Chemistry, Biochemistry, & Physics in Anesthesia
Heat, Temperature, & Humidity
Learning Objectives

By the end of this module, you should be able to:

1. Differentiate between temperature and heat.
2. Define the principles and operation of the mercury thermometer, the thermistor, and the thermocouple.
3. Relate readings from various sites to true human core temperature.
4. Define normothermia.
5. Understand the physiologic implications of hypothermia.
6. Relate expected temperature changes during the course of anesthesia to factors promoting heat gain or conservation and heat loss.
7. Describe the various appliances or devices used to conserve patient's heat during anesthesia; discuss their relative efficiency (thermal blanket, Pall HME, Fisher-Paykell).
8. State the reasons why patients become poikilothermic under anesthesia, and the implications of shivering and rewarming.
9. State the physiologic implications of hypothermia in each body system.
10. Define heat capacity, specific heat capacity; relate specific heat of water to that of other substances including gases.
11. Define latent heat, latent heat of vaporization, specific latent heat, and state specific applications of these concepts to anesthesia.
12. Define relative and absolute humidity, state the principles and devices by which they are measured, and clinical implications.
Heat

Heat is a form of energy that can be transferred from a hotter substance to a cooler one with the energy consisting of the kinetic energy of the molecules of the substances in question. Temperature is the thermal state of the substance which determines whether it will give heat to another substance or receive it. The temperature of a gas is a measure of its speed of molecular motion.

Temperature Scales

When heat is added to (or subtracted from) a substance, the temperature and other physical properties change. For example, the object may expand or its electrical resistance may change. Mercury, which expands in volume with temperature increases, was the original substance used by Fahrenheit to construct the first temperature scale.

Temperature scales have arbitrarily chosen fixed points (e.g., the freezing (0°C, 32°F) and boiling (100°C, 212°F) points of water). The SI (metric) temperature scale is Kelvin.

- One Kelvin = 1/273 of the temperature of the triple point of H₂O (that temperature where ice, vapor, and liquid phases of water are in equilibrium = 0°C).

- Celsius is also an accepted metric or SI temperature scale. It has the same size degrees as Kelvin.

- K = °C + 273; (therefore, 273 K = 0°C)
Introduction

Heat is a kind of energy that can be transferred from a hot to a cold substance. Temperature is the thermal state of a substance which determines whether it will give or receive heat. We will continue to revisit these topics as they apply to different states of matter, etc.

Keep in mind that physiologic processes occur under certain, controlled conditions, and temperature is one of them. When the body is altered in disease states, or if it’s too hot or too cold, physiologic processes are altered. Enzyme activity in particular is altered with temperature changes.

We maintain our core body temperatures by balancing heat production from metabolism and many environmental factors that heat or cool the body. Our central nervous system has many complex mechanisms for managing this process, including “set points” to produce and conserve heat and also to cool.

Remember that general anesthesia and regional (nerve-block) anesthesia inhibit the nerve pathways managing thermoregulation. The cold operating room and surgical exposure also contribute to heat loss. After induction of anesthesia, the transfer of heat from the core to the periphery occurs via AV shunts (vasodilation), and this process cannot be stopped once it starts!!! Most of our anesthetics are vasodilators. This is important! So, if you bring an already cold patient into the cold OR and vasodilate them, you will be fighting an uphill battle.

There are only 2 ways to effectively deal with heat loss:

1. We need to cover the most body surface possible to keep it warm, and
2. We need to deliver more heat than is being lost.

Prevention of heat loss as best possible is the goal.

Normothermia is defined by the American Society of Anesthesiologists (ASA) American Association of Nurse Anesthetists (AANA), and the American Society of PeriAnesthesia Nurses (ASPAN) as 36° - 38°C. Changes as little as 0.5°C have been associated with changes in physiologic processes.

Heat loss occurs via 4 mechanisms:

1. Conduction
   - Heat energy is transmitted through a substance by the transfer of the energy of motion of the molecules to adjacent molecules.
• Air is a poor conductor of heat so air trapped in clothing protects against this form of heat loss.

• Conductive loss is usually a negligible form of heat loss.

2. Radiation

• A hot object emits radiation over a wide range of wavelengths predominantly infrared; a bar of steel when heated will glow red then orange then blue then white. This radiation carries away heat and the object cools.

• An important form of heat loss normally and in the OR. It may account for up to 50-60% of the heat loss at room temperature in an unclothed patient.

• Radiant heat loss is increased when body is surrounded by cool objects and decreased by radiation from warm objects near it. For example, space blankets (silvered mylar film) passively reflect the body’s radiated heat energy back to it.

3. Convection

• The air layer adjacent to the body surface is warmed by conduction and expands and rises, since heated air is less dense. The resultant convection current carries heat away, like the "heat waves" one can see above the highway on a hot day.

• This form usually accounts for less than 20% of heat loss in the OR.

4. Surface evaporative heat loss

• The loss of latent heat of vaporization of moisture on the body surface.

• Accounts for around 20% of heat loss at room temperature, can be more in extremely warm environments or when greater areas of moist skin are exposed (e.g., larger incisions).

• Amount of heat lost is proportional to the water vapor pressure gradient between body and air, and to the total amount of skin exposed.
Why are we so concerned? The table below will illustrate the physiologic effects of hypothermia:

<table>
<thead>
<tr>
<th>SYSTEM or FUNCTION</th>
<th>EFFECT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metabolism</td>
<td>Postoperative shivering increases total body $O_2$ consumption</td>
</tr>
<tr>
<td>Respiratory</td>
<td>Blunted ventilatory response to $CO_2$; decreased tissue $O_2$ requirements; Left shift in the $O_2$ -hemoglobin dissociation curve</td>
</tr>
<tr>
<td>Cardiovascular</td>
<td>Systemic and pulmonary vasoconstriction; increased arterial BP; increased risk for ventricular dysrhythmia, MI, and cardiac morbidity in postoperative patients</td>
</tr>
<tr>
<td>Adrenergic</td>
<td>Sympathetic nervous system activation;100%-500% increase in norepinephrine; little or no adrenomedullary or adrenocortical response</td>
</tr>
<tr>
<td>Coagulation</td>
<td>Impaired platelet function and coagulation cascade; enhanced fibrinolysis; increased blood loss and transfusion requirement</td>
</tr>
<tr>
<td>Immune</td>
<td>Impaired function of neutrophils and macrophages; decreased tissue partial pressure of $O_2$; increased risk for bacterial wound infection; delayed wound healing</td>
</tr>
<tr>
<td>Pharmacokinetics</td>
<td>Increased effect and prolonged duration of neuromuscular blockers; decreased MAC (minimum alveolar concentration) for inhalation anesthetics</td>
</tr>
<tr>
<td>Psychological/emotional</td>
<td>Unfavorable recall of surgical experience by patients</td>
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We have not discussed state changes yet, but let’s introduce another clinical point here—anesthetic gases are apt to stay in solution as opposed to vaporizing (thus being able to be exhaled) in the cold patient, so they will take longer to wake up. We will revisit this; just plant the seed in your mind for now.

Certain patients are exquisitely susceptible to hypothermia: the very young, the very old, and the very ill.

Certain surgeries particularly afford the opportunity for hypothermia. Remember that when a large body surface area is exposed, a person will lose heat quickly. Specifically, cardiac surgery, thoracic surgery, organ transplantation, and total hip replacement have been shown to produce great heat loss. Some surgeries, such as cardiac surgery, require patients to be induced into a hypothermic state. This is especially challenging.

**It’s far easier to prevent hypothermia than it is to rescue hypothermia.**

**Body Temperature**

Humans are homeothermic—they control body temperature within narrow limits. Outside of those limits, normal functioning is increasingly difficult since enzyme activity is progressively disturbed with changes in temperature. Normal range = 37.0 ± 0.5°C.

There is a circadian or diurnal rhythm of 0.4°C seen:

- Lowest in early morning, highest in early evening.
- An increased temperature seen after ovulation and continuing through second half of menstrual cycle in females.

**Core Temperature**

Only the central core of the body is maintained at constant temperature. The core consists of the brain, thoracoabdominal organs, and the deep tissues of the proximal limbs. The surface or "shell" temperature varies, usually 32-35°C.
• Core temperature is determined by the heat production of metabolism and the heat loss through the shell.

• Heat production is determined by the general metabolic rate (increases 8% per °C elevation). Shivering increases heat production—heat is generated as a byproduct of muscle unit activation.
  
  o Vigorous shivering, often seen in PACU after volatile anesthetics, is utilized by the body after major cooling.
  
  • Problem: may increase myocardial O₂ requirement (MRO₂) by up to 400%, thus contributing to hypoxemia immediately post-op.
  
  o Shivering is usually activated after the body's mechanisms for heat conservation have been activated (i.e., peripheral vasoconstriction etc.).

Responses of the Body to Changes in Environmental Temperature

• Physiologic control of temperature is mediated by thermoreceptors in skin and receptors in hypothalamus. Control is centered in the thermoregulatory area of the hypothalamus.

• Mild environmental temperature changes cause reflex changes in vasomotor tone in the skin which decrease heat loss. Major body cooling leads to shivering. Excessive body heat leads to reflex sweating and vasodilation.

When heat energy is added to a substance, its temperature rises, and changes in physical properties occur. This is the basis for the mercury (Hg) thermometer, since mercury expands and contracts with temperature changes. Mercury takes a few minutes to equilibrate with itself and its surroundings, and since it's housed in a glass casing and can cause injury it is impractical for our use in the operating room.

Heat Loss in OR

All means of heat loss are directly proportional to the amount of exposed skin, and inversely proportional to the amount of insulation, which resists heat loss. Examples of insulation are clothing, adipose tissue, or air trapped just above the patient in a blanket. Respiration normally accounts for only 10% of basal heat loss: 8% in humidifying inspired gases and 2% in warming it. Inspiration of bone-dry anesthetic gases contributes to the risk of hypothermia.
**Hypothermia**

- Under anesthesia, humans become poikilothermic ie they begin to equilibrate with the temperature of their surroundings, as cold-blooded animals do.

- Anesthetics in general depress the thermoregulatory center, cause peripheral vasodilation (especially volatile anesthetics), and suppress shivering.

- Nitrous oxide increases SNS tone reflexively, thus it can be a minor pressor, while some narcotics (morphine) release histamine which vasodilates.

- Effects of hypothermia become clinically relevant with core temperature <34ºC.

**Effects of Surgery**

Ideally, minimum core temperature during surgery should be 35ºC, although this may be too great a drop for patients in a more fragile condition (extremes of age or poor condition pre-op). Temperature drops of 3-4ºC are common- 0.3 ºC/hour for 20 year olds, and nearly 3x that (or 1.1ºC /hour) for 80 year olds during surgery. This is due to:

- Convective heat loss, since large amounts of the body are exposed to an environment with temperatures of 18-20ºC.
  - Especially common in pediatrics since infants have large BSA/mass ratios

- Evaporative heat loss from breathing dry gases, prep solutions, open wounds

- Infusion of cold or room- temperature fluids, and

- Anesthetic depression of homeothermic reflexes.

Thus, an exposed patient in a cool environment with rapid air flow, exposed to an increased risk of evaporative heat loss means that hypothermia during OR is likely. Therefore we should take all means available to prevent the attendant complications: increase the room temperature, warm and humidify the inspired gases and infused fluids, etc.
**Shivering-prevention/treatment**

- Prevent intraop hypothermia (best method)
- Vasodilators- Nitrprusside during rewarming after CPB helps body heat equilibrate in periphery
- Radiant heating
- Meperidine- unique among narcotics, decreases shivering by direct hypothalamic effect. 25-50 mg IV will decrease shivering 50%
- Muscle relaxants (if ventilated and sedated)
- Phenothiazines such as prochlorperazine (Compazine™)

**Types of Temperature Measurement: Non-Electric**

**Mercury thermometer**

- Utilizes change in volume with temperature change
- Reliable
- Disadvantages clinically
  - 2-3 minutes required for thermal equilibrium
  - Difficult to introduce in some orifices or in certain patients since it is rigid, with risk of breakage and consequent injury.
Dial thermometer

- A bimetallic strip of two dissimilar metals fixed together in a coil
- A second type is a Bourdon-type in which a small tube of Hg expands or contracts exerting lesser or greater pressure on a needle

Types of Temperature Measurement: Electric

Resistance thermometer

- Principle: Electrical resistance of a metal increases linearly with increased temperature.
- Consists of a platinum wire resistor, battery to supply current, and ammeter to measure resistance. Usually incorporates a Wheatstone bridge to increase the device's sensitivity.
Thermistor

- Principle: A bead of metal oxide, the electrical resistance of which falls exponentially as temperature rises. Often also used with a Wheatstone bridge.

- Advantage: Smaller and cheaper than a resistance thermometer.

- Disadvantage: Calibration will change if device is subjected to severe changes in temperature (e.g., gas sterilization).

![Thermistor Graph]

Thermocouple

- Principle: Seebeck effect = at any junction of two dissimilar metals a very small voltage is produced, the magnitude of which depends on the temperature of that junction. Usually a measuring junction's voltage is compared to a reference junction which is maintained at a known temperature.
Clinical Implication: Choice of Sites for Temperature Measurement

Rectal

- Aesthetic considerations
- Perforation (infants)
- Slow equilibration with core temperature in adults

Bladder

- Depends on degree of urine flow
- In low urine flow states, this approximates rectal temperatures

Esophagus (distal 1/3)

- Upper esophagus may reflect temperature of inspired gases; lower esophagus is most nearly core temperature of all the sites which we measure in the OR, plus safe to measure.

Tympanic

- Close to core and brain temp
- Risks of perforation of tympanic membrane
- Artifact from cerumen
Nasal or nasopharyngeal

- Wide fluctuations unless intubated, in which case it reflects brain temperature (blood flow past the cribiform plate).

Skin

- Uses the liquid crystal method. These adhesive mylar strips use micrencapsulated liquid crystal color changing inks to precisely (±0.5°F) and reliably indicate temperature. However this is shell temperature.

- No risks in measurement.

- May be especially useful measured as a second site as it reflects the degree of shock and consequent peripheral vasoconstriction.

- Remember—temperature strips do not correlate with core temperature.
Axillary

- Accuracy will vary with placement (how close to axillary artery), blood flow to arm, whether arm adducted.

"Core"

- Tip of thermistor in the pulmonary artery directly reflects core temperature.

Deliberate hypothermia

- Induced in cardiac or some neurosurgeries to reduce metabolic and tissue demands for O$_2$, hopefully lessening tissue damage during times of relative or absolute tissue ischemia. At 30ºC, time for safe vascular occlusion is twice that at 37ºC. The threshold for ventricular fibrillation is a core temperature of 30ºC (some sources say 28ºC); lower temperatures may be seen with extracorporeal circulation.

Pyrexia

- In fever, the central "thermostat" is reset at a higher level due to pyogens from bacteria (endotoxins) or endogenous factors. If body temperature > 42ºC: cerebral impairment and deranged sweating control. If >45ºC, usually fatal.

Malignant hyperthermia

"Pharmacogenetic" disorder. We will discuss this in detail at another time—this is just to introduce a hyperthermic concept.

- Predisposition is genetic; expression is triggered by pharmaceuticals—most notorious of which are halothane, succinylcholine.

- Diagnosis—unexplained tachycardia, vastly increased CO$_2$ production, warm CO$_2$ absorber, increased core temperature, etc.

- Caused by massive Ca$^{2+}$ release from sarcoplasmic reticulum.
• Treatment:
  o Stop giving offending agent (discontinue anesthesia and surgery);
  o Give 100% oxygen;
  o Initiate drastic measures to cool the body (irrigate open body cavities with iced fluids, infusion of cold fluids intravenously, etc);
  o Get ABG’s and treat respiratory/metabolic acidosis; and
  o Give dantrolene (DantriumR) 1-2mg/kg/5min up to total of 10mg/kg

Burns
• Heating of skin or tissue to > 45°C (113°F) causes burns. Creation of a burn will be determined by the balance between heat arrival from outside sources, and the rate that the circulation removes heat energy from the tissue.
  o Therefore, since they are vasoconstricted peripherally, patients in shock are more susceptible.
  o The operating room temperature is raised into the 90°F range, since these patients have interrupted skin and large surface exposure.
  o The surgeon will always ask about temperature, and procedures are sometimes performed in stages if the patient becomes too cold (Typically, these patients are coming to the OR for debridements and skin graftings.).

Methods Available to Prevent Hypothermia in the Operating Room: What Is the "Best" Method?

Passive warming
1. Room temperature at least 21-24°C, especially in pediatrics.
   • Effective at maintaining normothermia; but in practice, uncomfortably high room temperatures need to be maintained throughout surgery. The surgeons are under hot lights and have to wear layers, so this gets really uncomfortable. It's important to INSIST on the room temp being increased in fragile neonates, for example.
Since most of our heat loss is via radiation, it makes sense that increasing the surrounding temperature is a good choice. You can also employ this technique towards the END of surgery, with varying degrees of successful warming.

2. Insulation

- Any type (space or cotton blankets, plastic sheeting, OR drapes) can decrease rate of cutaneous heat loss to some extent. Continuing to add layers of blankets to the same area does not diminish heat loss.

- However, one can only cover a certain amount of the surface area in surgery. So type chosen is unimportant, but covering as much of the patient as possible is important.

- Some studies advocate covering the head (which makes sense, since it is richly vascular) and face with blankets to maintain normothermia. Think about small babies in the hospital nursery—they wear cotton caps!

Active warming

3. Infrared radiant warmers (overhead warming lamps)
   - Good in peds, ineffective in adults.

4. Circulating water mattresses
   - Ineffective in adults, plus risk of burns.
   - Oddly enough (considering they are never used this way), they are very effective when placed over the patient as a blanket.
   - Alas, their effect is diminished by the practice of padding excessively between patient and mattress.

5. Forced-air warming
   - Effective at maintaining normothermia.
   - You must never use a forced air warming device without its warming sleeve (Never put it directly onto a patient). Serious third-degree burns have resulted.
6. IV fluid warmers

- It is not possible to warm patients by warming IV fluids.
- It is possible to cool them by rapid infusion of large volumes of cool blood or fluids.
- Problem is that heat gained by fluid is lost to the room by radiation before it reaches the patient, especially if flow rates <500-750 mL/hr.

7. Heated airway humidifiers

- Popular because they appear to be effective.
- However, much of the effect is artifact due to improper esophageal probe placement, and they can transfer only trivial amounts of heat to patients (Sessler 1993).

8. Heat and moisture exchangers

- Especially if used with low flows, can help reduce the rate of heat loss (similar to cutaneous insulation).

Some newer innovations on the horizon

- Thermal hydrogel pads that have a conductive water delivery system to provide uninterrupted skin contact, allowing the optimal transfer of energy from the heated water to the patient. Thus, less total surface coverage would be required.
- Newer water-based systems that could manage temperature better than or in conjunction with forced-air warmers, such as specially heated caps and gowns to start the warming process preoperatively.

In conclusion, best so far among the devices available (none of which are as good as increasing room temperature) is forced air warming blankets.
Areas of Concern

- Patient's airway where normal mechanisms of humidification (i.e., nose) are bypassed by ETT or tracheostomy.

- Low humidity in OR allows buildup of static charges; when combined with flammable agents (no longer used) may increase risk of fire/explosions. Though we no longer use flammable agents, risk of fire is ever-present because of presence of fuel and oxidizer.

How is Humidity Measured?

Absolute humidity (AH)

- The amount of water vapor which gas can contain at a specified temperature.

- Increasing the temperature of a gas increases the amount of water vapor it can carry. Decreasing the temperature lowers the kinetic energy of the vapor molecules to the point where they rain out or condense.

- Thus cold air holds less moisture, when fully saturated, than warmer air. Room temperature air (21°C) when 100% humidified holds 18 mg H₂O per liter of gas. Tracheal air at the carina (37°C) holds 44 mg H₂O/L.

Relative humidity (RH)

- Ratio of the mass of water vapor present in a given volume of gas, compared to the mass required to saturate that volume at the same temperature. Usually expressed as a percentage.
Measurement

- Most instruments measure RH.

- Hair hygrometer—Principle is a hair attached to a calibrated scale. The hair will lengthen with increases in RH.

- Wet and dry bulb hygrometer (common)
  - Consists of two thermometers, one dry reading ambient temperature, the other wetted, which reads a lower temperature because of the cooling effect of the evaporating water it is moistened with (loss of the latent heat of vaporization).
  - Difference between the two temperatures is related to the rate of evaporation which is related to ambient RH. Tables are used to read the RH.
Humidity: Clinical Aspects

- Dry air in the trachea inhibits ciliary function, causes dry, inspissated secretions which are difficult to clear, possibly mucous plugs. Cooling of trachea as it humidifies incoming dry anesthetic gases (loss of latent heat of vaporization as tracheal moisture evaporates) depresses ciliary function as well.

- There are two methods of humidifying inspired gases:
  1. Humidify the environment (ie oxygen tent, incubator), or
  2. Humidify the inspired gases only (generally we must pursue the second course).

Humidification of inspired gases

Pall heat and moisture exchanger HME

- Inside is an exchange medium with a large surface area and large thermal capacity and a hygroscopic condenser/humidifier (actively binds water molecules in exhaled gases).

- If the particular device incorporates a high-efficiency bacterial/viral filter, it is known as an "HMEF" (not all HMEs are HMEFs).

- Relative humidity of exhaled gases 100%; this excreted water is reclaimed, as gases are humidified by the HME with the next inspiration, hence the name "artificial nose".

- Problems:
  - Hazard of increased resistance to gas flow if clogged with secretions,
  - Too much VD for infants.

- Conclusion? easy to use, cheap, no chance of burns as with active airway humidifiers, little chance of bacterial transmission.
Heated humidifiers ("Fisher-Paykell", Anamed)

- "An instrument that emits water vapor by passing a stream of gas over or through a water reservoir."
- The most popular method for patients on ventilators.
- ICU-type ("cascade") humidifiers have relatively high internal resistance since the gas stream passes through the water, and are therefore unsuitable for anesthesia.
- For a while, these were common in OR as well. The type used in the OR uses a stream of gas passing over heated water ("Fisher-Paykell"), or a heated moistened wick within the inspiratory limb (Anamed). These devices have fallen out of favor as it has become recognized that they:
  - Are a poor way to keep the patient warm
  - Clog up the granules in the absorbent canister
  - Plug sampling lines for agent and capnography with droplets
  - May require high fresh gas flow (FGF) with excessive and costly volatile agent consumption
A heating element is necessary. If unheated, moisture output decreases with time since vaporization cools the water, thereby reducing its vapor pressure. Adding heat gives a more constant level of vaporization. The level of added heat is determined by the humidity required by the patient and the degree of temperature drop along the tubing.

Unless temperature within the breathing circuit hoses is just above ambient room temperature (at least), water will condense in the delivery hoses ("rainout") especially at lower fresh gas flows. Circuits used should be clear and have provisions for draining rained-out water.

Placement of humidifiers

- Put in circle system distal to inspiratory valve and oxygen analyzer, with no bacterial filter between humidifier and patient (clogs the filter).

- **Always** place lower than the patient so that aspiration will be prevented if tipped.

- Mandatory to have controls to prevent hyperthermia: airway burns are possible with any heated device.

- Fisher-Paykell requires FGF at least 5 L/min (or risk of both melted circuits and damage to heater).

- Anamed uses a wet wick in the inspiratory hose which is heated by an insulated wire. It does not require any minimum FGF.
• Advantages: Efficient in humidifying/warming gases to 37°C even with high flows, it is the most physiologic method of supplementing inspired humidity.

• Disadvantages: Bulky, difficult to mount, complex, costly, monitoring of gas temperature at patient end of circle mandatory, sticking of valves in circle secondary to higher humidity, condensate, possible aspiration, heat damage to respiratory tract, hyperthermia if other methods of heat loss depressed, effectiveness questionable.

Nebulizers

Gas-driven

• Principle is the Bernoulli effect, with water droplets being pulled up through an injector.

• The larger droplets are baffled out and finely divided by an "anvil" or distal obstruction.

• Problem: needs heating element to preserve efficiency, plus back pressure may alter entrainment ratio and thus output.
Ultrasonic

- Principle is that droplets of water are formed by a swiftly vibrating surface. A submerged plate is made to vibrate (by an electric motor) at a frequency of 2 MHz (2,000,000 cycles/sec).

- The size of the droplets is important: >20 micrometers will rain out in tubing or upper respiratory tract, 5 mcm will fall along the trachea, while droplets of approximately 1 mcm will penetrate to the alveolar level- ideal for carrying medication, for example.

- Disadvantages: Because droplets are added to the gas, 100% relative humidity can be exceeded, potentially causing fluid overload especially in pediatrics; hypoxia because of shunting of blood past water-filled alveoli or from increased resistance to breathing due to narrowed lumen of small air passages from a film of water; also infection.
Relative efficiency at humidification

- US nebulizer most efficient, HME has advantages but is least efficient at humidifying the airway. A heated humidifier (Fisher-Paykell) is also very good; more efficient than a condenser.

- Disadvantages: Because droplets are added to the gas, 100% relative humidity can be exceeded, potentially causing fluid overload especially in pediatrics; hypoxia because of shunting of blood past water-filled alveoli or from increased resistance to breathing due to narrowed lumen of small air passages from a film of water; also infection.