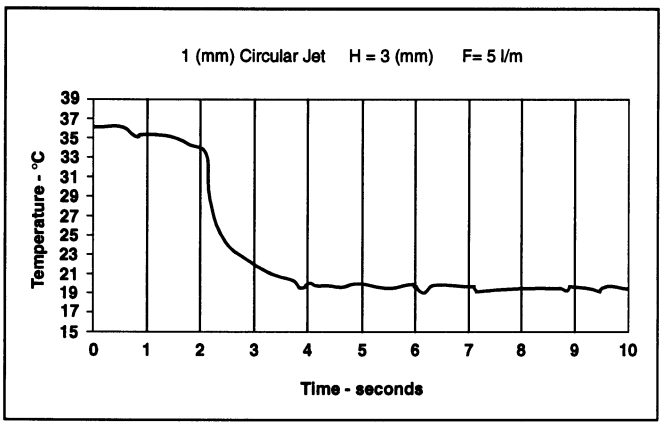

Figure 4. Experimental temperature transient – CP material.

for each thermocouple. The t/cs for this series, as were those of Phase 1, were small (0.2 mm diameter) sensors, with fast response times (time constant □ 0.6 sec), and positioned from below, at or just slightly below (~ 0.2 mm) the impingement surface. A 1 mm, inside diameter, Veress needle and a standard 10 mm trocar were used as the insufflation gas injection ports. These were positioned 2 to 5 mm above the tissue surfaces, and gas flows were varied between two and eight liters per minute.

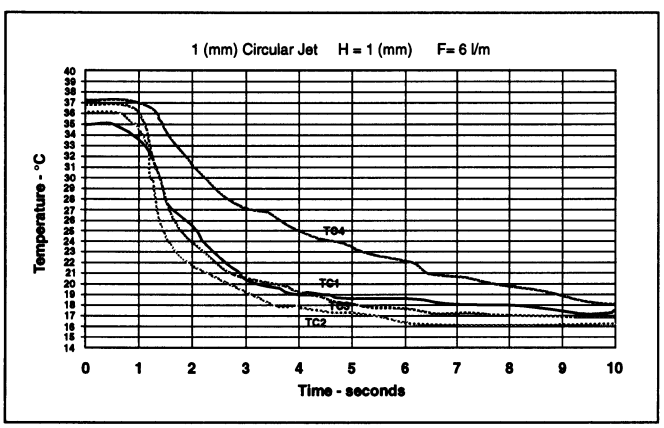

Figure 5. Experimental temperature transients – thick ham.

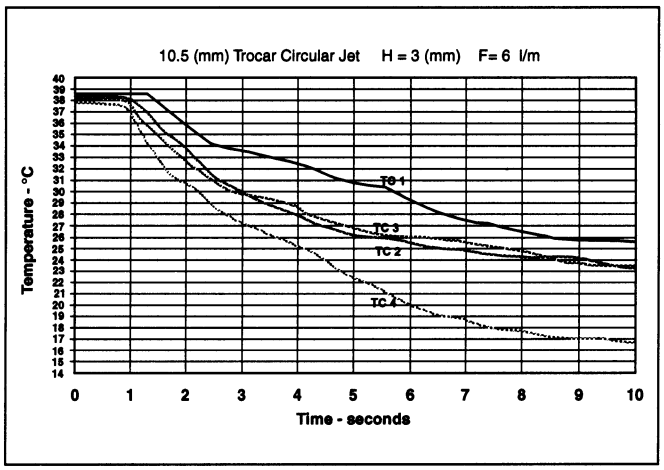

Figure 6. Experimental temperature transients – thick ham.

The experimental jet/impingement surface configuration of **Figure 1** was totally enclosed in a transparent container to provide an isolated environment that reproduced the gas space, temperature, and humidity conditions that the gas injection device and impingement surface experience during a laparoscopic procedure, (CO_2, 37 °C and □=100%). During all tests the "tissue" surface was irrigated with a temperature controlled sterile saline drip at 37 °C.

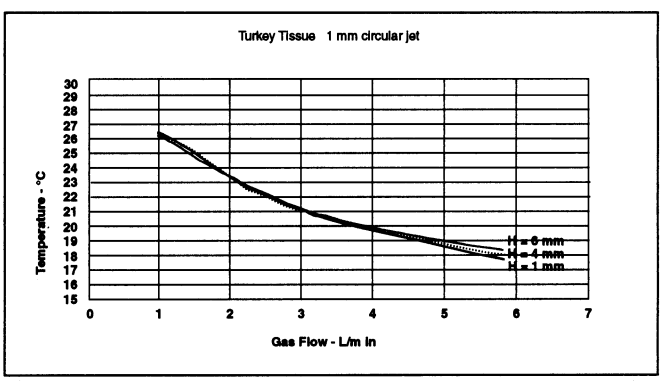

Figure 7. Gas flow effects on tissue temperature after five seconds.

EXPERIMENTAL RESULTS

Figure 4 shows the results of Phase 1 experimental tests of evaporative jet cooling at the stagnation point on a wet cellular polyurethane impingement surface at 37°C.

The results of a typical Phase 2 experimental test are seen in **Figure 5**, which shows the surface temperature cooling transient for ham tissue when evaporatively cooled by a 1 mm circular jet at approximately 6 liters per minute flow rate. These data are typical of the measurements obtained at the flow rates and jet height tests of this study. **Figure 6** shows typical impingement surface cooling transients resulting from an approximately 6 liters per minute CO_2 flow rate from a 10 mm trocar.

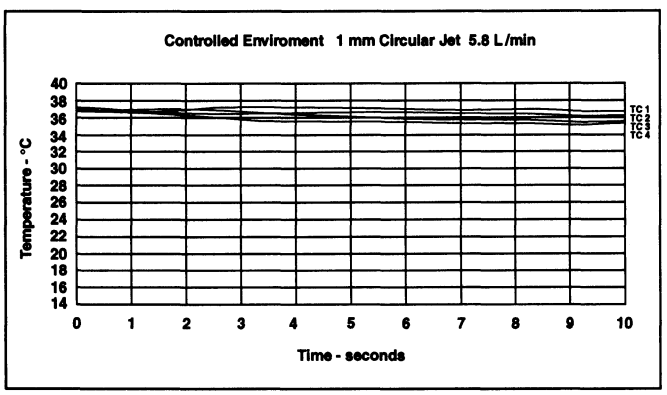

Figure 8. Experimental temperature transients – thick ham.

The effects of changes in insufflation gas flow rate and gas port height above the impingement surface on tissue temperature decrease with the initiation of evaporative surface cooling. **Figure 7** shows the results of these experiments. Here, the average of replicate runs of temperature measurements of thermocouple TC1 (the impingement point temperature), measured five seconds after initiation of the insufflation gas flow, is plotted against various gas flows. The parameters of **Figure 7** represent lines of constant height, H, of the tip of the injector above the tissue surface

To confirm that the rapid temperature drops demonstrated in the tissue tests of this study were caused primarily by evaporation of tissue-surface liquid, a series of experiments were carried out in which the insufflation gas was both heated (to 37°C) and humidified (to >95 relative humidity) prior to its introduction to the insufflation gas injection port. A typical result of these tests is shown in **Figure 8**, where thermocouples TC1 through TC4 measured the tissue surface temperatures at various distances from the impingement point for approximately eight seconds after initiation of the gas flow rate of approximately 6 liters per minute.

DISCUSSION

The results of the analytical modeling of evaporative jet cooling of tissue surfaces gives dramatic indications of rapid and significant cooling of these surfaces, as seen in **Figures 2** and **3**. These results predicted that, for circular jets, tissue surface temperatures could drop to under 20°C in less than three seconds after initiation of insufflation gas flow and cool a tissue area of more than 0.75 square centimeter. Our modeling of this cooling effect showed serious tissue temperature drops for a wide range of delivery port types, which resulted from jet streaming of gas and, importantly, for jet heights (H) up to 1 cm. Comparison of **Figures 2** and **3** demonstrates that the decrease of surface temperature is relatively independent of type of gas injection device, although the Veress needle injector caused a somewhat faster tissue-cooling rate (≈ 1.2°C/s) than the 10 mm trocar. Results, however, from the trocar analysis, predicted that considerably more tissue surface area would experience the cooling effect (≈ 1.9 cm^2).

Phase 1 experimental testing **(Figure 4)** showed very large cooling rates of -30°C/s in the first second of gas flow; larger, in fact, than cooling rates predicted by the analytical model. The temperature for these tests tended to reach an equilibrium level within two to five seconds of the initiation of the evaporative gas jet. This effect most certainly is due to the jet dispersing and evaporating the fluid in the region of the t/c. Under these conditions, the slower evaporation rate could be offset by internal heat conduction to the tissue surface.

Phase 2 results **(Figures 5-7)** confirm the theoretical prediction of the degree of evaporative cooling on wet tissue both qualitatively and quantitatively. At insufflation flow rates above 5 l/m, significant areas of "tissue" (> 2 cm^2) were cooled to temperatures less than 18°C within six seconds of initiating gas flow. These cooling effects, as can be seen in **Figure 7**, were relatively independent of the height, H, of the gas port site above the tissue sur-

face. That these cooling effects are caused by evaporation of surface fluid into jets of dry CO_2 is demonstrated by the results of **Figure 8**, where pre-heated and humidified insufflation gas jet streams with flow rates over 5 l/m caused less than 1°C of local surface cooling. In some cases, local tissue was heated approximately 1°C. These small temperature rises or drops experienced with the introduction of heated/humidified insufflation gas were caused by small temperature differences (positive or negative □1°C) between the temperature of the incoming gas and the temperature of the injection device.

The degree of tissue cooling, with either the Veress needle or the trocar gas injector were found, in Phase 2 experiments, to be independent of the types of tissue tested. The differences in maximum cooling rate and/or the minimum temperature reached by the tissue in the first five to seven seconds of evaporative jet cooling were not statistically significant for the different types of tissue tested.

The crossing of TC1 and TC2 curves after two seconds of evaporative cooling as shown in **Figure 7**, most likely is due to drying around the stagnation point. Tissue heat conduction from the sub-surface regions toward the stagnation point (SP) would heat this region after most of the resident liquid is evaporated and its cooling effect decreased.

CONCLUSION

The analytical modeling and experimental testing of this study show that substantial evaporative cooling occurs to extensive local regions of wet surface tissue when dry insufflation gas flows against its surface. Cooling rates of -20°C/s and local tissue temperature reductions of 20°C were measured. These findings suggest that local neurological reaction and tissue damage are possible from such hypothermic events and that this can be overcome.[5] This study demonstrates and is confirmation of theory validating experimental and clinical findings. Clinical observations and improvement of peri- and postoperative patient hypothermia by heating and humidifying the gas during laparoscopy has been previously demonstrated.[13] This study shows further that the effects of insufflation gas jet evaporative cooling during laparoscopy are completely eliminated by humidifying the insufflation gas stream.

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