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Problems of Inhalation Gas Mixture Conditioning in High-Frequency Jet Mechanical Lung Ventilation Apparatuses

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High-frequency mechanical lung ventilation (HF MLV) is a relatively new MLV method. In contrast to conventional MLV, HF MLV of adult patients deals with low volumes of inhaled air (100-200 ml) applied at high frequency (100-300 per min). Adequate HF MLV is provided at high speed of air jet (>50 m/sec), low compression volume (<50 ml), and low stretchability of respiratory circuit of the MLV apparatus (<0.1 ml/cm water column).

This ventilation mode gives rise to low pressure in respiratory pathways and negative pressure in the pleural cavity, thereby facilitating pulmonary and systemic circulation. High speed of air jet decreases physiological dead space and provides adequate alveolar ventilation with low air volumes [2, 7]. Jet HF MLV apparatuses provide more adequate saturation of blood hemoglobin with oxygen in patients with serious lung disorders. Open MLV circuit reduces barotrauma of lungs and solves the problem of ventilation in patients with conserved spontaneous respiration.

The advantages of jet HF MLV over conventional MLV are:

– effective ventilation with unsealed patient–apparatus system;

– effective long-term ventilation using a mask, a mouth-piece, or a catheter for connecting to the MLV apparatus;

– synchronization with spontaneous respiration, providing for ventilation in patients with conserved spontaneous respiration;

– adequate MLV in case of failure of conventional MLV.

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There are also some medical advantages of jet HF MLV over conventional MLV. However, jet HF MLV has a number of technological disadvantages. This is the problem of inhaled gas conditioning. Contemporary ventilation standards require inhaled gas mixture to have certain temperature and humidity. Jet HF MLV apparatuses provide high speed of inhaled air jet passing through a nozzle of small diameter, open respiratory circuit, and Venturi effect (in-leakage of atmospheric air). Conventional air humidification methods are not used in jet HF MLV apparatuses because of:

1) high pressure in the inhalation circuit (150-300 kPa);

2) limited volume of air manifold after valve (to prevent negative effect on gas jet parameters);

3) high speed and low time of contact of inhaled gas with heater and humidifier;

4) gas expansion at the nozzle outlet modifies its temperature and humidity.

Let us consider the fourth factor in more detail (Fig. 1). The oxygen speed at the nozzle outlet is tens of meters per second. Oxygen expansion at the nozzle outlet reduces its temperature and increases its relative humidity. The resulting temperature and humidity depends on oxygen temperature and pressure at nozzle inlet and nozzle diameter.

According to the Venturi effect, the gas jet at the nozzle outlet entraps surrounding air (injection effect) (Fig. 2). The gas jet is mixed with injected air, thereby modify-

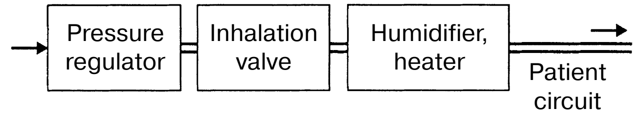

Fig. 1. Simplified scheme of the pneumotract of an HF MLV apparatus.

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ing its temperature, humidity, and oxygen concentration. The temperature sensor should be positioned near the tracheal tube to provide adequate regulation. Final gas temperature is determined by the following factors:

– gas temperature at heater output;

– adiabatic gas cooling caused by gas expansion at the nozzle outlet;

– inhaled gas cooling caused by its mixing with injected gas.

Adiabatic gas cooling is determined by nozzle diameter and output gas speed (input nozzle pressure). Input nozzle pressure is regulated by the patient based on normal oxygenation of arterial blood and removal of carbon dioxide.

Atmospheric air injection may vary depending on respiratory tract resistance and lung stretchability. The atmospheric air injection exerts a substantial effect on inhaled gas mixture temperature. It should be emphasized that jet HF MLV must be combined with gas heating and humidification, because otherwise it may cause severe destruction of respiratory tract mucosa [4, 6, 8]. Many researchers have reported that heating and humidification of inhaled gas mixture is necessary in case of jet HF MLV [3, 9].

In case of jet HF MLV, two methods of heating and humidification of inhaled gas mixture are used:

– simultaneous heating and humidification implemented as application of heated saturated vapor from a special evaporator into the respiratory circuit after a solenoid valve or directly into inhalation manifold near the connector;

– separate heating and humidification of gas.

There are advantages and disadvantages of each of the two methods. Although simultaneous heating and humidification provides stable humidification, it causes temperature regulation problems and hazard of tracheal mucosa burns in case of rapid vapor condensation. Outside location of the humidifier makes the apparatus design more expensive and complicated. Although separate heating and humidification does not cause temperature regulation problems, it is associated with serious humidification problems.

The problem of inhaled gas mixture conditioning in case of jet HF MLV has not been solved yet. A humidifier in the inhalation circuit increases compressed volume and causes deficiency of respiratory volume. A humidifier before the valve does not increase compressed volume, but moisture condensation reduces the valve service life. Liquid dropping before the injector nozzle used to be considered the most effective method of humidification. In this case, the physiological liquid jet reaches subsegmental bronchi.

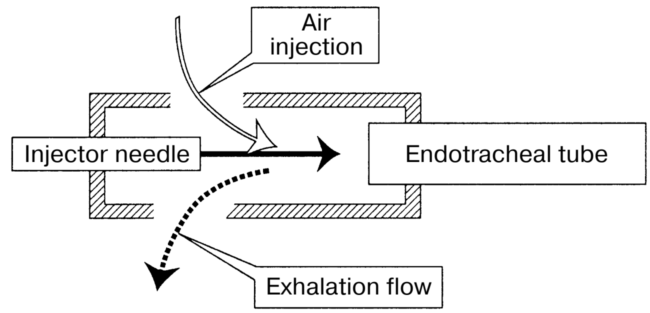

Fig. 2. Distribution of gas flows in jet MLV.

The volume of dropped solution ranges from 6-7 to 60-70 ml/h [5]. According to the literature [5], it is sufficient to inject 44 ml physiological solution per air flow liter per h. The following equation was suggested to calculate the volume of liquid:

$$Q = 2.64 \cdot V_T,$$

where Q is physiological solution run-off, ml/h; V_T is minute ventilation of lungs, liters/min.

Liquid evaporation in the inhalation manifold reduces gas temperature, which makes it difficult to maintain the temperature mode at the necessary level.

The two methods of humidification require information about minute ventilation, which is difficult to obtain in case of high ventilation frequency. A gas flow rate sensor should operate in a pure oxygen atmosphere and at high flow rate.

The Spiron-601 jet HF MLV apparatus developed at VNIIMP implements another method of gas conditioning [1]. Two injector valves separate exhaled and injected gas that passes through the UDS-2 automatic humidifier with heated tube. A heating sensor provides automatic regulation of inhaled gas temperature. Temperature decrease in the injector increases gas humidity to 100%.

In our opinion, gas heating and humidification directly in the patient manifold is the best method of gas conditioning [3]. This principle is implemented in various apparatuses available from many manufacturers of Ekaterinburg. However, our experiments revealed serious problems with gas humidification in such apparatuses. Either insufficient ventilation or moisture condensation in the patient manifold accompanied uncontrolled minute ventilation. A new approach to design of HF MLV apparatuses was required to solve this problem. The new model of HF MLV apparatus available from Triton ElectronicS implements this approach. It uses high-precision sensors of gas flow and temperature as well as microprocessor control system of inhaled gas.

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