Intraperitoneal temperature and desiccation during endoscopic surgery

Intraoperative humidification and cooling of the peritoneal cavity can reduce adhesions

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Problem: adhesion formation

During endoscopic surgery a pneumoperitoneum is needed to create a working space. For safety reasons, carbon dioxide (CO2) is used as an insufflation gas because it is highly soluble in water (1.45 mg/L) and it has a high exchange capacity in the lungs. This routine practice has been identified as a culprit in the development of postoperative adhesions, as a consequence of the associated mesothelial hypoxia and desiccation. The latter results from the flow rate, temperature, and relative humidity (RH) of the gas.

Trauma to the peritoneum followed by a local inflammatory reaction and mesothelial healing can lead to adhesions. The acute inflammation of the entire peritoneal cavity, however, is quantitatively the most important factor in adhesion formation. This acute inflammation results from the balance of bad factors such as mesothelial hypoxia associated with CO2 pneumoperitoneum, a mesothelial hypoxia when the pO2 is > 40 mm Hg, as occurs during open surgery (if air is roughly 20% oxygen, it has a pO2 of about 150 mm Hg), and desiccation of the mesothelium. The last, desiccation, has 2 opposing effects on adhesion formation—it directly damages cells by dehydrating them, but it also decreases the temperature of the affected area, and this is advantageous, since cells are more resistant to injury, such as hypoxia, at lower temperatures. For this reason, the damaging effect of desiccation has been difficult to isolate—and has been underestimated.

The degree of desiccation varies with flow rate, RH, and temperature of the gas used for the pneumoperitoneum, subsequently altering intraperitoneal and mesothelial temperature, mesothelial damage, peritoneal acute inflammation, and ultimately postoperative adhesion formation and pain. Over the last decade, humidification and temperature of the gas used during endoscopic surgery has received increasing attention. For example, it is clear that in a peritoneal cavity at 98.6°F (37°C) with a 100% RH, nonhumidified gas at 37°C will cause desiccation and some related cooling. Desiccation also obviously increases with the flow rate of the delivered gas. The relationship among desiccation, flow rate, and cooling, however, is more complex. First, the maximum amount of water a gas can hold increases linearly with temperature, and these maximum amounts are equivalent to 100% RH. At 25°C, 100% RH equals 25 mg/L whereas at 37°C this is 44 mg/L. Second, when flow rate increases desiccation increases, but when flow rate is too high, equilibration no longer occurs and the outgoing RH drops. Thirdly, when desiccation causes cooling this results in a cooling of the gas (thus the gas can hold less water) while simultaneously the cooling of tissues will slow down the rate of desiccation. Use of warm hu-
midified gas has also been said to result in decreased postoperative pain, although this remains controversial.\textsuperscript{11,12}

To understand cooling, the relationship among humidification, temperature, enthalpy of a gas, and the energy requirements for evaporation of water must be considered. While heating of a humidified gas requires the amount of energy needed to heat the water contained in that gas by definition, the energy to heat 1 mL of water by 1°C is 1 cal (4.1858 joules)–the energy required to heat 1 mL of dry gas by 1°C is only 0.00003 cal (0.0001 joules). In contrast, 577 cal (2415.2 joules) are needed to vaporize 1 mL of water at normal body temperature of 98.6°F (37°C). Therefore, practically, desiccation is the only important factor causing cooling, whereas cold humidified gas could cause some cooling, and the temperature of nonhumidified gas can almost be disregarded.

Desiccation and cooling are intrinsically related and have detrimental and favorable effects on adhesion formation, respectively. The quantitative effect of desiccation and peritoneal temperature on mesothelial damage during endoscopic surgery has not yet been investigated in detail. Indeed, the use of warm humidified gas has been suggested to be superior to dry and cold gas but it remains controversial\textsuperscript{11,12} whether it decreases postoperative pain, whereas there is still no evidence of decreased adhesion formation. The relationship between peritoneal damage caused by warm (37°C) and humidified gas and a high temperature and by cold and dry gas causing desiccation and cooling could be biphasic, with an optimum achieved with a little desiccation together with a little cooling. Experiments in mice, moreover, indicate that ideally, to reduce adhesions, prevention of desiccation should be combined with a little desiccation to maintain 100% RH at the end of the insufflation, a preset temperature between 77-96.8°F (25-36°C) at flow rates between 0.5-30 L/min.

The flow rate, RH, and temperature of the gas at the end of the insufflation tubing and the gas flowing from the peritoneal cavity—or a box used to mimic the peritoneal cavity in the in vitro experiments—were measured twice a second; temperature and RH were captured with a digital sensor (SHT75; Sensirion AG, Zurich, Switzerland). This permitted calculation of water loss, a marker for desiccation, in real time. Cooling by a third means of the peritoneal cavity was accomplished by nebulizing 3 mL/min of water at room temperature or at 32°F (0°C) with a nozzle set at 2 bar entry pressure. This cooling/nebulization/humidification device had a diameter of <5 mm so that it could be used through a standard 5-mm trocar.

To validate the setup in vitro, the bottom and side walls of a closed polystyrene box were covered with plastic bags containing a total of 6 L of water at 98.6°F (37°C) (Figure 1). It was assumed that temperature and RH coming out of the box would reflect temperature and RH inside the box. When the tubing was used for nonhumidified CO\textsubscript{2} or for gas humidified with the Storz humidifier, the gas was permitted to cool to room temperature or was heated to 98.6°F
(37°C) by putting the tubing inside a heated chamber.

First, the accuracy of the measurements of flow rate, RH, and temperature of the gas were validated. The exact water loss was measured by the difference in weight of the “desiccation recipient,” protruding moistened towels, before and after the experiment, and compared with the water loss calculated from the flow rate, RH, and temperature of the inflowing and outflowing gas with the following formula: humidity (g/m³) = RH (%)/100 × (3.1243 10e-4 × T³ + 8.1847 × 10e-3 × T² + 0.32321 × T + 5.018). RHs and temperatures at inflow and outflow equilibrated within 2 minutes, so we used the mean values during the last 10 minutes of the experiment to calculate water loss. Since the accuracy of desiccation calculation was crucial for the in vivo experiments, the measurements were validated over a wide range of conditions and performed in triplicate.

The measurements of flow rate, RH, and temperature were accurate, as judged by the linear relationship between the calculated and measured water loss (MatLab software, MathWorks™, Natick, Massachusetts, U.S.A.) (Table 1). Measurements of temperature and RH, made twice a second, had a coefficient of variation of 0.8%, 0.9%, 0.5%, and 0.5%, and of 2.2%, 3%, 12.4%, and 22.9% at flow rates of 2.5, 5, 10, and 20 L/min, respectively. Therefore, mean values over 5 minutes were used for all further calculations.

In the second experiment, the impact of desiccation, temperature of the inflowing gas, and humidification on the temperature and RH in the box was measured. To do this, dry gas or humidified gas was used at room temperature or at 98.6°F (37°C) at flow rates from 2.5 to 20 L/min. We confirmed, as expected, that the effect of desiccation was the most important factor for cooling. The gas temperature rapidly equilibrated with the ambient temperature at flow rates up to 20 L/min. Thus, when the tubing was in a chamber at 98.6°F (37°C), the temperature remained stable; otherwise the temperatures were similar to room temperatures.

When dry CO₂ at room temperature was used for insufflation, desiccation and a drop in temperature occurred, indicating that the water loss/min and the heat loss/min increased almost linearly with flow rate (Figure 2). With the Storz humidifier, temperature-in air the end of the tubing was, as predicted, at room temperature, while the RH decreased with flow rates. The near 100% RH at low flow rates is explained by condensation in the tubing due to cooling. With the Fisher and Paykel Healthcare Ltd humidifier, when the gas was heated to avoid condensation, the RHs at the end of the tubing were adequate for any flow rate. However, the temperature increased with the flow rate: it was 99 ± 0.68°F (37.2 ± 0.4°C), 101.8 ± 1.1°F (38.8 ± 0.6°C), 104.4 ± 2.1°F (40.2 ± 1.2°C), and 107 ± 3.3°F (41.7 ± 1.8°C) at flow rates of 2.5, 5, 10, and 20 L/min, respectively. It should be noted that in these experiments, we removed the luer lock on the original tubing, which prevents flow rates >7.8 L/min at 15 mm Hg insufflation pressure. Because of the increase in temperature, the modified Fisher and Paykel Healthcare Ltd humidifier was not further evaluated in vivo.

The third experiment evaluated the modified Fisher and Paykel Healthcare Ltd humidifier and its ability to deliver 100% RH at the end of the tubing regardless of the preset temperature for flow rates up to 30 L/min. Temperature and RH at the end of the tubing were measured for different preset temperatures to determine accuracy and fluctuations over time and the rapidity of response when the flow rates were changed. The third experiment confirmed that with the modified Fisher and Paykel Healthcare Ltd humidifier, the temperature was constant within 32.4°F (0.2°C) for any flow rate at preset temperatures between 82.4-93.2°F (28-34°C) with an RH >90% for any preset temperature. When flow rates were suddenly increased or decreased, the new equilibrium was reached within 2-3 minutes. The temperature-out and RH-out were as expected, with a slight decrease in temperature due to desiccation at higher flow rates.

We also examined the value of the cooling device and the effect of cooling on desiccation with a constant delivered gas temperature of 89.6°F (32°C) and an RH of 100%. Spraying 3-4 mL of nebu-

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**Table 1**

Validation of measurements of flow rate, relative humidity, and temperature

<table>
<thead>
<tr>
<th>Variable</th>
<th>Flow rate, L/min</th>
<th>RH, %</th>
<th>Temperature, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>No humidifier</td>
<td>2.5</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Storz humidifier</td>
<td>2.22</td>
<td>0.14</td>
<td>8.11</td>
</tr>
<tr>
<td>Fisher and Paykel humidifier</td>
<td>2.32</td>
<td>0.14</td>
<td>8.11</td>
</tr>
</tbody>
</table>

Data are expressed as mean ± SD. Differences were calculated with a repeated-measures ANOVA. *P* < .05 vs no humidifier or Fisher and Paykel humidifier.
Temperature and relative humidity (RH) in and out during laparoscopic surgery with flow rates of 2.5-15 L/min. These were measured while using dry gas at room temperature, Storz humidifier at room temperature, and modified Fisher and Paykel Healthcare Ltd (F&P) humidifier preset at 89.6°F (32°C). Similar observations were made in vitro (inset).

Temperature and RH in the abdominal cavity thus will not be homogeneously distributed. Using a CO₂ laser setup with insufflation through the laparoscope and aspiration through the central trocar produces a small compartment with relatively high flow rates; gas flows from the tip of the laparoscope to the central trocar. While these considerations do not affect the overall results, when the compartment is small, even low flow rates can cause important local effects, including desiccation. Therefore, any medication administered together with the insufflating gas or the nebulized water will not homogeneously affect the entire peritoneal cavity.

With flow rates of 10 L/min, as is used for smoke evacuation during CO₂ laser surgery, dry gas and the Storz humidifier caused constant desiccation of 0.3 and 0.05 mg/min, respectively, during the first hour of surgery. After 70-90 minutes of surgery the temperature-out, reflecting the intraperitoneal temperature, suddenly decreased to a mean of 83.5 ± 0.7°F (28.6 ± 0.4°C) in patients given dry gas and 84.9 ± 1°F (29.4 ± 0.6°C) for patients given humidified gas with Storz humidifier, reducing desiccation in all women within 5 minutes. Simultaneously, with decreased temperature, dry gas desiccation was eliminated. With the Storz humidifier, not only was desiccation abolished but condensation of almost all inflowing humidity occurred (Figure 4). With the modified F&P humidifier, desiccation was minimal and condensation never occurred.

The core body temperature of the patients, as measured by esophageal temperature, averaged 97.7 ± 0.5°F (36.5 ± 0.3°C), and remained unaffected in all women despite constant intraperitoneal temperatures <89.6°F (32°C).

From the experiments comparing the real water loss, as measured by weight loss, and calculated water loss, we can conclude that the measurements of flow rate, RH, and temperature were accurate, at least for flow rates up to 20 L/min. It should be stressed that these experiments were designed to evaluate intraperitoneal temperature and desiccation under different conditions of humidification, flow rate, and external cooling.

With the Storz humidifier, RH decreased rapidly with flow rate. The main problem was the cooling of the gas to room temperature when noninsulated tubing was used. Since at 77°F (25°C),...
CO₂ cannot hold >25 mg of water/L at 100% RH, condensation occurred in the tubing at low flow rates and humidification up to 5 L/min; entering a peritoneal cavity that is initially at 98.6°F (37°C), the gas temperature will increase (at this temperature and 100% RH, the gas holds 44 mg of water/L), resulting in peritoneal desiccation. This combination of insufflation of gas at room temperature and desiccation resulted in unexpectedly low peritoneal cavity temperatures, often <86°F (30°C). With nonhumidified gas, peritoneal temperatures were even lower.

The standard F&P humidifier prevented cooling in the tubing using a heating wire. At higher flow rates however, the gas temperature can be >98.6°F (37°C). The luer lock at the end of the tubing limits flow rates to 7.8 L/min at 15 mm Hg pressure. Therefore, when used according to operating instructions, this humidifier provided adequate humidification and a slight increase in temperature, which is probably compensated by cooling in the trocar. When the luer lock is removed to permit higher flow rates to be used with the Thermodiator for CO₂ laser surgery, humidification remains adequate but the intraperitoneal temperature could be slightly increased. However, it should be stressed that with use of a CO₂ laser setup and associated higher flow rates, desiccation and temperature changes mainly occur within a small compartment. For adhesion formation, it was demonstrated in the mouse model that desiccation is harmful while a constant intraperitoneal temperature is beneficial. Adhesions indeed decrease exponentially with temperatures of at least 77°F (25°C), with >80% of this beneficial effect being achieved at 87.8-89.6°F (31-32°C). With higher temperatures, adhesions increase rapidly, and at >98.6°F (37°C), the increase is dramatic. Clearly, neither the Storz nor the Fisher and Paykel Healthcare Ltd humidifier can completely prevent adhesion formation. The former resulted in desiccation, and the latter caused rather high intraperitoneal temperatures of 98.6°F (37°C). For both, effects on desiccation and temperature increased with flow rates. We, therefore, modified the Fisher and Paykel Healthcare Ltd humidifier to deliver fully humidified gas at a preset value of 87.8-89.6°F (31-32°C), since most of the beneficial effect was reached at that temperature. For clinical and biological reasons, we wanted to avoid temperatures <82.4°F (28°C). To avoid heating of the gas upon entrance, and thus desiccation, we anticipated that the peritoneal cavity had to be cooled by another means, such as a nozzle delivering water at room temperature. These experiments were designed to estimate how much cooling would be necessary to prevent desiccation in human beings.

To our surprise, when fully humidified gas at 89.6°F (32°C) was used, the desiccation and the heating of the gas was, within minutes, much less pronounced than expected. This can be explained only by rapid vasoconstriction of the peritoneal surface, especially in the compartment with the higher gas flow. Therefore, additional cooling to maintain temperatures of 87.8-89.6°F (31-32°C) in the peritoneal cavity—and avoiding desiccation—was much easier than anticipated. Indeed, a little extra cooling with intermittent application of 2-3 mL of saline at room temperature, combined with ordinary irrigation, prevented heating of the gas in the peritoneal cavity and desiccation.

Our finding that the temperatures of the bowel and peritoneal cavity seem to be regulated differently from the core body temperature was supported by the observation that, after some 70-80 minutes of surgery with insufflating gas at room temperature and desiccation (as seen with dry gas or the Storz humidifier), the temperature of the bowel and wall suddenly dropped below room temperature without affecting core body temperature. We conclude, then, that temperature regulation of this region is different from that of the core body temperature. Rather, it is similar to what occurs in the arms and legs, which diminish heat loss and preserve core body temperature through vasoconstriction. In addition, a constant intraperitoneal temperature <89.6°F (32°C) did not affect core body temperature, probably because of important vasoconstriction of mesenteric vessels. Vasoconstriction also explains why the calculated heat loss from the body never exceeded 100 cal/min and...
why condensation never caused fogging of the optical instruments.

In conclusion, in the absence of humidification, the intraabdominal temperatures were surprisingly low, which was mainly the result of desiccation. Even with a Storz humidifier, temperatures hardly exceeded 82.4-86°F (28-30°C). Desiccation could be prevented completely when a modified Fisher and Paykel Healthcare Ltd humidifier that maintains the peritoneal cavity temperature at 87.8-89.6°F (31-32°C) is combined with additional cooling. Surprisingly, minimal cooling was sufficient, and this could be explained by the unexpected finding that, as with the limbs, temperature regulation of the bowel and abdominal wall appears to be different from that of core body temperature. Evidently, rapid vasoconstriction prevents heat loss during surgery.

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REFERENCES