CASE REPORT

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“Tails-up” capnogram: the role in detecting anaesthetic equipment malfunction

Kapnogram sa “uzdignutim repom”: uloga izmenjene kapnografske krivulje u otkrivanju poremećaja funkcionisanja anesteziološke opreme

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Abstract

Introduction. Capnography is an essential part and standard monitoring tool during the perioperative period, which can be invaluable in detecting anaesthetic equipment malfunction. **Case report.** The atypical, ”tails- up” capnographic waveform was noticed during routine surgical operation. Comprehensive physico- mathematical and graphical explanation of this complex capnographic pattern has been given, together with in- depth analysis of possible differential diagnosis and clinical significance for routine clinical practice. **Conclusion.** “Tails-up” capnographic trace gives early clue to diagnosing and fixing the problem of cracks in sampling line, before leading to an inadequate course of action. The understanding of the physics and physiology behind capnography is of vital importance for the analysis of capnographic waveforms, for early detection of anaesthetic equipment malfunction and for safe clinical practice.

Key words:
capnography; monitoring, intraoperative; equipment and supplies; equipment failure; physics; physiology.

Apstrakt

Uvod. Kapnografija predstavlja standardni uređaj za monitoring tokom perioperativnog perioda, koji može biti od neprocenjivog značaja u otkrivanju problema u funkcionisanju anesteziološke opreme. **Prikaz slučaja.** Atipičan oblik kapnograma sa “uzdignutim repom” zabeležen je tokom rutinske operacije. Prikazano je detaljno fiziko-matematičko i grafičko objašnjenje ovog kompleksnog kapnografskog oblika, zajedno sa analizom mogućih diferencijalnih dijagnoza i kliničkim značajem za svakodnevnu praksu. **Zaključak.** Oblik kapnograma sa “uzdignutim repom” omogućava ranu dijagnozu i rešavanje problema pukotina u sistemu za uzorkovanje izdahnutog gasa, pre nego što dovedu do daljih neadekvatnih postupaka. Detaljno razumevanje fizike i fiziologije nastanka kapnografske krivulje značajno je za uspešnu analizu kapnografskih talasa, za ranu detekciju kvara anesteziološke opreme i za bezbednu kliničku praksu.

Ključne reči:
kapnografija; fiziološke funkcije, intraoperativno praćenje; oprema i pribor; oprema, malfunkcija; fizika; fiziologija.

Introduction

Capnography is a standard monitoring equipment used during perioperative period, and it can be utilized to monitor several physiologic parameters, body metabolism, systemic and pulmonary circulation and ventilation. The integrity of anaesthetic machine and equipment can be monitored and misconnections and faults diagnosed, which could be lifesaving [1, 2]. First of all, one can easily misdiagnose type of capnographic trace with similar ones seen in pregnant, obese patients and in patients with low compliance states of the lungs [1–3]. Low CO_2 levels could easily be misinterpreted as a hyperventilation, hypoventilation, or hypometabolism. Moreover, falsely low levels of anaesthetic gases can lead to inadequate depth of anaesthesia.

We present unusual and atypical capnographic trace known as the “tails-up” capnogram [4, 5], with its in-depth analysis and clinical importance, by using the basic fundamental laws of physics.

Case report

A 65 years old male patient was admitted to the emergency department with acute abdominal pain located in

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the epigastric area. The diagnosis of perforated gastric ulcer was made, and the patient underwent emergent laparotomy. All vital signs were within normal limits during surgery, including the values of electrocardiography, pulse oximetry, intrathoracic pressures and ventilatory parameters. However, after two hours of surgery, the change in capnographic trace was recorded with anesthetic gas monitor (Draeger Vamos, Lübeck Germany) (Figure 1). After careful examination of the sidestream sampling line, the small slit-like hole was found approximately in the middle of the line (Figure 2). The sampling line was exchanged, the waveform returned to normal and the surgical procedure was finished uneventfully.

Discussion

The atypical capnographic waveform was seen during uneventful anesthesia, which led to the diagnosis of the broken sidestream sampling line. The sampling line is a thin, long and frail plastic tube, vulnerable to cracks and brakes during machine movement[3].

The prominent features of changed capnographic waveform are the dip, or the “valley” part, and the “tail” part of capnogram. In order to understand this capnographic pattern, we need to briefly review the basics of capnography. The normal capnogram consists of four segments and two angles, corresponding to various phases of respiratory cycle (Figure 3): the first phase represents the elimination of a CO_2 – free gas from anatomical dead space, following with expiration of a mixture of gases from anatomical and alveolar dead space –phase two; the third phase, or alveolar plateau represents the elimination of the CO_2-rich gas from alveoli, followed by the beginning of inspiration of CO_2-free gas and sudden drop to the baseline. The alveolar plateau phase is especially important for the explanation of the “tails-up” capnogram, and it can be conceptualized as the proportion between the volume of the CO_2 gas in the mixture of gases, or the CO_2 content within the volume of all exhaled gases from the patient and inside the sampling tube.

Sidestream sampling line is a long, rigid and thin plastic tube, 100–200 cm in length and with 1–1.5 mm inside diameter, which aspirates the gas from the patient’s end of the breathing system, at a rate between 100–250 mL *per* minute. Since it is rigid and non-collapsible, we can apply the modified Ohm’s law for laminar flow of gas (or fluid) through the rigid tube (Equation 1):

$$Q = \frac{\Delta P}{R}$$

which states that the flow (Q) is directly proportional to the pressure drop (ΔP) along the tube and indirectly proportional to the resistance (R) of the tube.

The Hagen-Poiseuille Law (Equation 2):

$$R = \frac{8 \times \mu \times l}{\pi \times r^4}$$

states that the resistance of the tube is directly proportional to the length (*l*) of the tube and viscosity of the gas (μ), and indirectly proportional to the fourth power of the radius of the tube (r^4)[4].

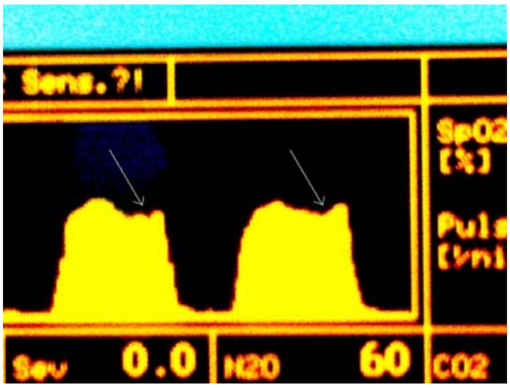

Fig. 1 – The “Tails-up” capnogram. Note the valley part (arrow) and the “tail” part of the capnographic trace.

Fig. 2 – The hole (arrow) in the sidestream sampling line.

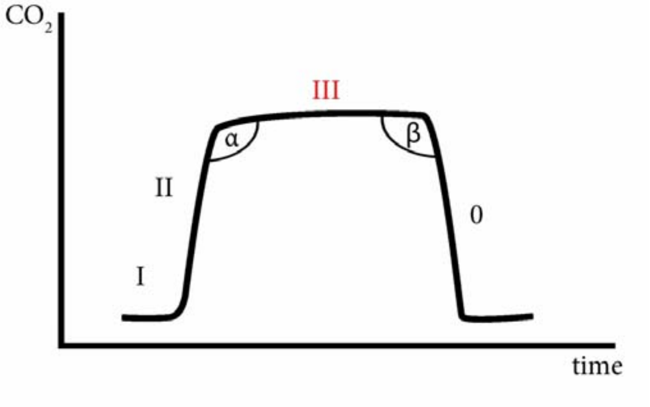

Fig. 3 – The model of the sidestream sampling line.

Rearranging these equations (Equation 3):

$$\Delta P = Q \times \frac{8 \times \mu \times 1}{\pi \times r^4}$$

we can see that the drop in pressure along the tube is directly proportional to the length of the tube (all other parameters held constant). This means, the longer the tube, the greater the drop in pressure, and *vice versa*.

Based on this theoretical consideration, a model of the sidestream sampling line was built (Figure 4). P1 represents the pressure at the patient (breathing system) end of the tube, P2 is further away along the tube, inside the tube is aspirated gas from the breathing system (P_{ins}) under some amount of pressure, and outside the tube is atmospheric air with atmospheric pressure (P_{atm}). The resistance is directly proportional to the length of the tube, and there is a drop in pressure from P1 to P2. At some point of the sampling tube, there has to be equalization of the outside and inside pressures, or an equal pressure point (EPP). After passing this point, the pressure outside the tube will be greater than the pressure of the aspirated gas inside, i.e. $P_{atm} > P_{ins}$.

We can add to this consideration the Law of conservation of energy, which states that "energy cannot be created or destroyed, but can only change from one form to another" [4]. This means that the total energy (i.e. the pressure – P_0) of the system, in this case the rigid sampling tube, must always be constant, i.e. the sum of the kinetic energy (dynamic pressure – *q*), which is a function of the velocity of the gas, and the potential energy (static pressure – *p*), is always constant (Equation 4).

$$P_0 = p + q$$

So, if the velocity of flow increases, the pressure within the tube must decrease which is, actually, the practical application of the Law of conservation of energy, known as The Bernoulli's principle [4].

The Law of conservation of flow relates the velocity of gas through the rigid tube with a cross-sectional area of the tube and states that the flow through any part of the tube must remain constant. This means that the smaller the cross-sectional area of the tube (or, the greater the resistance), the velocity along that part of the tube has to increase (Figure 5).

Combining the principle of conservation of flow, with the previously explained Hagen-Poiseuille Law and Bernoulli's principle, it can be stated that the smaller the radius, i.e. the cross-section of the tube, the greater the velocity inside the tube and the smaller the pressure that is exerted on the wall of the sampling tube. A longer tube, higher resistance of the tube and higher gas velocity is needed in order to conserve the constant flow inside the tube. This leads to a greater drop in pressures, the gas flows further away from the patient end of the sampling tube, finally reaching the EPP.

If a crack or a breach appears in the sidestream sampling line as in our case the following changes are present (Figure 6). During the expiratory phase of positive pressure mechanical ventilation (IPPV), the pressure inside the line will progressively decline along the length of the line, until it equalizes with the atmospheric pressure, i.e. until it reaches the EPP. When the pressure inside the tube becomes lower than the EPP, the suctioning of atmospheric air occurs across

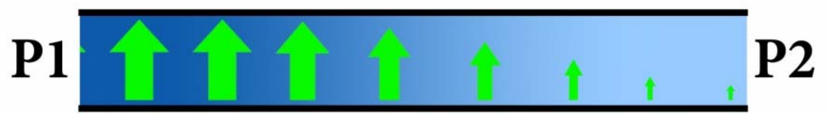

Fig. 4 – The model of the sidestream sampling line.

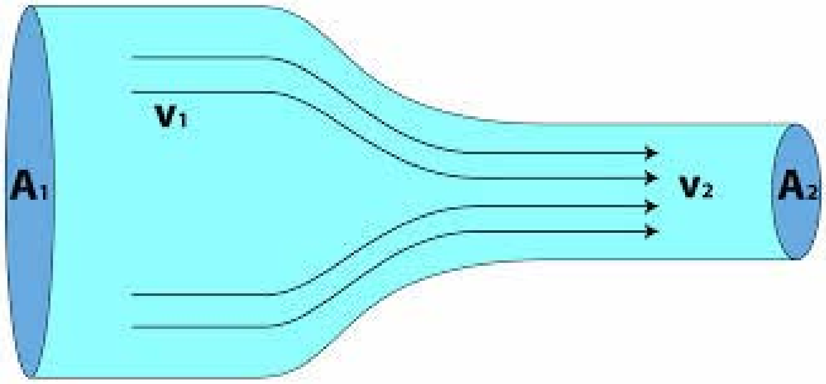

Fig. 5 – The conservation of flow: the velocity (V2) of the gas inside the tube increases with decreasing diameter, i.e. the cross- sectional area (A2) of the tube. The pressure at A2 will be lower than pressure at A1 (p2 < p1).

Fig. 6 – The model of the sidestream sampling line, with the breach in wall. When the Pins < Patm during expiration, the suc-tioning of the atmospheric air occurs.

the pressure gradient (the Venturi effect) [3]. This leads to the dilution of the in-line CO_2, which gives rise to the "valley" part of the capnographic trace (Figure 7). However, during the beginning of the inspiratory part of IPPV (Figure 8), just before the opening of the inspiratory valve of the breathing circuit, there is a building-up of pressure inside the breathing system.

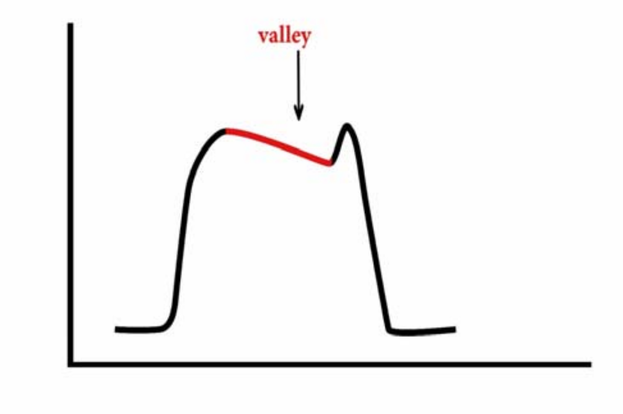

Fig. 7 – The "valley" part of the capnographic trace.

Fig. 8 – During inspiratory part of the positive pressure ventilation, the $P_{ins} > P_{atm}$, there is a functional sealing of the hole, which prevents the suctioning of the atmospheric air.

This positive pressure transmits to the sampling line, which leads to the constant positive pressure exerted all along the line. Since the pressure inside is higher than the atmospheric pressure, this leads to the functional sealing of the hole, which prevents suctioning of atmospheric air and dilution of in-line CO_2. The end-tidal CO_2 value instantaneously returns toward normal, which gives rise to the "tail" part of the capnographic trace (Figure 9).

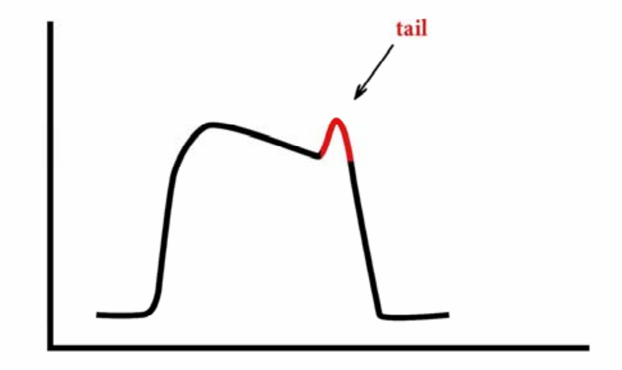

Fig. 9 – The "tail" part of the capnographic trace.

Tripathi et al. [5] confirmed experimentally the theoretical background and predictions stated in this article, that during the expiratory phase of IPPV, lower levels of CO_2 and anaesthetic gases exist inside the breached sampling tube, and that atypical capnographic trace can be seen. On the other hand, during spontaneous breathing, there is a drop of pressure inside the sampling tube in both phases of the respiratory cycle, the dilution and lower levels of CO_2 and anaesthetic gases occur in both inspiration and expiration, and the pseudo-normalization of capnographic trace can be seen.

Conclusion

"Tails – up" capnographic trace gives early clue to diagnosing and fixing the problem of cracks in sampling line, before leading to an inadequate course of action[5]. Regular inspection of the sampling lines should be performed as a routine and mandatory part of the pre-anesthetic machine check-up protocol.

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