

Topical Humidified Carbon Dioxide to Keep the Open Surgical Wound Warm

The Greenhouse Effect Revisited

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Background: Perioperative hypothermia is common in open surgery and is associated with increased rates of wound infection. This is a result of decreased wound tissue oxygenation, which can be normalized by local warming. Recently, a technique has been developed to establish a carbon dioxide atmosphere in an open surgical wound. Therefore, the authors studied the possible "greenhouse effect" of carbon dioxide insufflation and operation lamps on wound temperature.

Methods: In a fully ventilated operating room surface temperature was measured at steady state in a model of an open surgical wound containing blood agar. The wound model was randomized to either no insufflation or insufflation of dry and humidified carbon dioxide or air, respectively, at a flow of 5 l/min via a gas diffuser. The surface temperature was measured with operation lamps switched on and off, respectively. Evaporation rates were also measured.

Results: With the operation light off, the surface temperature in the control was 31.8°C, and with the operation light on, the temperature increased by 1.5°C ($P < 0.001$). Additional insufflation of dry carbon dioxide increased the surface temperature another 1.9°C ($P < 0.001$). When the carbon dioxide was humidified, the evaporation rate was lowest and the surface temperature increased further to 35.6°C ($P = 0.002$). In contrast, insufflation of dry and humidified air did not have a significant effect on the evaporation rate and only marginally increased the wound temperature in comparison with the control.

Conclusions: Insufflation of humidified carbon dioxide in combination with light from the operation lamps may help to keep the open wound warm during surgery.

WOUND infection is a serious complication after open surgery resulting in increased hospital stay, costs, and mortality.^{1,2} Because most wound infections are established intraoperatively,^{3,4} intraoperative countermeasures should be considered. One possible method is to keep the wound warm during surgery.

An open surgical wound is exposed not only to airborne bacterial contamination but also to the lower temperature and humidity of ambient air. This exposure causes continuous heat loss from the open wound

through evaporation and radiation, which contributes to a decrease in body core temperature.^{3,5} Hypothermia increases the risk of wound infection,⁴ as it decreases tissue blood flow and oxygenation.^{6,7} The process is reversed when local warming leads to vasodilatation and thus restores tissue oxygen tension to normal values.^{6,8}

Current techniques to reduce heat loss from the surgical wound, such as plastic impermeable bags,^{5,9} are often impractical and may interfere with surgery. An alternative solution is to create a modified atmosphere with maximal humidity and minimal gas currents inside the open wound. We have recently developed a new device to fill an open surgical wound cavity with carbon dioxide for the prevention of arterial air embolism in open-heart surgery.¹⁰⁻¹³

A local atmosphere of greenhouse gases, *i.e.*, carbon dioxide and water vapor, in the open wound may have an insulating effect, *i.e.*, it will absorb and reemit long wave energy to the wound surface. Moreover, a humidified gas may also attenuate heat loss by reducing evaporation from the wound. In a randomized experimental trial we thus tested the hypothesis that insufflation of humidified carbon dioxide may reduce evaporation and heat loss in an open surgical wound model and that operation lamp heat may have a warming effect.

Materials and Methods

The surface temperature in an open surgical wound model was measured at steady state during five different conditions: without gas insufflation (control) and during insufflation of dry and humidified air and carbon dioxide, respectively. We also studied the heating effect of the operation lamps.

Set-up

The wound model (fig. 1) was placed on the operating table of a fully ventilated operating room (laminar airflow of approximately 2500 m³/h from the ceiling downward). The wound model consisted of a heat-regulated water container (Tempette TE-8A, 50 × 30 × 20 cm³ (30 l), 1000W; Techne, Princeton, NJ) with a central elliptical opening in its top cover. To represent a wound cavity we positioned a removable container in the opening, a length, width, and depth of 20, 12, and 5 cm, respectively. The wound cavity was made of 1-mm thick aluminum to maximize heat conduction. During the experiment the cavity was kept surrounded by water. The

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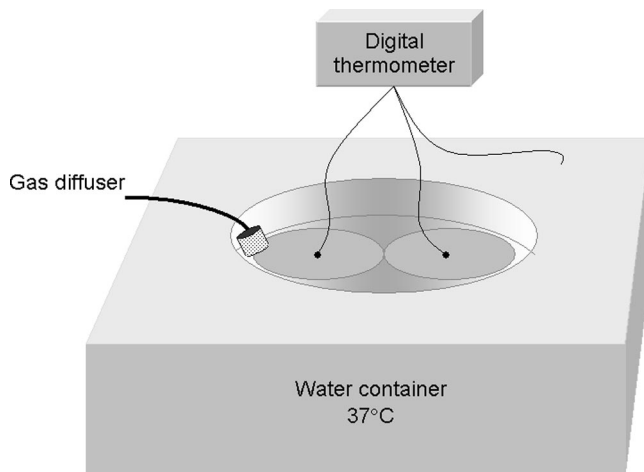


Fig. 1. The figure shows the model of an open elliptical surgical wound, with a length, width, and depth of 20, 12, and 5 cm, respectively. Two 9-cm layers of blood agar were positioned at the bottom, simulating wound tissue. Temperatures were measured at the center of the agar surfaces. The figure also shows how the insufflation device was positioned during the experiment.

water temperature was kept at 37°C, controlled with a penetration probe (FK 1020, Pt-100; Heraeus Sensor-Nite GmbH, Kleinostheim, Germany) to represent body core temperature. To simulate the surface of fresh wound tissue, we positioned two intact layers of blood agar directly at the bottom of the model (fig. 1). Each blood agar layer was taken out in one piece from a standard blood agar plate (9-cm Petri dishes, 5% horse blood). A thin-film temperature sensor (M-FK 1020, Pt-100, 18 mm²; Heraeus Sensor-Nite GmbH) was positioned on the center of each agar layer to measure the surface temperature. The temperature sensors were connected to a digital temperature instrument (2802A Thermometer, 34740A Display; Hewlett Packard, Palo Alto, CA), which has a resolution of 0.01°C. For optimal accuracy the instrument was calibrated and each temperature sensor was connected to the instrument *via* a 4-wire connection, according to the manual of the manufacturer.

Gas was insufflated into the wound model *via* a low-velocity outlet device, a gas diffuser (Cardia Innovation AB, Stockholm, Sweden) that consists of a thin fixable tube with a diffuser of polyurethane foam at the end.^{11,12} The insufflation device was positioned at the acute end of the wound cavity model, with the diffuser positioned at half the depth of the cavity. Medical air or carbon dioxide was delivered at a flow of 5 l/min, controlled with back-pressure compensated flowmeters (AGA Gas AB, Stockholm, Sweden). The flowmeters and the used calibration procedure have earlier been described in detail.^{11,12} Air was taken from the central anesthetic gas system in the operating room, and carbon dioxide was delivered from a pressurized gas cylinder (AGA Gas AB). The gases were humidified *via* a disposable bubble humidifier containing sterile water (Aquapak 340 ml; Hud-

son Respiratory Care Inc., Temecula, California). A pilot study showed that for the humidity of the administered gas to remain constant, the humidifier had to be kept at a constant temperature. Thus, during the experiment the humidifier was kept at room temperature in another heat-regulated water bath (Haake D8/L; Haake Mess-Technik GmbH u. Co., Karlsruhe, Germany). We did not exceed room temperature to prevent condensation in the gas delivery system, which might have interfered with our measurements. Two operation lamps (Angénieux, Type AX 14, 300W; ALM SA, Orléans, France) were focused towards the wound cavity at a distance of 1 meter. The lamps were positioned at opposite sides of the wound model at an angle of 45° to minimize disturbance of the operating room ventilation.

Measurements

First, while the operation lamps were kept switched off, temperature and humidity in the air above the operating table were measured with a digital hygrometer (HygroPalm 3; Rotronic AG, Bassersdorf, Switzerland). Thereafter, the surface temperatures were recorded at steady state, *i.e.*, when values fluctuated around a constant value over 30 s. The operation lamps were then switched on, whereupon the temperatures were followed and again measured at steady state.

The evaporation rate of the wound cavity model was then studied during the above described five conditions with the operation lamps switched on. The wound cavity was first closed with a plastic lid, which had been preheated to more than 37°C to avoid condensation. The cavity was then removed from the water container. Thereafter, the cavity was completely dried with a clean and dry tissue and weighed on a precision scale (Sartorius L420S, resolution 0.001g; Sartorius GmbH, Göttingen, Germany). The cavity was then put back into the water container, the lid was removed, and gas insufflation was started (if used). Ten min later, the cavity was closed, dried, and weighed again, as described above. The evaporation rate could thus be expressed as water loss in mg per cm² of agar surface and minute.

A fresh pair of blood agar layers was used for every new measurement. The five conditions were repeated 10 times in random order, resulting in 50 randomized measurements.

Statistical Analysis

Surface temperatures and evaporation rates in the wound model are presented as medians with 25th and 75th percentiles ($n = 10$), whereas room temperature and room humidity are presented as means and standard deviations ($n = 50$). The average surface temperature of both agar layers combined was used for comparison of surface temperatures between the five groups. The non-parametric Mann-Whitney *U* test and Wilcoxon test

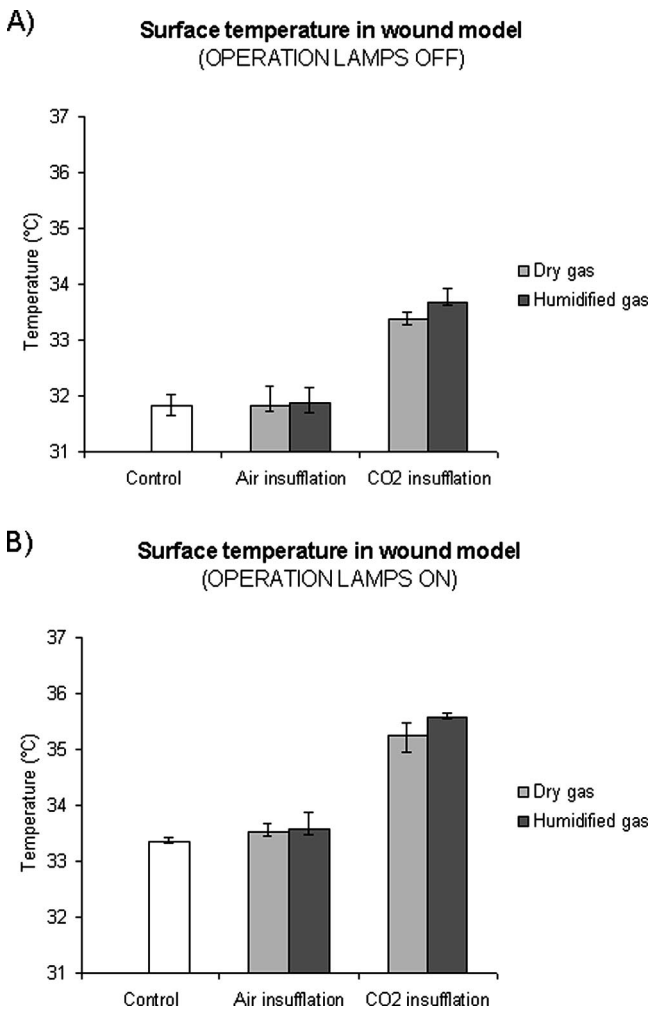


Fig. 2. Median and 25th and 75th percentiles of the surface temperature at steady state in the wound cavity model, without insufflation (control) and with insufflation of dry and humidified air and carbon dioxide, respectively, at a flow of 5 l/min. The temperatures represent the average values of the two agar layers, with the operation lamps switched off (A) and switched on (B), respectively.

were used when appropriate. Differences were considered statistically significant if $P < 0.05$.

Results

During the experiment the temperature was $19.4 \pm 0.2^\circ\text{C}$ and the relative humidity was $21.6 \pm 2.6\%$ (mean \pm SD) in the operating room. When the operation lamps were switched off, the surface temperature in the wound cavity in the control group was 31.8°C (fig. 2A). Insufflation of dry and humidified air did not have any statistically significant effect on the surface temperature. With dry carbon dioxide, the surface temperature was higher in comparison with the control and the air insufflation groups ($P < 0.001$). With humidified carbon dioxide, the surface temperature (33.7°C) was even higher than with dry carbon dioxide ($P < 0.001$).

Evaporation rate in wound model (OPERATION LAMPS ON)

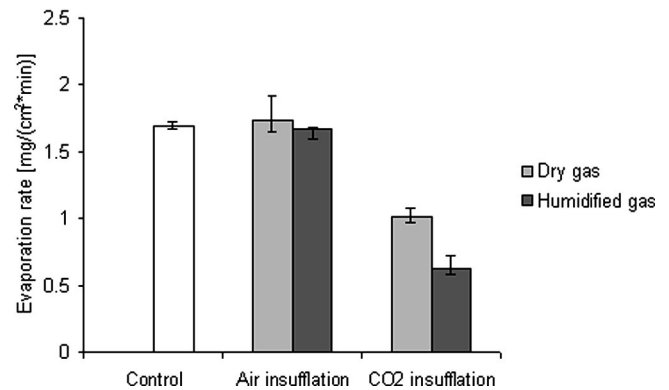


Fig. 3. Median and 25th and 75th percentiles of the evaporation rate [$\text{mg}/(\text{cm}^2 \cdot \text{min})$] in the wound cavity model with the operation lamps switched on. The cavity was either not insufflated (control) or insufflated with dry and humidified air and carbon dioxide, respectively, at a flow of 5 l/min.

When the operation lamps were switched on, the surface temperature increased in all five groups ($P < 0.001$, fig. 2B). The increase in surface temperature was greater both with dry ($P = 0.02$) and humidified ($P = 0.007$) carbon dioxide in comparison with the control group. The corresponding increases for dry and humidified air were not statistically significantly different from the control. With the lamps switched on, the surface temperature in the control group was 33.3°C . In comparison with the control, the surface temperature was slightly higher both with dry ($P = 0.03$) and humidified ($P = 0.05$) air. With dry carbon dioxide, the surface temperature was higher (35.2°C) than in the control and air insufflation groups ($P < 0.001$). With humidified carbon dioxide, the surface temperature was significantly higher (35.6°C) than with dry carbon dioxide ($P = 0.002$).

With the lamps switched on, the evaporation rate did not differ between the control and when dry and humidified air was insufflated (fig. 3). With dry carbon dioxide, the evaporation rate was almost 40% lower than the control ($P < 0.001$). When the carbon dioxide was humidified, the evaporation rate was even lower ($P < 0.001$): it was approximately 60% lower than the control group.

Discussion

Our major finding is that the creation of a local carbon dioxide atmosphere reduced heat loss from an open surgical wound model. The warming effect was enhanced by the radiative heat from operation lamps and by humidifying the insufflated carbon dioxide.

Experimental Set-up

When a new technique is to be tested, the logical first step is to study its effect in a controlled experimental setting, while keeping in mind that, as pointed out by Sessler,³ “The contribution of evaporation [to heat loss] from within surgical incisions remains to be determined in humans because of technical difficulties. An additional difficulty is that surgical incisions presumably also substantially increase loss by radiation.”

As part of our efforts to reproduce the conditions of clinical practice, the experiment was carried out on an operating table in a fully ventilated operating room. The wound cavity model^{11,14} was large enough to hold two standard 9-cm blood agar layers. Blood agar provides a wet surface similar to a fresh surgical wound. An open water surface has earlier been used to represent evaporation from an open wound¹⁵ on the grounds that “a wound after full-thickness excision of skin transmits water vapor at a rate equal to 91% of that for an open water surface.”¹⁶ In control experiments, we compared the water loss from Petri dishes containing blood agar and water, respectively, and found that the evaporation rates were equal. In contrast to water, in which circulation may occur, blood agar provides a solid but constantly wet surface on which a surface temperature can be measured. The wound model included a core thermal compartment, the water container, which provided a realistic core-to-wound temperature gradient.

Carbon dioxide was insufflated at a constant flow of 5 l/min with the gas diffuser positioned below the brim to create a complete carbon dioxide atmosphere inside the cavity.^{11,12} The gas diffuser was positioned at the acute end of the cavity, which is a suitable position during surgery.¹⁰ By measuring the surface temperature at two different locations, close to and further away from the insufflation device (fig. 1), we obtained a reliable estimate of the average surface temperature in the wound cavity model during gas insufflation.

Study Outcome

In the current study, the average surface temperature in the wound model in the control group with and without the operation lamps on was 3.7°C and 5.2°C lower than the core temperature (37°C) in the water container, respectively (fig. 2). It is worthy of note that Lamke *et al.*¹⁷ found that the surface temperature of bowels fell by 3–5°C during open abdominal surgery. The current study showed that the operation lamps had a heating effect, which increased the surface temperature in all studied groups. During the experiment the two operation lamps were positioned at approximately 1-m distance with the light directed towards the wound model at an angle of approximately 45°. In pilot studies we found that the surface temperature could be increased further by shortening the lamp distance from the wound model and by decreasing the light angle.

The heating effect of the lamps was even greater when an insulating carbon dioxide atmosphere was present in the cavity. Why did not air insufflation have the same effect? First, carbon dioxide may cause a greenhouse effect, *i.e.*, absorbing and reemitting long wave energy to the surface of the wound model. Second, as it is heavier than air, carbon dioxide gravitates in the wound model and covers it like a protective layer. Thus, carbon dioxide reduces convection in the wound model caused by air currents from the operating room ventilation. This may explain why insufflation of completely dry carbon dioxide resulted in a substantially lower evaporation rate than the control and even humidified air.

Humidification of carbon dioxide had a marginal but statistically significant effect on the surface temperature in the wound model. Why was this effect not greater? As indicated by figure 3, although considerably reduced, evaporation from the wound model was still present when humidified carbon dioxide was used. When the insufflated gas, humidified at room temperature, entered the wound model, it was heated up at the wound model surface. Because warm gas can carry more water than cold, the relative humidity of the insufflated gas decreased as a result.

If evaporation could be eliminated the remaining heat loss from the wound model would be mainly radiant. This is where the operation lamps come in. In combination with a local carbon dioxide atmosphere, the radiant heat from the lamps may not only compensate the heat loss from the wound model but also cause a net influx of heat if the surface temperature is higher than the core temperature.

Clinical Implications

The current study may have several clinical implications. Hippocrates' statement that “Wounds love warmth”¹⁸ still holds true today, as it is current practice to prevent perioperative and postoperative hypothermia to reduce the incidence of surgical complications.^{3,4,6,19–22} A humidified carbon dioxide atmosphere may provide an effective thermal insulation of an open surgical wound and the light emitted from the operation lamps may be used for heating. The two factors should be combined because mere heating with lamps will most likely increase the evaporation and desiccation in the wound. This method to warm an open wound does not substantially interfere with surgery.^{10,13}

An increased wound temperature may promote wound healing by increasing tissue oxygenation *via* locally mediated vasodilatation and increased oxygen deposition in tissue.^{21,23} Accordingly, increased arterial and subcutaneous oxygen tension is found to significantly reduce the incidence of surgical wound infection.⁷ Furthermore, oxygen tension in subcutaneous wound tissue is found to be a strong predictor for the risk of surgical wound infection.²³ The presence of a carbon dioxide

atmosphere in the wound will theoretically provide synergistic effects, as topically applied carbon dioxide alone causes local vasodilatation as well as augmented tissue oxygenation by the Bohr effect,^{24,25} *i.e.*, a rightward shift of the oxygen saturation curve.

The combination of humidified carbon dioxide and operation light may also affect body core temperature. Perioperative heat loss mainly occurs *via* the anterior body surface²⁶ and rapidly reduces core temperature.²⁷ A substantial amount of heat is lost through the open surgical wound *via* radiation and evaporation.^{3,5} Moreover, it is well known that core hypothermia is more pronounced during large operations than during small operations,^{28,29} with most of the difference presumably resulting from an increased evaporation.³ Because anesthesia causes vasodilatation, heat is more easily redistributed from the body core out to the wound surface and *vice versa*.^{19,27} The lower the surface temperature, the greater is the core-to-peripheral temperature gradient and thus the rate of heat redistribution and heat loss.¹⁹ Consequently, if the wound surface temperature can be kept warm, the core temperature may also be kept up, decreasing the risk of wound infection. Kurz *et al.*⁴ found that a decrease in perioperative core temperature of only 1.9°C (from 36.6°C to 34.7°C) tripled the incidence of surgical wound infection and prolonged hospitalization after colon resection. Maintaining normothermia has other beneficial effects, such as less blood loss,³⁰ decreased incidence of morbid cardiac events,³¹ and improved immune functions.^{20,32,33} Clinical trials are needed to evaluate the clinical effects of intraoperative insufflation of humidified carbon dioxide.

References

- Mangram AJ, Horan TC, Pearson ML, Silver LC, Jarvis WR: Guideline for prevention of surgical site infection, 1999. Hospital Infection Control Practices Advisory Committee. *Infect Control Hosp Epidemiol* 1999; 20:250-78
- Poulsen KB, Bremmelgaard A, Sorensen AI, Raahave D, Petersen JV: Estimated costs of postoperative wound infections: A case-control study of marginal hospital and social security costs. *Epidemiol Infect* 1994; 113:283-95
- Sessler DI: Perioperative heat balance. *ANESTHESIOLOGY* 2000; 92:578-96
- Kurz A, Sessler DI, Lenhardt R: Perioperative normothermia to reduce the incidence of surgical-wound infection and shorten hospitalization: Study of wound infection and temperature group. *N Engl J Med* 1996; 334:1209-15
- Roe CF: Effect of bowel exposure on body temperature during surgical operations. *Am J Surg* 1971; 122:13-5
- Sheffield CW, Sessler DI, Hopf HW, Schroeder M, Moayeri A, Hunt TK, West JM: Centrally and locally mediated thermoregulatory responses alter subcutaneous oxygen tension. *Wound Repair Regen* 1996; 4:339-45
- Greif R, Akca O, Horn EP, Kurz A, Sessler DI: Supplemental perioperative oxygen to reduce the incidence of surgical-wound infection. Outcomes Research Group. *N Engl J Med* 2000; 342:161-7
- Ikeda T, Tayefeh F, Sessler DI, Kurz A, Plattner O, Petschnigg B, Hopf HW, West J: Local radiant heating increases subcutaneous oxygen tension. *Am J Surg* 1998; 175:33-7
- Rowe MI, Taylor M, Sheehan K: Prevention of water and heat losses from the exposed intestine. *J Pediatr Surg* 1982; 17:608-10
- Persson M, Svenarud P, van der Linden J: What is the optimal device for carbon dioxide de-airing of the cardiothoracic wound and how should it be positioned? *J Cardiothorac Vasc Anesth* 2004; 18:180-4
- Svenarud P, Persson M, van der Linden J: Intermittent or continuous carbon dioxide insufflation for de-airing of the cardiothoracic wound cavity? An experimental study with a new gas diffuser. *Anesth Analg* 2003; 96:321-7
- Persson M, van der Linden J: De-airing of a cardiothoracic wound cavity model with carbon dioxide: theory and comparison of a gas diffuser with conventional tubes. *J Cardiothorac Vasc Anesth* 2003; 17:329-35
- Svenarud P, Persson M, van der Linden J: Effect of CO₂ insufflation on the number and behavior of air microemboli in open-heart surgery: A randomized clinical trial. *Circulation* 2004; 109:1127-32
- Persson M, van der Linden J: Wound ventilation with carbon dioxide: a simple method to prevent direct airborne contamination during cardiac surgery? *J Hosp Infect* 2004; 56:131-6
- Bowker P, Martin CJ, Fulton D, Muir IF: The use of infrared radiation to reduce heat loss in burned patients: Experiments with a phantom. *Clin Phys Physiol Meas* 1981; 2:257-70
- Larkin JM, Moylan JA: Evaporative water losses in patients treated in a laminar flow burn unit. *J Surg Res* 1978; 24:65-9
- Lamke LO, Nilsson GE, Reithner HL: Water loss by evaporation from the abdominal cavity during surgery. *Acta Chir Scand* 1977; 143:279-84
- Majno G: The healing hand: Man and wound in the ancient world. Cambridge: Harvard University Press, 1975, pp 181
- Sessler DI: Complications and treatment of mild hypothermia. *ANESTHESIOLOGY* 2001; 95:531-43
- Beilin B, Shavit Y, Razumovsky J, Wolloch Y, Zeidel A, Bessler H: Effects of mild perioperative hypothermia on cellular immune responses. *ANESTHESIOLOGY* 1998; 89:1133-40
- Rabkin JM, Hunt TK: Local heat increases blood flow and oxygen tension in wounds. *Arch Surg* 1987; 122:221-5
- Harper CM, McNicholas T, Gowrie-Mohan S: Maintaining perioperative normothermia. *BMJ* 2003; 326:721-2
- Hopf HW, Hunt TK, West JM, Blomquist P, Goodson WH 3rd, Jensen JA, Jonsson K, Paty PB, Rabkin JM, Upton RA, von Smitten K, Whitney JD: Wound tissue oxygen tension predicts the risk of wound infection in surgical patients. *Arch Surg* 1997; 132:997-1004
- Komoto Y, Nakao T, Sunakawa M, Yorozu H: Elevation of tissue pO₂ with improvement of tissue perfusion by topically applied CO₂. *Adv Exp Med Biol* 1988; 222:637-45
- Diji A: Local vasodilator action of carbon dioxide on blood vessels of the hand. *J Appl Physiol* 1959; 14:414-6
- Hynson JM, Sessler DI: Intraoperative warming therapies: A comparison of three devices. *J Clin Anesth* 1992; 4:194-9
- Plattner O, Xiong J, Sessler DI, Schmied H, Christensen R, Turakhia M, Dechert M, Clough D: Rapid core-to-peripheral tissue heat transfer during cutaneous cooling. *Anesth Analg* 1996; 82:925-30
- Morris RH: Influence of ambient temperature on patient temperature during intraabdominal surgery. *Ann Surg* 1971; 173:230-3
- Morris RH, Wilkey BR: The effects of ambient temperature on patient temperature during surgery not involving body cavities. *ANESTHESIOLOGY* 1970; 32:102-7
- Schmied H, Kurz A, Sessler DI, Kozek S, Reiter A: Mild hypothermia increases blood loss and transfusion requirements during total hip arthroplasty. *Lancet* 1996; 347:289-92
- Frank SM, Fleisher LA, Breslow MJ, Higgins MS, Olson KF, Kelly S, Beattie C: Perioperative maintenance of normothermia reduces the incidence of morbid cardiac events: a randomized clinical trial. *JAMA* 1997; 277:1127-34
- Leijh PC, van den Barselaar MT, van Zwet TL, Dubbeldeman-Rempt I, van Furth R: Kinetics of phagocytosis of *Staphylococcus aureus* and *Escherichia coli* by human granulocytes. *Immunology* 1979; 37:453-65
- Wenisch C, Narzt E, Sessler DI, Parschalk B, Lenhardt R, Kurz A, Graninger W: Mild intraoperative hypothermia reduces production of reactive oxygen intermediates by polymorphonuclear leukocytes. *Anesth Analg* 1996; 82:810-6