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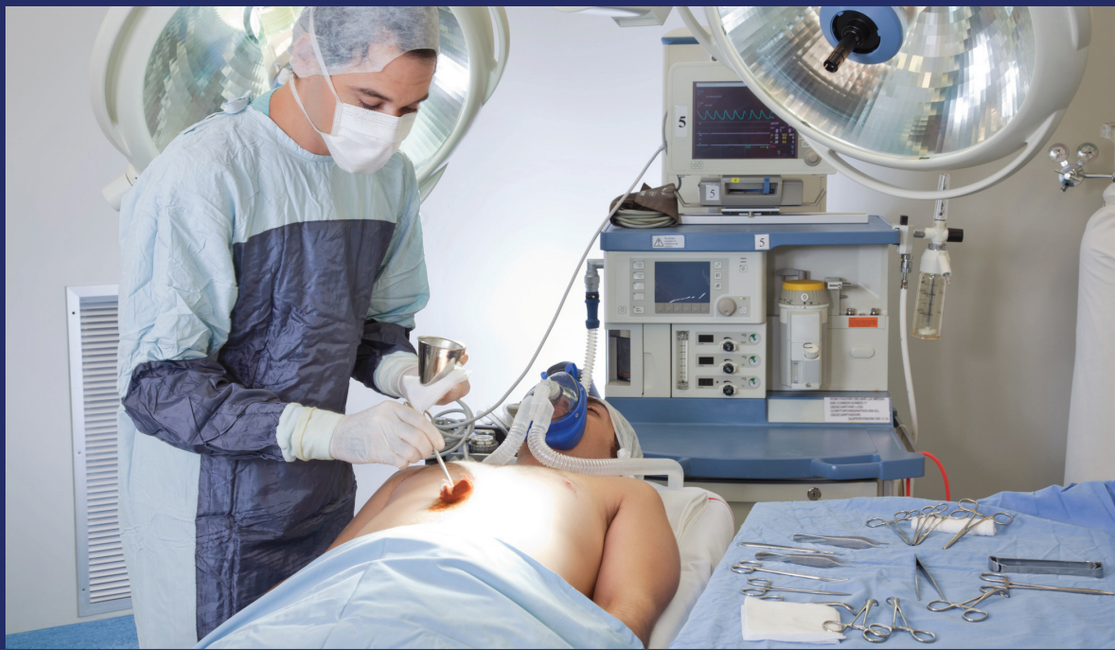
Alexander Berlin is an engineer and patent expert. He was born in Russia, in 1943. Having starting in Israel (2001-2005) and comleted in Russia (2006-2011), he devised and introduced into medicine new mini-Vaporizers and Anesthesia Machines. Berlin AZ is the author of about 20 serial devices, 100 patents and 3 books.

978-613-9-83673-4



Alexander Berlin

Portable Vaporizers and Machines for Inhalation Anesthesia

Victoria Lyublinskaya. Translator and proofreader

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Imprint
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Cover image: www.ingimage.com

Publisher:
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is a trademark of
International Book Market Service Ltd., member of OmniScriptum Publishing Group
17 Meldrum Street, Beau Bassin 71504, Mauritius

Printed at: see last page
ISBN: 978-613-9-83673-4

CONTENTS

Summary

Draw-over vaporizers pose an alternative to plenum vaporizers in emergency situations and in remote areas despite the low precision of the former.

The instability of the existing draw-over vaporizers stems from the significant difference of flow regimes and geometry of bypass and vapor channels. This difference causes a dramatic dependence of the splitting ratio on the total gas flow. At low gas-flow rates through the vaporizer, the rate of flow through control valves is comparable with the rate of secondary gas flows arising from non-uniform density, variations of pressure and instant velocity during artificial or spontaneous ventilation and because of other disturbing factors.

However, low hydraulic resistance is not necessarily related to low accuracy.

The main problems of inhalation anesthesia may be solved by using a more perfect vaporizer that would be accurate as a plenum vaporizer, simple and low-resistant as a draw-over one.

An attempt to regularize the governing processes (gas flow, mass and heat transfer) within the laminar flow regime enabled us to design new low-resistance vaporizers "MINIVAP" (**Pocket 400 g**/stainless steal & **300 g/titanium** and **Universal**), which are capable of dosing out anesthetics in the flow range of 0.2-15 L/min just like plenum vaporizers.

The book considers characteristic features of portable anesthesia machines "Colibri" based on the above vaporizers, related to Breathing Circles, saving of anesthetics and gases, Auto-Analgesia and compatibility with medical Gas Sources (Mixers) and Automatic Ventilators.

Due to the low resistance and virtual independence from fresh gas flow rate, temperature and ambient pressure, "MINIVAP" vaporizers are instantly adaptable to needs of on-site emergency surgery, military and urgent situations, remote areas, veterinary anesthesia and more sophisticated demands of a general/district hospital.

The smallest vaporizer "MINIVAP-20/I" (400 g) and the most powerful "MINIVAP-20/S" (up to 10vol% of sevoflurane) provide effective anesthesia for adults and

children as well and animals (from a mouse to a horse) in operating and emergency situations.

Key words: Inhalation Anesthesia, low resistance (draw-over) Vaporizers, volatile Anesthetics (Sevoflurane, Isoflurane), Breathing Circuit (circle), portable Anesthesia Machines (AM) and Automatic Ventilators.

Examples and clarifications are italicized to facilitate reading.

77 pages, **21** figures, **4** tables.

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Alexander Berlin. Portable Vaporizers and Machines for Inhalation Anesthesia

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INTRODUCTION

Advantages of inhalation anesthesia **[1- 7, 31]**:

1 - Natural way of anesthetic delivery (through the lungs) along with the necessary oxygen without compromising vital body tissues (as opposed to intravenous anesthesia).

2 - Absence of pain syndrome (pediatric anesthesiologists call it "warming up the throat", as the syringe is unacceptable for children under 14 years old).

3 –More precise control on the anesthesia depth (rapid induction and especially rapid recovery from anesthesia, in contrast to intravenous agents).

4 - Low biotransformation of modern anesthetics.

Main problems of inhalation anesthesia include:

1- The inhalation equipment (apparatus and gas supply system) is bulky in comparison with intravenous one.

2 - At the minimum fresh gas flow of 250 ml/min the supply of "anesthetic agent reaches its limits…with isoflurane – and that would be more striking with enflurane or halothane – the individual uptake of an adult patient exceeds the amount of agent which maximally can be supplied into the breathing (VOC) system" **[2]**,even at the maximum dial setting. The lower the flow, the higher concentration on the control dial should be to maintain the necessary anesthesia depth.

3 - Because of the low anesthetic vapor delivery rate during low flow anesthesia (gas flow from 0.2 to 2 L/min), the inspired anesthetic concentration significantly differs from the concentration on the vaporizer dial after the concentration switch (Table 1). The lower the fresh gas flow **F**, the greater the difference $\mathbf{C_S - C_I}$, as well as the stabilization (delay) time of the inspired concentration $\mathbf{T \geq V_c/F}$, where $\mathbf{V_c}$ is the breathing circuit volume.

4 - Well-known draw-over vaporizers (OMV, Ohmeda PAC, Goldman) are associated with unpredictable output concentration and inadaptability to low gas flows (below 4 L/min).

Table 1

Sevoflurane (S) and Isoflurane (I) low-flow anesthesia with a vaporizer OUT of the breathing circuit (VOC) **[2]**

Fresh gas (O_2) flow **F**, L/min		0,25	0,5	1
Vaporizer setting / Inspired concentration, $\mathbf{C_S}$/ $\mathbf{C_I}$	S	**8/2.8**	**5/2.8**	**3/1.8**
	I	**5/1.2**	**5/1.8**	**2/1**
Anesthetic vapor delivery $\mathbf{F_A = C_S\ (1\text{-}C_S)^{-1}\ F}$, mL/min	S	21	26(max 42)	31(max 84)
	I	13	26	20 (max 53)
Time delay concentration, $\mathbf{T \geq V_c/F}$, min		20	10	5

Example 1*. The time delay of Anesthesia Machine (AM) is greater than* ***10 min*** *with a standard volume* $\boldsymbol{V_c}$*= 5L and a flow rate* ***F****= 0.5 L/min. The real time delay* ***T*** *significantly increases due to the anesthetic uptake and elimination by the patient tissues and not ideal rinsing of the respiratory circuit.*

The delivered anesthetic vapor flow $\mathbf{F_A}$ may be increased by serially connecting agent-specific vaporizers kept out of the circuit **[8]**. On the other hand, the super-complex anesthesia machine PhysioFlex™ with an electronically controlled vaporizer changes sevoflurane concentration from 0 to 2 vol.% in 80 to 510 s **[16]**. However, the mentioned methods and equipment are impractical.

Thus, the anesthesiologist without the gas analyzer cannot practically assess the anesthetic inspired concentration despite the high precision of the vaporizer.

The world market is saturated with stationary Anesthesia Machines (AM) based on traditional high resistance or plenum vaporizers working on compressed gas pressure of about 400 kPa. There is an acute shortage in portable AM based on stable draw-over vaporizers operating irrespective of the power sources at a limited workplace in the field and emergency situations.

“This has left something of a generation gap in the equipment available since the draw-over vaporizer development all but stopped some 2 decades ago”**[5]**.

However, despite instability, “draw-over anesthesia is the system of first choice for small hospitals” **[6, 7]**.

"An austere environment imposed by the tactical situation or geographical location may demand innovative approaches to what are normally routine clinical problems. For example, the scarcity of medical-grade compressed gas may require the anesthetist to use draw-over vaporizers … not in common practice in the US" **[9, 10]**.

Attributes of inhalation anesthesia provision for remote areas and major disasters:

- Low body weight, portability, user friendliness;
- Superb performance: efficient and accurate, nonspillable;
- Multiple agent option;
-Supplemental oxygen provision when available;
- Ambient air use as a carrier gas.

These various and contradictory requirements can be formulated in one phrase: the **perfect vaporizer should be precise as plenum vaporizer and simple as draw-over one**.

The emergence of relevant vaporizers and AM, first, will remove the above mentioned deficit, second, will expand their application in situations where there is no alternative adequate intravenous anesthesia (for example, with a massive blood loss) and, third, will increase the effectiveness of traditional inhalation anesthesia.

Models of stabilized (by carrier gas consumption, temperature and pressure) low resistance vaporizers were developed in 2001-2005 in Israel within the framework of the start-up firm "LaminarTechnology Ltd", although the development of prototypes, medical certification and industrial production is organized in Russia (costs in tens of times less) in 2007-2011 **[11-13]**.

Several portable AM "Colibri" are made on the basis of the two vaporizers: "MINIVAP-20/I" (3 times smaller than the best analog OMV) and "MINIVAP-20/S" (twice as powerful as Vapor 2000) for adults and children, as well as for animals (from a mouse to a horse).

The development, manufacture and commercialization of medical products are particularly complex and costly (the multi-stage research, technical and medical tests,

and certification). Currently more than 100 portable AM “Colibri” and “MINIVAP” vaporizers are utilized in Russia and “the near abroad” mainly in the district hospitals and veterinary clinics. That is a “drop in the sea” compared to the USSR situation in 1970’s, when 3 thousand vaporizers “Anestezist-1” and “Anestezist-2” were annually produced for the Medicine and Army needs (chapter **6**).

Such portable equipment is necessary in emergency situations (ambulance), military surgery, remote areas, man-made disasters as well as in district hospitals and veterinary medicine.

Here are a few important facts.

Annual sales of Sevoflurane total is more than $ 1 mrd. Estimated yearly revenue of Isoflurane is $ 200 million. 1/3 of Isoflurane yearly sales go for veterinary medicine. The maintenance of one-hour operation takes less than 20 ml of Sevoflurane. Such operations take place in more than 50% of all cases. The price of 1 ml Sevoflurane is about 1$, then the amount of **annual only Sevoflurane anesthesia** equals more **50 million**.

More than 100,000 vaporizers are produced annually in the world with $ 800-5000 prize per unit.

The cost of a stationary AM with mass over 50 kg, including monitors and ventilator, is tens of thousands dollars.

The correlation between inhalation and intravenous general anesthesia changed radically in different historical periods. Thus, in the Crimean War (thanks to N.I.Pirogov, first surgeon in Europe to use anesthetics) and the civil war in the US, inhalation anesthesia was exclusively used. Tens of thousands of operations were performed annually in the absence of a perfect apparatus and anesthetics. Inhalation anesthesia also dominated in the World War I and World War II, in Korea, Vietnam, local conflicts in Bangladesh, Cambodia, Angola, Chad, the Falkland Islands and Iraq.

However, according to the military anesthesiologists A.I. Levshankov and Yu.P. Polushin, “Russian military inhalation anesthesia lost its priority in Afghanistan

(1980-88) and remained completely unclaimed in Chechnya (1994-96)" because of the incompatibility of anesthesia equipment to extreme climatic conditions that are low atmospheric pressure and high temperature.

1. METHODS OF REGULATING OUTPUT CONCENTRATION AND POPULAR VAPORIZERS

Vaporizers with dilution of the saturated vapor are prevailing among others. Their working principle is as follows: one part $\mathbf{F_c}$ of gas flow **F** is saturated with anesthetic vapor in the vapor chamber to an equilibrium $\mathbf{C_S = P_A/P}$ ($\mathbf{P_A}$ is the partial pressure of the saturated vapor pressure (SVP) – Table 1, **P** is atmospheric pressure) and diluted by the second (bypass) part $\mathbf{F_b = F - F_c}$ to a given concentration **[14]**

$$\mathbf{C = [1+ (P\ P_A^{-1} – 1)\ F\ F_c^{-1}]^{-1}} \qquad \mathbf{(1)}$$

There are two main conditions of vaporizer stability:

1 - Equilibrium saturation of gas flow through the chamber with anesthetic vapors up to $\mathbf{C_S = P_A/P}$

2 - Constant splitting ratio of gas flow through the vaporizer $\mathbf{F/F_c}$.

That is, the output concentration **C** is stable (constant) when the relative variables $\mathbf{P_A/P}$ and $\mathbf{F/F_c}$ are also constant.

Constant splitting ratio $\mathbf{F_c/F}$ would mean identical flow regime in the bypass and the vapor channels. In a low-resistance vaporizer this takes place only in laminar flow.

The equilibrium concentration of the least volatile anesthetic, Sevoflurane, is more than 20 vol.% (MAC - minimum alveolar concentration in oxygen is only 2.05 vol.%) at standard conditions (20^{o}C and 760 mmHg); the equilibrium concentration of the most volatile Isoflurane and Halothane is more than 30 vol.% (MAC values are respectively 1.15 and 0.75 vol.%, see Table 2).

In a number of high-resistance vaporizers, a liquid anesthetic is dosed into the carrier gas stream (for example, by using a suitable syringe and vapor chamber). In this case, there must be a directly proportional relationship between the supply of a liquid anesthetic and the consumption of the carrier gas, which is usually carried out using an anesthetic gas analyzer and a computer control system.

If equilibrium saturation of the entire carrier gas flow is used, the outlet anesthetic concentration in such vaporizers is conveniently represented as the ratio of the saturated vapor pressure of the anesthetic (SPV) to the total pressure $\mathbf{C_S = P_A/P}$.

Table 2

Physical properties of modern inhalation anesthetics

	*S	I	H	E
Molecular mass, g/mol	200	184	197	184
Density, r/ml	1,52	1,5	1,87	1,52
Boiling point, ^{o}C	58,5	48,5	50,2	56,5
SPV, mm Hg at 20 ^{o}C	157	238	243	175
Equilibrium concentration $\mathbf{C_S}$, vol.%	20,6	31,3	32	23
MAC in 100% O_2	2,05	1,15	0,75	1,8
MAC in 70% N_2O	0,66	0,56	0,29	0,57
Biotransformation, %	3 - 5	0,2	20	2
Refractive Power, $(n-1)10^6$ at 0 ^{o}C **[15]**	1538	1566	1606	1544

*S - Sevoflurane, I - Isoflurane, H - Halothane, E – Enflurane

The saturated vapor pressure (SPV) is regulated either by change in temperature (it is necessary to cool below 50 °C) or using solid or liquid sorbents (anesthesia station PhysioFlex) **[16]**.

A special vaporizer was developed with a function of regulating anesthetic concentration by changing the total pressure **P** (tens of atmospheres) in a thermo-stabilized vapor chamber.

Accurate plenum vaporizers cannot be considered ideal for a number of parameters: mass and dimensions, efficiency, universality of gas supply (Table 3).

Table 3

Comparative data of anesthetic vaporizers

Data	Drager Vapor 2000	Penlon UK		USSR	
		Delta	OMV	Anestezist-1	Anestezist-2
Dial setting range,vol.% H & I	0 - 6	0 - 6	0 - 4	0-5 (20 Ether)	0-5 (20 Ether)
Gas flow range, L/min	0,25 – 15	0,2 –15	4 - 8	1 - 10	2 - 15
Temperature range, C	10 – 40	15 – 35	18 - 22	15 - 30	10 - 30
Anesthetic volume, mL	360	250	50	100	100
Wick volume, mL	60	60	10	0	10
Pressure drop at 10 L/min, mm H_2O	1100	1000	<10	300	<10
Angle of tilt, degrees	30	10	30	10	30
Mass, kg	6,5 – 8,5	5,7	1,3	6	3,2

On the other hand, unstable low-resistance draw-over vaporizers are more effective in anesthetic vapor delivery, since the entire breathing mixture passes through the vaporizer (and not only a low oxygen flow). These vaporizers with a conventional control dial concentration were popular more than 50 years ago, however now they have limited distribution in military field conditions and remote areas, where simplicity of design and independence from compressed gases sources (O_2 cylinders and concentrators) is more important than their instability.

The difficulty in designing low-resistance vaporizers lies in the rational use of its limited resistance for stable division of the carrier gas stream. At the same time, it is necessary to minimize the factors that disrupt the ordered laminar flow and, consequently, splitting ratio $\mathbf{F/F_c}$.

Thus, the best low-resistance vaporizer "OMV" (Table 2, Attachment 10.3) practically stops working with a carrier gas flow of less than 3 L/min. In this case its output anesthetic concentration drops to zero. Another draw-over vaporizer "Ohmeda PAC" has a similar disadvantage.

To determine the cause of this typical drawback, it is not necessary to consider in detail the design and construction of such vaporizers. It is enough to look at the location of the control valve **[17]** in relation to the vapor chamber (approximately 50-70 mm higher in a vertical position, **Fig.1**) and recall the density difference of carrier gas and anesthetic vapor (density of SPV mixture, for example, of Isoflurane is almost three times greater). At low flow rates 1-2 L/min, the vaporizer resistance (control valve) drops to 1 Pa, which is comparable to the pressure drop due to the density difference of carrier gas and anesthetic vapor. Therefore, the gas simply cannot enter the vapor chamber (squeeze out heavy anesthetic vapor) and accordingly the anesthetic vapor does not enter the patient's breathing circuit.

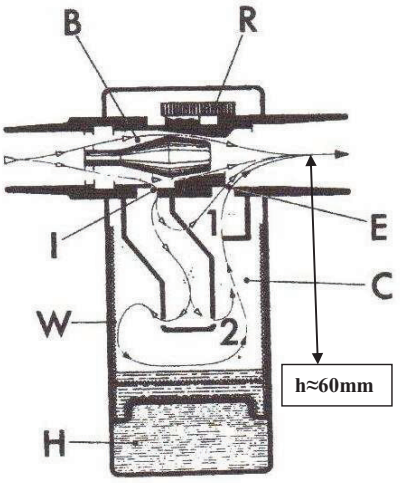


Fig. 7-56. Cross section of the Tri-Service draw-over vaporizer, which is used by the British armed forces. Air enters the vaporizer and a portion of the stream goes into the vaporizing chamber (C) through the inlet of the vapor chamber opening controlled by a sliding valve (R). The remainder of the air stream enters the bypass passage (B). Wicks (W) of stainless steel mesh increase the evaporation surface area inside the vaporizing chamber. A heat reservoir (H) filled with antifreeze liquid compensates for temperature changes. Air and anesthetic vapor pass out the vaporizing chamber outlet (E) to mix with the air coming through the bypass passage. Two different paths (1 and 2) through the vaporizing chamber provide a method of temperature and flow compensation. Photograph: Printed with permission of Penlon, Ltd, Abingdon, England.

W. CLAYTON PETTY. MILITARY ANESTHESIA MACHINES.
Chapter 7. Anesthesia and Perioperative Care of the Combat Casualty.
www.bordeninstitute.army.com.mil

Fig. 1. Penlon Oxford Miniature Vaporizer (OMV)

2. VAPORIZER PHYSICS

In Chapter 2 (equation **1**) two main factors of vaporizer stability are formulated:

1 - Equilibrium saturation of gas flow through the chamber with anesthetic vapors up to $\mathbf{C_S = P_A/P}$

2 - Constant splitting ratio of gas flow through the vaporizer $\mathbf{F/F_e}$.

An additional condition of stability in connection with the change of ambient temperature and atmospheric pressure is the temperature and pressure compensation of the outlet anesthetic concentration.

Constant splitting ratio $\mathbf{F_e/F}$ in a low-resistance vaporizer takes place only in laminar flows through the vapor chamber and bypass.

Indeed, a limited resistance range (up to 10 mm H_2O) is used more rationally [**14**]. This is so, because under laminar flow conditions, resistance or pressure drop is proportional to the flow rate, while under turbulent flow conditions it increases as the square of the flow rate. There is in a draw-over vaporizer the gas flow during inspiration instantly rises from zero to a maximum (about three times a minute ventilation with the inspiration and expiration ratio I:E = 1:2) and vice versa. Obviously, “the flow through either the bypass or the vaporizing channels should not change from laminar to turbulent (or vice-versa) at any point within the operating range of the vaporizer. If that did occur there would be a large and abrupt change in the calibration curve at that point” **[18]**.

Nevertheless, well-known draw-over vaporizers (Goldman, OMV, Ohmeda PAC and others) work just at non-stable *transient* flow mode and therefore cannot deliver stable anesthetic concentration at low gas flows.

Design Difficulties with Low-Resistance Vaporizers

Ensuring constant splitting ratio $\mathbf{F_e/F}$ in low resistance vaporizers is much more difficult than in plenum vaporizers. First, the resistance of the draw-over control valves is about two orders of magnitude less (100 times), that is why at small flow rates (below 3 L/min), their control effect is comparable with the effect of

disturbance factors which are of small importance for the plenum vaporizers. Second, the instant velocity, as noted above, varies in a wider range (from zero to maximum) in a draw-over vaporizer and further destabilize the splitting ratio, especially when there are considerable geometrical differences between the bypass and vapor channels (length, volume, configuration).

Example 2. *Consider dependence of outlet Isoflurane concentration on the total gas flow rate in the Goldman type vaporizer where:*
- turbulent gas flow through the bypass channel has a rate from 3 to 12 L/min and square-law dependence of pressure drop on the flow rate: $\Delta p_b = k_b F_b^2$, *where* $k_b = 0.011\ Pa.min^2 L^{-2}$ ***[18, 19]***;
- transient flow through the vapor channel has rate below 3 L/min and pressure drop $\Delta p_c = k_c F_c^n$, *where, in first approximation* $k_c \approx 3.8\ Pa.min^{1.5} L^{-1.5}$ *and the exponent is* $n = 1.5$;
- the vaporizing chamber delivers saturated Isoflurane vapors with concentration $C_c = p_a p^{-1} = 0.31$ *or 31 vol. % (20°C, 760 mm Hg).*
The delivered concentration from such vaporizer may be calculated using the formula **(1)** $C = [1 + (p\, p_a^{-1} - 1)\, F\, F_c^{-1}]^{-1}$.

The calculation results are:

Bypass flow F_b, *L/min*	*3*	*6*	*12*
Pressure drop of the bypass or chamber channels, Pa	*0.1*	*0.4*	*1.6*
Chamber flow F_c, *L/min*	*0.09*	*0.22*	*0.56*
Splitting ratio $F\, F_c^{-1}$	*35.1*	*28.3*	*22.4*
Outlet concentration C, *vol.%*	*1.3*	*1.6*	*2.0*

Thus, outlet concentration of the *Goldman* type vaporizer decreases approximately by 35% when gas flow rate decreases from 12 to 3 L/min because of **different flow regime** through bypass and chamber channels (the exponent of pressure drop in the bypass channel is **n** = **2**, while the chamber exponent is **n** = **1.5**).

An additional fall of concentration can appear because of decreasing *mass transfer* in the vapor chamber. In that case, laminar stream of carrier gas passes strait from chamber inlet to outlet openings aside of evaporating surfaces and the very low rate of diffusion of agent vapor across the local streamlines above the liquid surface being a determining factor in the *Goldman* type vaporizer **[18]**.

Different density of carrier gas and anesthetic vapors is another disturbance factor for the draw-over vaporizers. At low flow rates of the carrier gas, say below 2 L/min, the pressure drop of the control valves is very low and comparable to the weight difference between the carrier gas and the anesthetic vapors.

Example 3. *Evaluate outlet halothane concentration of Oxford Miniature type Vaporizer (OMV) at low flow rate. The vaporizer resistance is* $\Delta p = k_c \cdot F_c^n$ *where* $k_c \approx 0.8$ *and* $n \approx 1.5$ *are experimental coefficients.*

If the vaporizer pressure drop is $\Delta p = 100$ *Pa at 25 L/min (approximately equals to the bypass drop or the chamber drop), then* $\Delta p = 2.3$ *Pa at 2 L/min.*

Due to the pressure differential, part of carrier gas flow passes through the vapor chamber. However the liquid anesthetic level is lower than the bypass axes by $h \approx 60$ *mm* ***(Fig. 1)*** *and there is a negative chamber pressure drop that is proportional to density difference of the carrier gas and the anesthetic (halothane) mixture:*

$\Delta p_d \approx (\rho - \rho_d) \cdot g \cdot h = (1.21 - 3.45)\ [kg/m^3]\ 9.8\ [m/s^2]\ 0.06\ [m] = -1.3$ *Pa.*

Thus, the actual chamber pressure differential is $\Delta p_c = \Delta p - \Delta p_d \approx 2.3 - 1.3 = 1$ *Pa, or about* ***40%*** *of the vaporizer pressure drop. Accordingly, the chamber gas flow rate* F_c *and the outlet vaporizer concentration decrease, as follows from equation* ***(1)****. For example, at the dial setting* ***1%,*** *the outlet concentration will be only about* ***0.4%,*** *and at* ***3%*** *- only* ***1.2%****.*

This drop of concentration because of density non-uniformity is typical for *OMV, Ohmeda PAC* and *Goldman* vaporizers. The less is the gas flow through the vaporizer, the more of flow pressure differential is spent on the density pressure drop. In the **Example 3**, when carrier gas flow is ≈1.5 L/min, the output concentration drops to zero!

Achievement of **equilibrium saturation** of gas flow through the vapor chamber should not interfere with the constant **splitting ratio**. However, the chambers of the well-known *Vapor, TEC* or *PPV Sigma* vaporizers (long, deep, with sharp turns) are not suitable for low resistance vaporizers due to differences in geometry with respect to bypass (short and direct). In the case of high-resistance (plenum) vaporizers, these differences do not stand out due to the insignificant relative resistance of the vapor chamber.
Only two traditional draw-over vaporizers “Cato Halothane” (Drager) and “Anestezist-2” (Table 2) had a stable outlet concentration at continuous (from 2 to 10/min) and intermittent gas flows, however “Cato Halothane” weighs 14.5 kg (4 times heavier than “Anestezist-2”).

The effect of the density difference in the anesthetic vapor and carrier gas on the outlet concentration is proportional to the height **h** of the bypass above the liquid anesthetic level $\mathbf{\Delta p_d \approx h (\rho - \rho_a) \bullet g \bullet h}$. When the height **h** decreases, the influence of this destabilizing factor goes down proportionally.

A method for stabilization of an anesthetic concentration at the vaporizer outlet is provided, comprising dividing the total gas flow by means of laminar hydro-mechanical resistances, saturation of the one gas part passing through a vapor chamber with anesthetic vapor, then diluting to a predetermined concentration with the second gas part passing through the bypass. In case of increasing the outlet concentration at small total gas flow, ***the level of the bypass relative to the vapor chamber is to be raised or to be lowered in the opposite case [20]****.*

According to this patent RU 2329832, the concentration control valves are installed horizontally inside the vapor chamber. This minimizes the height **h** of the bypass above the liquid anesthetic level and decreases the destabilizing effect of the density difference in the anesthetic vapor and carrier gas on the outlet anesthetic concentration.When designing the “MINIVAP” vaporizers, the optimum height **h** of the bypass is determined experimentally.

The general formula **(1)** is specified depending on the type of the concentration setting dial (control valve system of the chamber and bypass lines) and the gas flow mode.

For example, in "Anestezist-1"vaporizer turbulent mode is realized due to the use of calibrated orifices- watch stones. Thus, the output anesthetic concentration, depending on the size of the concentration control dial setting (the ratio of bypass and the chamber hole diameters $\mathbf{d_b/d_c}$), physical properties of the anesthetic and carrier gas, temperature and pressure,

$$\mathbf{C = P_A/P\ [1+(d_b/d_c)^2\ \rho_m^{0,5}\ ]^{-1}} \qquad \mathbf{(2)}$$

where $\boldsymbol{\rho_m}$- relative density of the vapor-gas mixture and carrier gas.

For laminar valves (well streamlined, for example, cone and slot), formula (**1**) can be represented as follows (for vaporizers "Anestezist-2" and "Vapor"):

$$\mathbf{C = P_A/P\ [1+(R_b^2 - r_b^2)(R_b - r_b)R_bL_c\mu_m/(R_c^2 - r_c^2)(R_c - r_c)R_cL_b]^{-1}} \qquad \mathbf{(3)}$$

where $\mathbf{R_b, r_b, R_c, r_c}$– external and internal radii of conical valves on the bypass and the vapor chamber lines; $\mathbf{L_c, L_b}$ - the length of the corresponding valves; $\boldsymbol{\mu_m}$ - the relative dynamic viscosity of the vapor-gas mixture and carrier gas.

The higher the resistance of the vaporizer, the smaller the error of the ratios **(2)**, **(3)**. So, for the high resistance "Anestezist-1" vaporizer (about 3 kPa at 10 L/min), the calculated error is about 10% of the dial setting range. These formulas are useful in designing and using vaporizers under non-standard conditions (in hyperbaric chamber, at high altitude, at low or elevated temperature, for various anesthetics and gas mixtures).

Backpressure ("pumping effect of back pressure")

The vaporizer output concentration at pressure pulsation during artificial ventilation can be significantly higher than without it. This pressure pulsation difference $\mathbf{\Delta C_{pp}}$ is the larger, the larger the vaporizer volume **V**, the higher the pulsation frequency **f** and the amplitude $\mathbf{P_I}$, the smaller the carrier gas flow **F [19]**

$$\mathbf{\Delta C_{pp} \approx V\ f\ P_I\ (P_A - P\ C)\ F^{-1}\ (1-C)^{-1}\ P^{-2}} \qquad \mathbf{(4)}$$

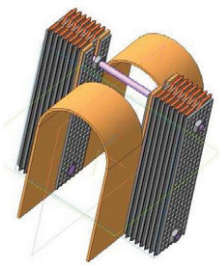
where $\mathbf{P_A}$= SPV(Table 2), **P -** atmospheric pressure.

Example 4. *Let's compare the difference* $\boldsymbol{\Delta C_{pp}}$ *of the vaporizers "MINIVAP-20/I" and "OMV" (vaporizer volumes about 0.1L and 0.25L) at the standard frequency* $\boldsymbol{f}$*=15* $^{-1}$*, amplitude* $\boldsymbol{P_I}$*=30 cm of* H_2O *and flow* $\boldsymbol{F}$ *= 1 L/min on the dial setting* $\boldsymbol{C}$ *= 1.5% vol of Isoflurane (0.015).*

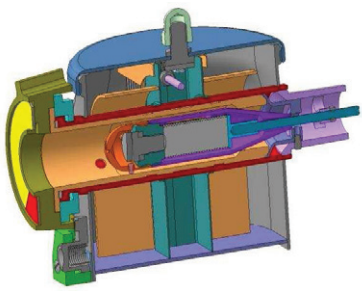
In the first vaporizer, according to formula **(4)** $\boldsymbol{\Delta C_{pp}} \approx 0{,}7\%$ *vol., in the second - twice as much as the vaporizer volumes.*

3. LOW RESISTANCE VAPORIZERS “MINIVAP”

It is in the laminar regime with minimal energy costs (resistance to gas flow) that efficient schemes of dividing the carrier gas stream and its equilibrium saturation with anesthetic vapors can be organized, in analogy with living systems. In an ideal scheme, the gas flow occurs both in the airway of a person and mass exchange - as in the gills of fish **[21, 22, 24]**.



a



b

Fig. 2. Vaporizer “MINIVAP-20/I”

Evaporative elements **- a** in the form of plates of porous metal (fine mesh) are located on both sides of the concentration control - **b**, on the axis of which there is a drop-shaped thermobarocompensator with a nickel or bronze mini-bellows (USA) filled with a low-boiling liquid

*The vaporizer “MINIVAP-20/I” (**Fig. 2**) contains a chamber with a set of vertically arranged evaporative elements from the capillary material and a horizontally located concentration control in the form of a rotary tubular slide valve with a concentration setting dial, slot channels on its outer surface opposite the inlet and outlet chamber openings. Inside the concentration control there is a bellows with a longitudinally movable fairing at the inlet and a cone at the outlet of the vaporizer.*

*The vaporizer is equipped with an additional valve in the form of a confuser made in the shape of a bellows cone and mounted with the possibility of longitudinal displacement, depending on the angle of the rotary tubular slide valve rotation **[22]**. The vapor chamber is provided with input and output arched boxes with side walls and an end wall, covered inside and outside with a capillary material.*

The conjugate surfaces of the tubular slide and additional valves are made in the form of a threaded pair (left thread) that converts the dial rotation counterclockwise from zero to maximum into the translational displacement of the confuser relative to the cone. The capillary material is made in the form of a fine mesh (cell size of about 50 microns, diameter of stainless or brass wire of about 30 microns) or porous stainless plates (pore size of about 10 microns) connected to the carcass of evaporating elements, boxes and inner walls of the chamber by vertical joints 5-10 mm with the formation of an optimum gaps of about 0.1 mm for the maximum supply of a liquid anesthetic to the evaporation surface. Joints can be made mechanically (rivets or wire clips), by means of condensation welding or soldering.

The liquid anesthetic enters the evaporation surfaces through the wall slot gaps of the carcass (more than 95% of the total flow) and the capillaries of the material due to surface tension forces. In this case, vertical joints ensure a tight fit of the capillary material to the "warm" carcass of the evaporation elements, ensuring maximum delivery of the liquid anesthetic to the evaporation surface.

The anesthetic vaporizer works as follows.

The carrier gas stream (oxygen + nitrous oxide, or oxygen + xenon, or atmospheric air) enters the vaporizer and is then divided into two parts according to the required anesthetic concentration. The first part of the gas enters the inlet chamber, spreads along parallel channels between the evaporative elements and is saturated to the equilibrium concentration. Then passes to the vaporizer outlet, where it is diluted to the required clinical concentration by the second part of the gas bypassing the vapor chamber (through the bypass).

In addition to the main dependencies **(1-3)**, we briefly consider the processes of mass and heat transfer in a few simple cases.

Mass transfer, or evaporation of an anesthetic into a carrier gas stream

Relative concentration **C** of the anesthetic in the laminar flow of carrier gas **[23]**

$$\mathbf{Ln\ (1- C)^{-1} = 1{,}75\ \pi\ (D_a L\ F^{-1})^{2/3}} \qquad \mathbf{(5)}$$

where $\mathbf{D_a}$ is the diffusion coefficient of the anesthetic vapor in the carrier gas, **L** is the path length.

Example 5. *We estimate the outlet concentration of anesthetic (halothane) in the air flow passing through the vapor chamber. The chamber has* $\boldsymbol{N}$ *= 18 parallel rectangular channels (length* $\boldsymbol{L}$ *= 15 mm, width* $\boldsymbol{b}$ *= 1 mm and height* $\boldsymbol{H}$ *= 30 mm) formed by plates of capillary metal (porous or mesh,* ***Fig. 2a****), air flow* $\boldsymbol{F}$*=2 L/min, or 33.4* cm^3/s *at a temperature t = 20 °C;* $\boldsymbol{D_a}$ *= 0.066* cm^2/s.
We obtain from **(5)** $\boldsymbol{C}$ *= 0.28 (28% vol.) or 87% of the equilibrium concentration (*$\boldsymbol{C_S}$ *= 0.32) at 20 °C.*
The concentration was measured by the Riken FI-21 anesthetic vapor indicator (dial setting range 0-6 vol%, accuracy ± 3%) with 5-fold dilution of the vapor-gas mixture, the air flow rate was measured with flowmeters with an accuracy of ± 3%.

Heat transfer

The necessary heat transfer is determined by the flow rate of the liquid anesthetic, which evaporates into the carrier gas stream. The anesthetic consumption during induction and maintenance of anesthesia is calculated from the ratio

$$\mathbf{V_A \approx k_A(C_1 F_1 \tau_1 + C_2 F_2 \tau_2)} \qquad \mathbf{(6)}$$

where for Sevoflurane, $\mathbf{k_S}$ = 0.055; for Isoflurane, $\mathbf{k_I}$ = 0.051; **F** - gas flow, $\boldsymbol{\tau_1}$, $\boldsymbol{\tau_2}$ - respectively duration of anesthesia induction and maintenance, min.

Example 6. *Induction with isoflurane at a concentration of* $\boldsymbol{C_1}$ *=5 vol% and an oxygen flow rate* $\boldsymbol{F_1}$*=6 L/min continued for* $\boldsymbol{\tau_1}$*=5 min and during the operation (*$\boldsymbol{\tau_2}$*=60 min) at the average concentration* $\boldsymbol{C_2}$*=1.5 vol% and oxygen flow* $\boldsymbol{F_2}$*=1.5 L/min.*
Then the total consumption of Isoflurane was, according to ratio ***(6)****, about 15 ml (7.7 + 6.9 = 14.6).*

Accordingly, the necessary heat flow for evaporation of the anesthetic during induction is about 10 W, while for anesthesia maintaining **-** 0.5 W.

On the other hand, there are 3 heat sources in the vaporizer: heat exchange with ambient air, heat capacity of the vaporizer itself and heat exchange with the carrier gas passing through the vaporizer.

The heat exchange with the ambient air of the "MINIVAP-20/I" vaporizer (the body size of about 60 mm, the mass of 400 g, **Fig. 3**, above) can be estimated at 0.5 W (natural convection with a temperature difference of 5 °C, the heat exchange surface is about 25 cm^2).

The use of the heat capacity of a vaporizer 0.4 kg with cooling at 5 °C for 2 min of induction gives about 10 W.

The heat exchange with the carrier gas at maximum flow rate of 6 L/min and temperature difference of 5 °C is about 1 W.

Thus, the estimated heat flow due to heat exchange with the surrounding atmosphere and with the gas passing through the vaporizer corresponds to the heat costs of the anesthetic evaporation during the low flow anesthesia of the average person in the maintenance regime.

When working at open and semi-open circuits for 15-30 minutes (an emergency, transportation of the patient) it is advisable to use an additional heat stabilizer or a more powerful vaporizer.

So, for the purpose of temperature stabilization, the mass of the first modification of “Vapor” was about 15 kg, with the vaporizers “Anestezist-1”, “Anestezist-2” and “OMV” (see Table 2) having a water (or antifreeze) shirt from 1 to 0.1 L, respectively.

It is interesting to note that the heat capacities of “Vapor” and “Anestezist-1” are equivalent despite more than double difference in mass, since the heat capacity of water is 10 times higher than the heat capacity of copper.

The “MINIVAP-20/S” vaporizer is 5 times more powerful than the “MINIVAP-20/I”, designed for patients with a mass up to 300 kg (**Fig. 3**, below).

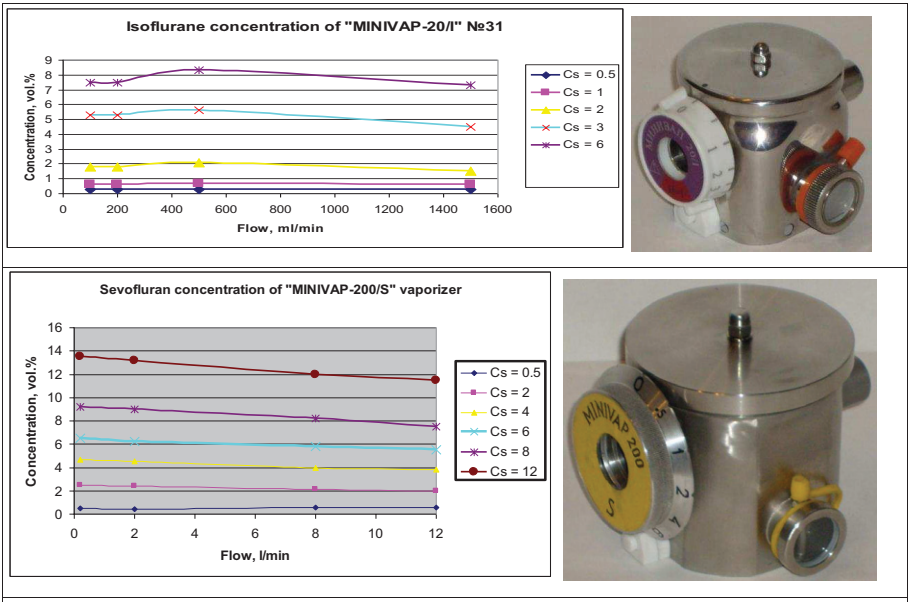
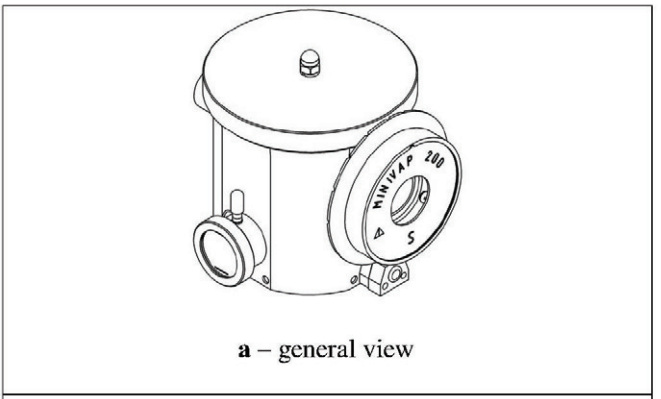


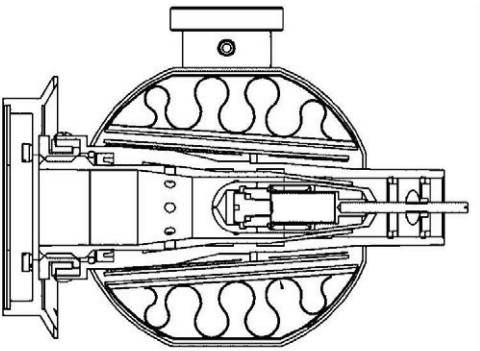
Fig. 3. Anesthetic vaporizers «MINIVAP-20/I» (above) & «MINIVAP-20/S»

The "MINIVAP-20/S" vaporizer ***[24]*** *contains an anesthetic chamber with evaporation elements and a heat stabilizer, a concentration control located therein with a concentration dial in the form of longitudinally movable, by means of a threaded pair, a tubular slide valve with a two-sided tapered tip that cooperates with the conical seat around it at the chamber outlet and the conical core obturator (****Fig. 4****). The concentration control is provided with a conical valve at the entrance of the chamber in the form of the second obturator on the outer wall of the slide valve and the seat surrounding it on the inner wall of the chamber is set horizontally.*

The evaporation elements are made in the form of the inner walls of the chamber in the form of vertical cylinders with a streamlined profile, covered from the outside with a capillary material in the form of a fine mesh net or a porous metal and filled with a thermostabilizing liquid. They are equipped from the inside with heat-conducting fins, symmetrically placed on both sides of the concentration control with the formation of parallel slot channels.



a – general view



a – longitudinal section

Fig. 4. Vaporizer «MINIVAP-20/S»

The chamber is equipped with a box, covered inside and outside with a capillary material and installed above the concentration control, with the chamber inlet and outlet separated by a partition and communicated respectively with the inlets and outlets of parallel slot channels.

The concentration control elements are made in the form of streamlined bodies of revolution, its axis is located at the same distance from the chamber cover and the

middle level of the anesthetic, while the volumes of the concentration control and the chamber above the liquid anesthetic are commensurate with each other.
The passage through the slot channels of the anesthetic chamber is directly proportional to the distance between its inlet and outlet.
Paraffin is selected as a thermostabilizing liquid, with a solidification temperature of 18 °C, that is, above the lower limit of the operating temperatures of the vaporizer.
The quantity (volume) of liquid paraffin is chosen on the basis of the vaporizer maximum output and anesthesia induction time (about 150 ml, which is equivalent to 5 liters of water when the temperature is changed by 1 °C).
The anesthetic vaporizer works as follows.
Gas from an external high source (cylinders) or low pressure (oxygenator, ventilator with manual or mechanical drive, patient breathing effort) enters the vaporizer and is divided into two parts. The first part of the gas passes successively through the slide valve-controlled channels at the inlet and outlet of the chamber, the inner walls of the box and the slot channels, spreading a thin layer between the evaporation surfaces of the capillary material and saturating with anesthetic vapor to an equilibrium concentration (of the order of 20 and 30 vol.% for Sevoflurane and Isoflurane, respectively), and then diluted to the desired clinical concentration with a second portion of the gas that passes through the adjustable bypass channel between the conical core obturator and the inner side of the tip.
At the maximum concentration (for example, during the anesthesia induction), the control dial is turned counterclockwise, moving the slide valve to the extreme position, with the tip overlapping the bypass channel, while maximally opening the chamber inlet and outlet.
Heat to evaporation surfaces comes from the environment through the heat-conducting walls of the chamber and from the liquid paraffin in the cylinders. The average temperature in the chamber does not drop below 17 ° C at maximum concentration and gas flow, when paraffin cools and solidifies, releasing the amount of heat necessary for the evaporation of the anesthetic due to the phase transition (> 20 cal/g). In non-operating mode, the paraffin is melted again and heated to room

temperature by means of metal fins that transmit heat throughout the volume of frozen paraffin. With zero concentration, the second obturator and the tapered tip close the inlet and outlet of the chamber, respectively, and the entire gas flow passes through the bypass.

The liquid anesthetic flows to the evaporation surfaces through the slot gaps (of the order of 0.1 mm) between the capillary material and the metal walls of the cylinders and the chamber, and also through its (mesh or porous metal) capillaries due to surface tension forces.

When the gas flow rate is changed from 0.1 L/min (low-flow anesthesia of the hamster) to 20 L/min (horse), the constant splitting ratio of gas flow $\boldsymbol{F/F_c}$ *through the chamber and the bypass is maintained due to the similarity of their hydromechanical characteristics.*

The minimum chamber volume above the liquid anesthetic, comparable to the concentration control volume, excludes the effect of "back pressure" on the vaporizer output concentration during artificial ventilation.

Table 4

Technical Data of “MINIVAP” vaporizers

Parameters	«MB-20/I»	«MB-20/S»
Dial setting range, vol.%	0 - 6	0 - 10
Temperature range, ^{o}C	5 - 35	15 - 35
Atmospheric pressure, kPa	70 – 110[1)]	70 - 110
Gas flow range, L/min	0,2 - 10	0,2 - 15
Pressure drop at 10 L/min, mm H_2O	≈20	≈10
Anesthetic volume, mL	40	100
Wick volume, mL	3	5
Angle of tilt, degrees	180^{o}	90^{o}
Mass, kg	0,4	1,5
Input/Output	15F/15M	22F/22M

[1)]3 km above sea level

Technical characteristics of the anesthetic vaporizers “MINIVAP” are presented in Table. 4. From Tables 3 and 4 it is clear that the vaporizers “MINIVAP” are

comparable in outlet stability with the best plenum analogs, and for portability and economy at times exceed them. Wherein:

- the minimum gas flow through the “pocket” vaporizer “MINIVAP-20/I” is ten times smaller (0.1 instead of 3 liters per minute, respectively, wider operating range of gas flow) compared to the draw-over vaporizer “OMV”;
- the maximum concentration of “MINIVAP-20/S” is 1.5 times higher than that of plenum analogs.

4. PORTABLE ANESTHESIA MACHINES «COLIBRI»

a **b** **c**

Fig. 5. AM «Colibri» for emergency anesthesia:
a - vaporizer MV-20/I or MV-20/S with non-reversing valve and face-mask; **b** – "a" + Ambu bag; **c** – AM kit in handbag 250x150x100 mm; Mass: 1 kg with MV-20/I; 2 kg with MV-20/S

4.1. Open circuit. With spontaneous breathing the vaporizer inlet is opened, and the

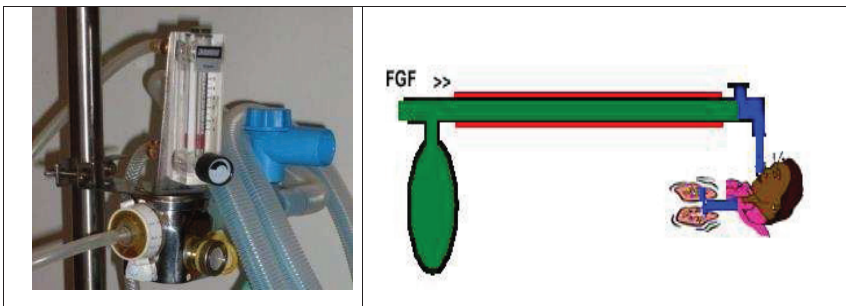


Fig. 6. AM «Colibri» with Mapleson A ciruit
(vaporizer MV-20/I or MV-20/S, flowmeter O_2). Mass: 1,5 / 2,5 kg

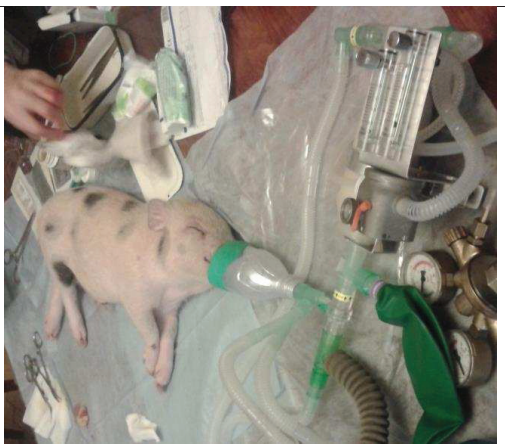
outlet is connected via a non-reversing valve and face-mask to the patient (**Fig. 5a**).

a **b** **c**

Fig. 7. Semi-closed circuit with **VOC:** **a** – AM «Colibri» with MB-20/I and absorber 300 ml, circuit Ø15 mm; **b** - AM «Colibri» with MB-20/S and absorber «Intersurgical», circuit 22 mm; **c** - vaporizer «MB-20/S» OUT of circuit of AM "MK-110", Japan

Inspire air is saturated with anesthetic vapor to the desired concentration, and the expire gas through the non-reversing valve nozzle withdrawn from the surgical field into the atmosphere.

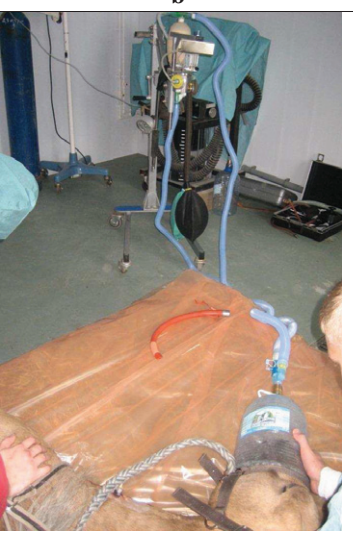
At manual ventilation Ambu bag is connected to the vaporizer inlet (**Fig. 5b**).



a

b

c



d

Fig. 8. Inhalation Anesthesia by Doctor of Veterinary Sciences Nechaev A.Yu.

AM «Colibri» VOC**: a, b, c** – vaporizer «MV-20/I», **d** - vaporizer «MV-20/S» (pony)

Semi-open "Mapleson A" breathing circuit (**Fig. 6**, is most effective during spontaneous breathing) is connected to the vaporizer outlet, while its inlet is connected to the outlet of oxygen flowmeter.

During expiration deadspace gas flows together with the oxygen in the breathing bag and alveolar gas with a high CO_2 content is vented through the safety valve (located at the mask) into the atmosphere. If you set the oxygen flow one third less minute ventilation of the patient and adjust the safety valve to periodical filling and emptying the breathing bag without its inflating or sticking, it is possible to *save up to one third of oxygen and anesthetic.*

4.2. AM "Colibri" Semi-closed circuit with VOC (Vaporizer **OUT** of Circuit).

Expired gas portion is returned to the circuit and cleaned in a sterilizable absorber (**Fig. 7a**) or in the Clear-Flo "Intersurgical" absorber (**Fig. 7b**), and then inhaled by the patient together with the fresh gas mixture.

To install "MINIVAP" vaporizer **OUT** of any **other AM or Ventilator** breathing circuit, the vaporizer input and output are to be connected to the gas flowmeters and the breathing circuit of the ones, respectively (**Fig. 7c**).

Inspired anesthetic concentration over time is approaching the vaporizer dial setting concentration $\mathbf{C_I \rightarrow C_V}$.

4.3. Semi-closed circuit with **VIC** (Vaporizer **IN** Circuit)

In this case, the entire respiratory mixture passes through the vaporizer with maximum anesthetic flow in the AM breathing circuit.

The inspired concentration, depending on the ratio of oxygen supply and minute ventilation $\mathbf{F_{O2}/MV}$(without taking into account the absorption of anesthetic by the patient's body), is set at the level

$$\mathbf{C_I \approx C_V\, MV(1 - C_{as}) / F_{O2}} \qquad \mathbf{(7)}$$

where $\mathbf{C_V}$ – vaporizer dial setting, $\mathbf{C_{as}}$ – equilibrium concentration.

This ratio is observed at small and medium anesthetic concentrations, but at higher concentrations a more complicated formula, taking into account the concentration gradient ($\mathbf{C_{as}-C_I}$) in the vapor chamber (curves in **Fig. 10**)

$$C_I = C_V / [(C_V/C_{as}) + F_{O2}(1-C_V) / MV(1-C_{as})] \quad (8)$$

a

b

Fig. 9 - Vaporizer «MINIVAP-20» ("Pocket") **VIC**
a – AM «Julian» (left, below - «MV-20», above – «Vapor 2000»); **b** - AM «MK-110»

The inspired concentration can be **much higher** than that on the vaporizer concentration control dial $\mathbf{C_V}$ at low (relative to minute ventilation **MV**) oxygen flow $\mathbf{F_{O2}}$. Thus, at an oxygen flow rate $\mathbf{F_{O2}}$ = 1 L/min and a minute ventilation **MV** = 5 L/min, the inspired concentration $\mathbf{C_I} \approx$ 10 vol. %! at the control dial setting $\mathbf{C_V}$= 5.

***Example** 7* **[12].** *A 5-year-old child (20 kg) will have to undergo a planned adenotomy under balanced endotracheal general anesthesia. After an anesthesia induction (N_2O/O_2 =2: 1 + halothane) with the high gas flow (6.0 L/min), the tracheal intubation was performed, after which the child was transferred to artificial ventilation (V_{Tin}=0.16 L, f =17 min^{-1}, **MV** = 2.7 L/min). The anesthesia maintenance: (N_2O / O_2=2: 1 + Halothane 0.8 vol.%) with the low gas flow ($\mathbf{F_{O2}}$= 1.0 L/min), "MINIVAP"vaporizer is installed **IN** the breathing circuit (VIC). Based on the formula **(7)**, the inspire concentration $\mathbf{C_I}$= 0.8 vol.% Halothane was obtained at the control dial setting $\mathbf{C_V}$ = 0.8 / 2.7 = 0.3. If the anesthesia with a minimum gas flow ($\mathbf{F_{O2}}$= 0.5 L/min) was planned, the vaporizer control dial setting would be $\mathbf{C_V}$= 0.8x0.5 / 2.7 = 0.15.*

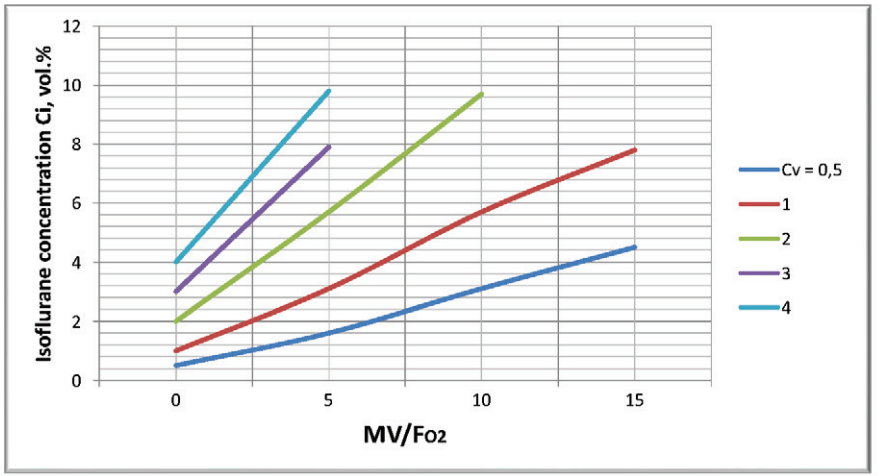


Fig. 10. Isoflurane inspired concentration $\mathbf{C_I}$ of AM «Colibri» **VIC**, depending on the ratio of the minute ventilation and oxygen flow $\mathbf{MV/F_{O2}}$

Thus, at minimal or low flow anesthesia in children, the "MINIVAP" vaporizer IN the circuit allows a much quicker achievement of the desired anesthesia depth compared to the standard VOC high-resistance vaporizers.

Liquid anesthetic consumption was evaluated by the difference of the vaporizer filling and draining anesthetic volumes at the start and end of the operation. The average consumption of Halothane during high flow anesthesia (6 L/min, 1vol%) was 20 ml/h. On the contrary, during low flow anesthesia (0.5 L/min, 1 vol.%), the average anesthetic consumption was only 5-7 ml/h and approximately half of these was consumed during anesthesia induction.
Moreover, anesthetic losses on "MINIVAP"vaporizer wicks are only 3-5 ml, against 60 ml of standard high-resistance ones - Table 2).

According to the results of long-term clinical trials, including the rapid switching of the "VIC/VOC" modes by means of a special tap-switch (in **Fig. 9a** it is between the "MINIVAP" vaporizer and the «Julian» inspired limb), Sidorov V.A., Doctor of Medical Science, suggested in his book [**3**, Table. 1.2] to classify the stabilized low-resistance vaporizers "MINIVAP" as "VIC/VOC".

ATTENTION: **Vaporizer IN the breathing circuit (VIC) requires an anesthetic Gas Analyzer and a highly skilled Anesthetist!**

4.4. AM "Colibri" VIC for small animals [25]

The distinctive feature of these devices (**Fig. 11**) is a rapid increase of the inspired anesthetic concentration due to the circulation of the respiratory mixture within the reversible breathing circuit, according to equations **(7)** or **(8)**.
Additional (to minute ventilation) gas circulation is added by the Ambu bag in the form of a mask (**Fig. 11b**). In this case, **to achieve the maximum inspired anesthetic concentration**, it is necessary to set the vaporizer control dial to maximum, close the safety valve and, with maximum frequency and amplitude, compress the Ambu bag attached to the patient.

a – with Ambu bag for air supply and the safety valve

b – with Ambu bag in the form of a mask, O_2 flowmeter and absorber (vertical Ambu)

Fig. 11. AM «Colibri» VIC for small animals (up to 3 kg)

Example 8. *If the Ambu bag (volume of 300 ml) is squeezed at a frequency of 10 cycles/min, the gas circulation through the vaporizer is about 2 l/min (0,2L x 10 min^{-1}), whereas the inspired concentration* $\boldsymbol{C_I}$ *reaches* ***8 vol.%*** *in the circuit (volume 1 liter) at the dial setting* $\boldsymbol{C_V}$ *= 4 vol.%, with* O_2 *flow 0.5 L/min through the flowmeter (**Fig. 11b**) according to equation **(8)** and **Fig. 10 (**$\boldsymbol{MV/F_{O2}}$ *≈4).*

The rate of change in the inspired anesthetic concentration $\Delta C_I/\Delta t$ (**Fig. 12** – the calculated curves without taking into account anesthetic uptake and elimination in a patient) depends on the concentration gradient $\Delta C = C_{as} - C_I$ in the stabilized vaporizer (its vapor chamber), the volume V_C of the breathing circuit, mixture circulation rate $F_C = MV$ and oxygen supply F_{O2} (or Air) to the circuit and is determined (at the initial time t = 0) by the relation

$$\Delta C_I/\Delta t = [C_V/(1-C_V)V_C]\ \{[(C_{as}-C_V)(1-C_{as})F_C/(1-C_V)C_{as}] - F_{O2}\} \qquad (9)$$

where C_V – vaporizer dial setting, C_{as} – concentration of anesthetic saturated vapors.

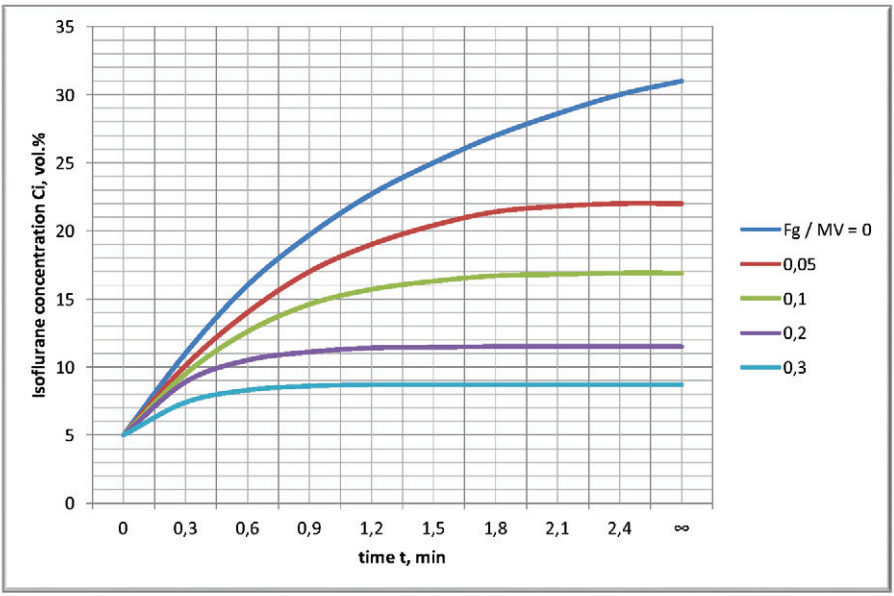


Fig. 12. Dynamics of Isoflurane inspired concentration in the AM «Colibri» VIC, depending on the ratio F_{O2}/MV ($C_V = 5$; $MV = F_C = \Delta V \times f = 6$ л/min, ΔV - Ambu bag volume change, L; f – frequency, min^{-1}; the circle volume is about 1 L)

Usually we need to additionally supply oxygen or air into the breathing circuit due to leakage of the connection mask to the patient-animal, even with a closed safety valve. At short-term operations with animals up to 3 kg in the reversible breathing circuit of AM "Colibri" without absorber (**Fig. 11a**), it is necessary to supply at least 200

ml/min of oxygen or air (squeeze the Ambu bag 300 ml 1 time/min) to prevent moderate hypercapnia and hypoxia (Pa CO_2 = 50 mmHg or 7% by volume), compare Table 15 page 85 **[26]**.

To **reduce** the inspired anesthetic concentration it is necessary to reduce the vaporizer control dial concentration and a gas circulation.
Example 9. *At control dial setting «1» inspired concentration in the previous example is about 2 vol. %. If we reduce the circulation rate up to 5 cycles/min (1 L/min), the inspired concentration will further decrease up 1,3 vol.%.*

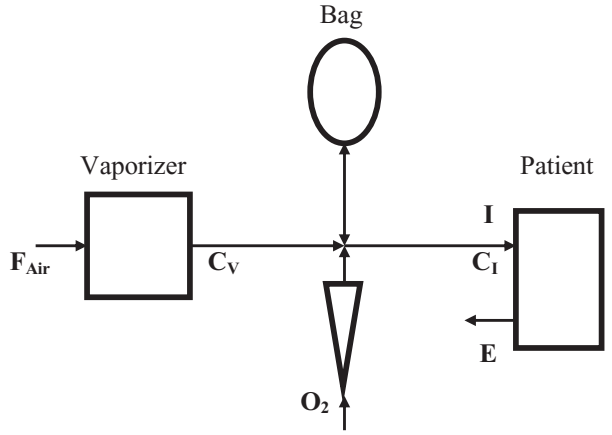
To **stop** the anesthetic supply, check the vaporizer concentration control is in the zero position, open the safety valve completely and blow the breathing circuit.

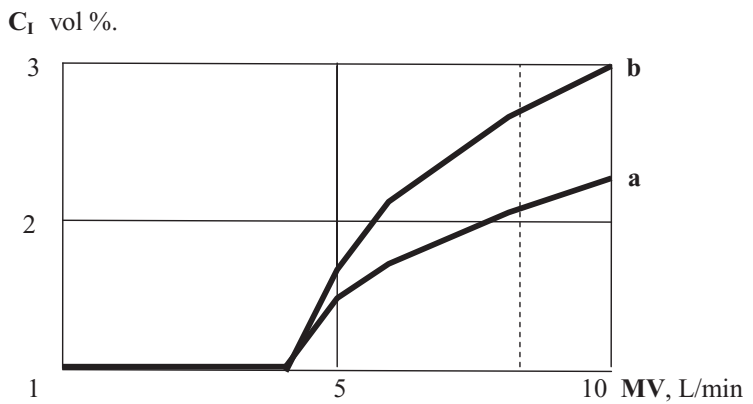
4.5. **Autoanalgesia**

Maintaining an adequate anesthesia depth, taking into account traumatic effects during surgical manipulations, requires the operative regulation of anesthetic inspire concentration. The complex PhysioFlexTM anesthesia station is ideal in time and concentration, solves this problem **[16]**, but its use in broad practice is unrealistic (the price of one device is more than $ 100,000).

At the same time, most surgical operations in dental, gynecological and veterinary are performed with spontaneous breathing, when **the patient's minute ventilation depends on the anesthesia depth and traumatic effects.**

Thus, minute ventilation (frequency and depth of breathing) reflexively increases if increase traumatic effects and a decrease in the depth of anesthesia (Isoflurane, Sevoflurane, Halothane), and vice versa: «If the plane of anesthesia becomes too light, respiration will be less depressed, minute volume will increase» **[28-30]**.





$$C_I = C_V (1 - F_{O2} / MV)$$

where $MV = F_{Air} + F_{O2}$, F_{O2} = 4 L/min, «a» C_v = 3 vol %. , «b» C_v = 5 vol. %.

Fig. 13. Auto Analgesia by AM «ANESTAT-Auto» during spontaneous breathing **[29]**

This relationship is used to easily and quickly regulate the inspired anesthetic concentration C_I when the draw-over vaporizer "Anesthesist-2" was installed OUT of the respiratory circuit (**Fig. 13**).

In accordance with the required anesthesia depth, the oxygen flow rate is set at a level of, for example, 60% of the initial minute ventilation of a patient, forcing him to suck

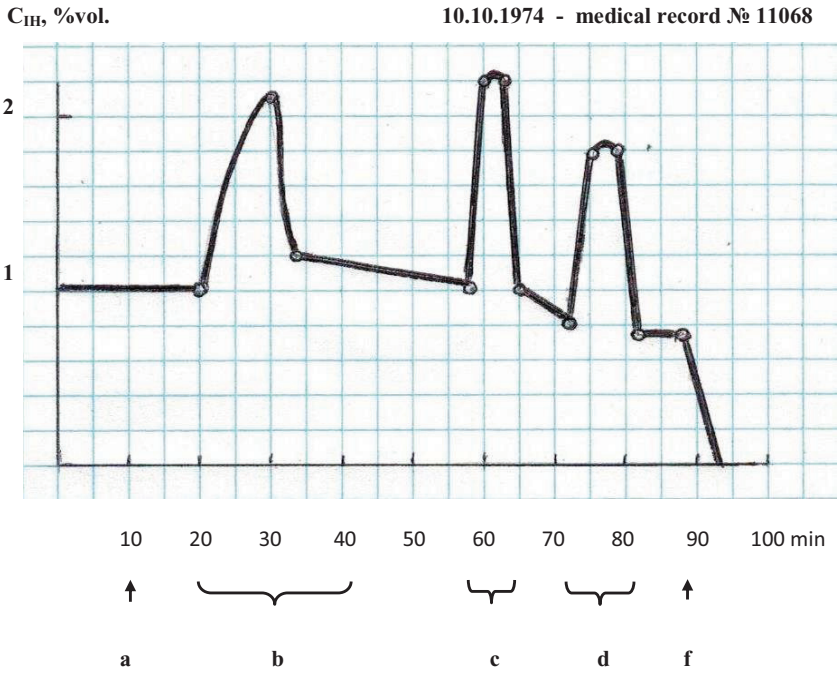


Fig.14. Self-regulation of Halothane inspired concentration C_{IH} during the surgical operation depending on spontaneous ventilation **MV**:
a - the beginning of the operation, **b** - drilling of the periosteum; **c, d** - the imposition of **Ilizarov's** apparatus and its regulation, **f** - the end of the operation

through the vaporizer atmospheric air with anesthetic vapor at a given concentration. When the required anesthesia depth is reached, the patient's minute ventilation is reduced, for example, by 20% of its initial value and automatically (reflexively) maintain an adequate inspired anesthetic concentration due to the excess of the current minute ventilation over the set oxygen flow rate. With insufficient anesthesia depth during surgical procedures, the inspired concentration is increased by a reflex increase in the patient's current minute ventilation. With excessive anesthesia depth, the patient's minute ventilation and inspired anesthetic concentration are reduced, respectively.

At the end of the operation, the oxygen flow is increased to the initial minute ventilation, disconnecting the vaporizer from the patient.
In this regulation scheme (**Fig. 13**), when the minute ventilation **MV** is below safe level, the patient inspires only pure oxygen.

Example 10*.Before starting anesthesia, the patient is supplied with the oxygen flow at 6 L/min equal to the initial minute ventilation* $\boldsymbol{MV_0}$*. After Halothane induction, the oxygen flow is reduced to 4 L/min (60-70% of* $\boldsymbol{MV_0}$*), the vaporizer control dial is set in the position "4" and the minute ventilation is reduced to 5-5.5 L/min, so that the patient sucks through the vaporizer ≈1.3 L/min atmospheric air with anesthetic vapor at a given concentration* $\boldsymbol{C_V = 4\ vol\ \%}$*, which is diluted with oxygen to an inspired concentration* $\boldsymbol{C_I}$*≈ 1 vol % (**Fig. 14**). During surgical intervention (periosteum drilling), the patient's ventilation reflexively increases to almost 9 L/min, so that the halothane inspired concentration increases to 2.2 vol %, respectively. Approximately one and a half minutes later, respiration depression (up to 5.5-6 L/min) comes as well as a corresponding decrease of the inspired concentration to 1-1.2 vol %. During the installation of the Ilizarov apparatus and its adjustment, the minute ventilation and the inspired concentration similarly increase. At the end of the operation, the oxygen flow is increased to the initial ventilation of 6 L/min and the vaporizer is disconnected from the patient. The operation lasted 68 min, anesthesia - 88 min.*
During the entire anesthesia, the oxygen supply was not lower than 4 L/min, which eliminated the possibility of an anesthetic overdose (the vaporizer is switched off when the patient's ventilation ***MV*** *is ≤4 L/ min).*

Similar self-regulation of the inspired concentration is obtained when the "MINIVAP" vaporizer is **IN** the breathing circuit (**VIC**, section **4.3**) and the anesthetic inspired concentration varies in proportion of the reflex change in a patient's minute ventilation, according to equation **(7)** $\boldsymbol{C_I \approx C_V\, MV(1 - C_{as}) / F_{O2}}$.

Example 11. *Magnetic Resonance Imaging (MRI) of the patient (8 year-old dog, 10 kg) with Isoflurane anesthesia. We set the inspired anesthetic concentration* $\boldsymbol{C_I}$ *= 1.5 vol % (1.2 MAC of Isoflurane), based on the oxygen flow* $\boldsymbol{F_{O2}}$ *= 0.2 L/min and spontaneous minute ventilation at rest* ***MV*** *= 1 L/min, setting the vaporizer control dial, according to the ratio* ***(7)****, in the position* $\boldsymbol{C_V}$ *= 1,5x0,2 / 1x (1-0,31) ≈ 0,5 vol%. At 15 min of MRI, the minute ventilation increased to* ***MV****=1.6 L/min and the inspired concentration increased by the ratio* ***(7)****, to* $\boldsymbol{C_I}$ *≈ 2.5 vol %. At 18 min of MRI, the anesthesia alveolar concentration and the depth increased with simultaneous reduction of spontaneous minute ventilation to the baseline level* ***MV*** *= 1L/min, so that the inspired concentration automatically decreased to a predetermined* $\boldsymbol{C_I}$ *≈ 1.5vol %.*

In this case, the feedback **"$C_I/C_V \leftrightarrow$ MV"** (control factor) in such a **VIC** circuit (**Fig. 11a**) will be significantly higher compared to the **VOC** circuit (**Fig.13**), namely **$MV(1-C_{as})/F_{O2} > 1-(F_{O2}/MV)$**. Thus, for the numerical values of the Example **11**, the left-hand side of the inequality is 1(1- 0.32)/0.2 = **3.4**, and the right-hand side is (1- 0.2) = **0.8**. However, this **VOC circuit** is **much, much safer** than **VIC circuit** for an anesthetic overdose!

In the considered self-regulation schemes, the apparatus duplicates an anesthetist action during anesthesia maintenance at spontaneous breathing of a patient. In any moment, the anesthetist can manually adjust the concentration on the vaporizer concentration control dial.

A similar self-regulation scheme was carried out at Northwick Park Hospital, UK **[30]**, however, a less efficient (in concentration) and less stable (in gas flow) Komesaroff vaporizer was used.

When using old draw-over halothane vaporizers with a large (≥ 1 L) vapor chamber, an overdose with a sharp deep breathing is very dangerous (a relatively large volume of gas mixture with a very high concentration comes to the patient) **[28]**. A high inspired concentration and subsequent overdose is possible even with low-efficiency

draw-over vaporizers **IN** semi-closed and closed breathing circuits with repeated circulation of exhaled anesthetic vapors.

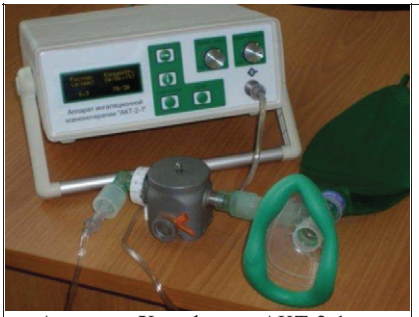
On the other hand, such popular draw-over vaporizers as OMV, Ohmeda PAC& Goldman will be ineffective and unpredictable **IN** breathing circuits of small patients with a minute ventilation ≤3 L/min due to their instability (see Examples **2, 3**).

5. COMBINED MACHINES

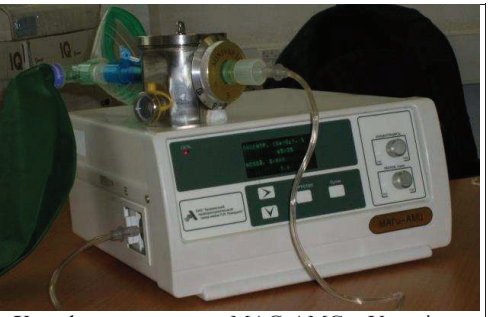
Due to the low resistance and virtual independence from gas flow rate, “MINIVAP” vaporizers are adaptable to any Source of medical gases (respiratory mixtures) and Automatic Ventilators **[35]**.

5.1. Combined anesthesia with “MINIVAP” vaporizers

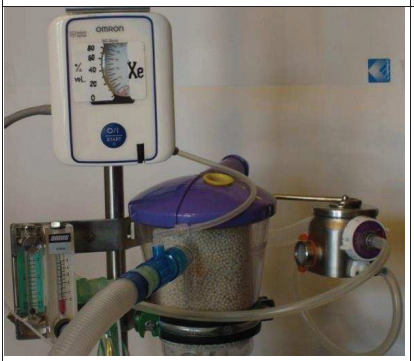
Variants of schemes and devices for combined xenon (Xe) anesthesia are given in Fig. **15 [33, 34,13]**.



Apparatus **Xe**notherapy AKT-2-1 + Vaporizer "MV-20/I" + Mapleson circuit



Xenotherapy apparatus MAG-AMC + Vaporizer “MINIVAP-20/S” + Mapleson circuit



AM “Colibri” with “Intersurgical” absorber and "MV-20/I" + **Xe** pneumo-electric Indicator (model)

AM Artec STEPHAN +“MINIVAP-20/I” OUT of **Xe** closed breathing circuit

Fig. 15. Complexes for combined Xe anesthesia

At the same time, pneumo-electric Indicator model of the **Xenon** binary mixture in oxygen was developed and investigated **[13],** which differs advantageously in speed and mass from the RU serial gas analyzer GKM-03-INSOVT.

Xe pneumo-electric Indicator (model), relative density **Xe/O_2** = 4,37:

- measuring range **Xe + O_2**	**0-80 vol.%**	**-** sample flow rate	**0,5 L/min**
- basic error	**10÷15 %**	**-** mass	≈ **300 g**
- stabilization time	≈ **5 s**	**-** dimensions	**150x100x80 mm**

Example 12*. Combined Xenon anesthesia with AM Artec STEPHAN with "MINIVAP-20/I" OUT of closed breathing circuit,* ***Fig. 15, [34]****.*
After induction and stabilization of the ratio Xe:O_2 = 70:30, when the inspired concentration of Xe decreased to 50-60% due to tissue desorption N_2, Isoflurane was delivered to the circuit (4 × τ = 2 min with oxygen flow F_{O2}= 0.25 L/min, vaporizer control dial C_I= 3%). The Isoflurane inspired concentration was maintained at 0.3-0.5 % and the exhaled concentration - at 0.25-0.4 %vol.
The consumption of liquid Isoflurane for 2 hours anesthesia (total τ= 8 min) from the ratio ***(6)*** *V_I =0.64 ml (1g) corresponds to the vaporizer mass difference of 1.2 g before and after anesthesia.*
Similar results were obtained when the "MINIVAP-20/I" vaporizer was IN the closed circuit of the AM "Xena-010"(RU).

By delivering small amounts of Isoflurane through the "MINIVAP-20/I" vaporizer into the closed breathing circuit (inspired and exhaled concentrations about 0.3vol.%, the total consumption of liquid Isoflurane is about 1 ml in 2 hours), the Xe consumption decreased by approximately 25% .

Fig. 16 shows a version of the anesthesia complex consisting of **"N_2O +O_2 MEDPROM" Gas Mixer** and the **"MINIVAP-20/I"** vaporizer connected to a semi-closed breathing circuit Ø15 mm with a sterilizable absorber 300/600 ml

(assembled at the request of the anesthetist-resuscitator A. Logunov, director of "AnestHelp" Ltd).

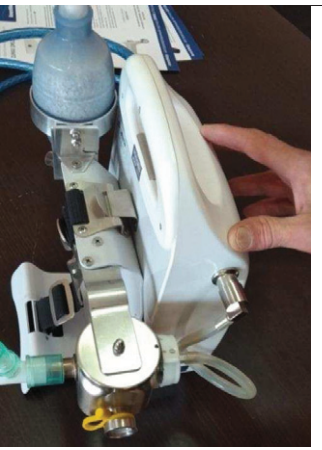


Fig. 16. "N_2O +O_2" MEDPROM Gas mixer with "MINIVAP-20/I" vaporizer and semi-closed breathing circle

5.2. Portable complex AM "Colibri" & Ventilator "SAVe"

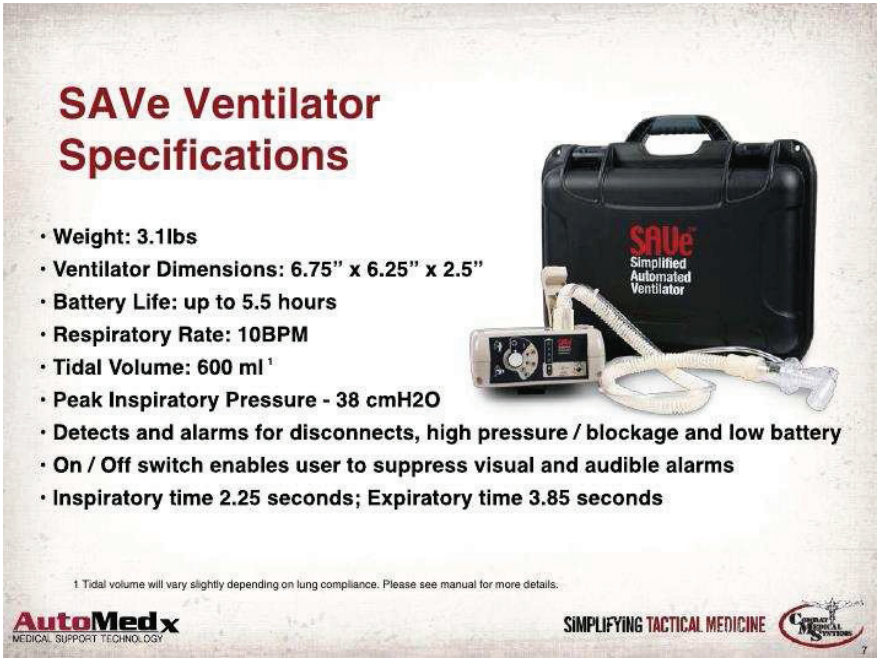
As a rule, it is necessary to use rather complicated Automatic Ventilators with a reversible breathing circuit to carry out automatic artificial ventilation during inhalation anesthesia, the cost of which is 5-10 times higher than the cost of portable AM. Simultaneously, simpler Automatic Ventilators for resuscitation and intensive care, which do not allow modern inhalation anesthesia because of the absence of a reversible breathing circuit (in these devices, the exhaled gas is released into the atmosphere), become wide spread.

The simple device - **"Bag in Vessel" [32]** connects two portable devises (the "SAVe" ventilator and the "MINIVAP" vaporizer) into an effective mini-complex for inhalation anesthesia and automatic ventilation in district hospitals and remote regions, as well as in emergency situations (military field conditions, natural and man-made disasters).

“MINIVAP” Vaporizer
(0,4 kg)
www.minivap.net

Ventilator SAVe (1,4 kg)
www.combatmedicalsystems.com
www.AutoMedX.biz

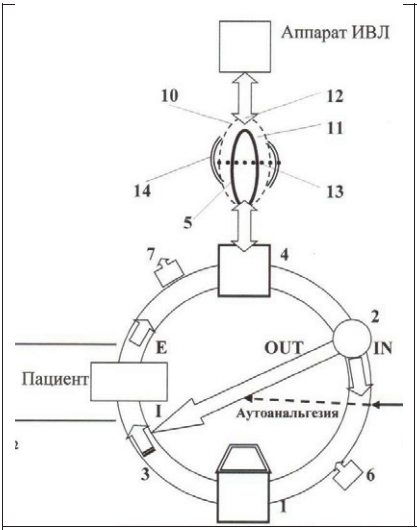
Fig. 17. Portable kit (virtual) for inhalation anesthesia and artificial respiration

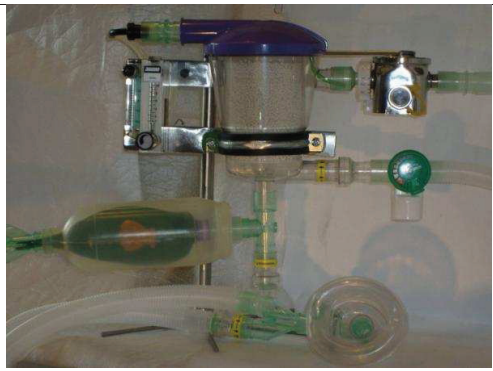


“The SAVe (Simplified Automated Ventilator) was originally designed for Special Force medics where size, weight, and extreme ease of use are paramount.
The SAVe uses a rechargeable battery driven pump to deliver an American Heart Association compliant tidal volume and respiratory rate for 5+ hours.

Low pressure supplemental oxygen can be used if desired. The SAVe will deliver ambient air for up to 5.5 hours on a single battery charge and may be recharged from a standard AC outlet.

It is ideally suited for situations where the use of pressurized gas is inadvisable or unavailable, or where size, weight, ease of use, and portability are considerations".





Semitransparent silicone Shell 10
with breath Bag 5
(left diagram and upper photo)

Рис. 18. «Bag in Vessel» patent RU 2466749

*The chamber is in the form of a shell 10 of transparent or semitransparent silicone rubber covering the breath bag 5 to form a cavity 11 between them, communicating with the ventilator outlet through the aperture 12 (**Fig. 18**).*

The shell 10 can be provided with a volumetric indicator 13 of the excursions of the breathing bag 5 (in the form of measured lines on its outer surface) and an adjustable maximum flow limiter 14 (in the form of a clamp with oval locating blocks). An Ambu bag of semitransparent silicone with a volume of 1200 ml or 600 ml is used as the shell 10.

During the inhalation phase, the gas (atmospheric air) from the ventilator comes in the cavity 11 and displaces the respiratory mixture from the bag 5 through the

absorber 4 and the vaporizer 1(or direct in OUT position) to the patient. In the exhalation phase, the respiratory mixture returns to the breathing bag 5, and the gas from the cavity 11 exits into the atmosphere. Ventilator "SAVe" performs here the role of "pneumatic hands" in relation to the breathing bag 5. This excludes the infection of the ventilator breathing circuit and, accordingly, the need for its disinfection.

The maximum tidal volume will be at the extended clamps 14 and the minimum - with shifted ones. For the Ambu bag 1,2 L, the respiratory volume is regulated by the clamps 14 from 0.6 to 0.15 L; for Ambu 0.6 L - from 0.45 to 0.1 L.

Thus,"SAVe" provides automatic ventilation of the lungs through a semi-closed respiratory circuit.

The result is the smallest complex for inhalation anesthesia and artificial respiration with an oxygen source that fits into the design of two new AM "Colibri" (**Fig. 19**). This portable complex can also be equipped with an O_2 mini concentrator (Airsep Focus miniature portable oxygen concentrator).

a **b**

Fig. 19. Portable complex AM "Colibri"& Ventilator SAVe(a–"MINIVAP-20/S"vaporizer, absorber"Intersurgical"; **b**–"MINIVAP-20/I", absorber 600 ml)

6. HISTORY FRAGMENTS

1 part – **VNIIMP** (All-Union Research Institute of Medical Equipment).

Semyon Glukhov opened the curtain of this three-part story on the distribution of the Moscow Institute of Chemical Engineering graduates in the spring of 1966. His voice was decisive for sending Alexander Berlin to the AM Laboratory (not in the Central Scientific Research Institute for Complex Automation, as he had dreamed, and not "far away", as the Distribution Commission had threatened). The Laboratory (the Department of Anesthesia and Respiratory Equipment) and domestic inhalation equipment was created by Alexander Semyon Perelmuter, who assembled the team, nurtured and began yielding the following devices: artificial lung ventilation, inhalation anesthesia, lung diagnostics, oxygen therapy and even blood pressure sensors above the world level (Tolya Levin).

As a prologue, my thesis on auto relaxation (the first patents using "induced reflexes") and the fight against "deadspace" in the sensors of pneumotachographs.

Right from the following year the first part of the story began: the high resistance vaporizer (plenum) "Anestezist-1" (wickless vapor chamber – Attachment **8.8**, as an "internal protest" against the "bulky" wicks of most vaporizers, and the concentration control in the form of a calibrated orifice set).

A few years later, the draw over vaporizer "Anestezist-2" (direct flow switchgear and vapor chamber with porous metal plates as analogs to the animal's respiratory tract and the gill mass transfer system of fish – Fig.**20**, US Patent 3836129, 17/09/1974) and the AM kit for military field conditions "NARKON-2" on its basis. The two dust-waterproof cases of 15 kg (Attachment **8.9**), which were not a burden on me while going for industrial development in beloved "Krasnogvardeets" (a leading Soviet Union now Russian enterprise manufacturing anesthesia breathing systems and stitching devices, Saint-Petersburg) or for testing in Kuibyshev, Odessa, Kaliningrad.

It is clear why in the 2nd (from 2000) and the 3rd (from 2006) parts I give preference to mini-devices: the first model of the "pocket" vaporizer (chamber Ø 60 mm - a can of tuna) weighed 300 grams.

Thus, the first part of the story lasted until 1980. A year before its end, Leonid Nemirovsky reasonably advised me to turn my candidate's thesis, rejected by the Higher Attestation Commission under the USSR Council of Ministers, into the book "Anesthesia and Anesthetic Dosing", which was done together with A.V. Meshcheryakov, MD. Periodically I open it using the calculated formulas and experimental data.

The Higher Attestation Commission rejected my candidate's thesis because of insufficient "scientific contribution", its practical value was undoubted (serial devices, gold and silver medals, dozens of patents). A new "scientific contribution" of the revised but not submitted thesis was the hydrodynamic calculation of the curvilinear channel (the model of the vapor chamber) with multilevel mathematical formulas – Attachment **8.7**). I was surprised at the intelligent numerical solution of the computer.

Part 2. Engineering Renaissance in Israel

Medico-technical creativity ceased for 20 years.

Suddenly it was restored in Israel, where I went up after my son (curriculum "Aliya").

Prior to that, I was not even allowed to go to friendly Bulgaria in the late 1970s (I got "friendly" explanations: the second Jew in a delegation of 3 people is contraindicated). Although the Bulgarians sent me a call for the industrial development of my portable vaporizer "Anestezist-2", the samples of which the Bulgarian plant successfully manufactured, counting on licensed serial production. At that time, "Anestezist-2" was already mass-produced at "Krasnogvardeets" for 1000 pcs/year (the "NARKON-2" apparatus was accepted for supply by the Soviet Army).

After all, in Israel we were noticed a year later and the three of us (with my son Leib Berlin and Victor Mazin, an engineer from the Jerusalem hospital) opened our own

"start-up" firm (with the money of a private sponsor and under the guidance of Hime Galperin, a lawyer) to develop portable anesthetic vaporizers.

This project continued my main (in terms of time and results) professional subjects - devices for inhalation anesthesia (15 years at the **VNIIMP**, 5 developed and mass-produced devices - "Krasnogvardeets" manufactured about 50 thousand "my" devices from 1970 to 1985, 50 patents and RU author's inventions).

We rented a small room in a private house of a neighboring village, arranged a laboratory there and a couple of years later, after the repeated attempts, finally we made a couple of promising mini-vapor prototypes (**Fig. 20**).

Fig. 20. Alexander and Leib Berlin with "Pocket" and "Universal" vaporizers

In a small device - the anesthetic vaporizer there are three most common processes: the evaporation (**mass transfer**) of a liquid anesthetic into the gas stream (**aeromechanics**) inhaled by the patient; for the anesthetic evaporation requires adequate heat (due to **heat transfer** with the surrounding air).

These three processes are considered using the same physical and mathematical principles (a remarkable book “Transfer phenomena” by Byrd, Stewart, Lightfoot **[21]**).

50-60 years ago, unstable low-resistance vaporizers (“draw-over”–where gas is inhaled through a vaporizer) dominated in inhalation anesthesia, but were then replaced by more accurate high resistance ones (“plenum” - where gas passes under a differential pressure 100 times greater than when breathing). At the turn of the millennium, the famous anesthetist Nunn GF **[5]** asked, “Why did draw-over anesthesia stop?”, despite important advantages (independence from high-pressure gas sources and efficiency).

Therefore, it was natural to solve the “complicated problem”: to make a **perfect vaporizer as precise as** “**plenum” but simple and low-resistance as** “**draw-over”**.

The problem is difficult to solve, since the best draw-over analogs cease to work at a gas flow rate ≤ 2 L/min (at a low resistance of 5-10 Pa, pressure and temperature pulsations, density irregularity “crushed” the anesthetic concentration control).

The vaporizer “Anestezist-2” had the main components of the stabilized low-resistance one: a direct-flow concentration control and an vapor chamber with slot channels (**Fig. 21**), which favorably distinguished it from known foreign analogs at low gas flow rates (<3-4 L/min).

In Ginot-Shomron laboratory, 30 years later, I eliminated the main reason for the instability of even the best foreign vaporizers. “Heavy” anesthetic vapors are not washed out from the vapor chamber by a weak stream of “light” gas-oxygen, but if the chamber is raised to the level of the concentration control, this micro-density difference is leveled. I immediately checked this idea on the old serial vaporizer “Anestezist-2” (this gift from Alexander Moshkovsky I brought to Israel). In the regular vertical position of the vaporizer, the anesthetic concentration exceeded

United States Patent [19]
Perelmutr et al.

[11] **3,836,129**
[45] **Sept. 17, 1974**

[54] **EVAPORATOR FOR LIQUID ANESTHETICS**

[76] Inventors: **Alexandr Semenovich Perelmutr,** Dmitrovskoe shosse, 29, kv. 123; **Alexandr Zinovievich Berlin,** 2 Sinichkina ul., 19, kv. 101; **Igor Konstantinovich Gorlin,** ul. Korolenko, 2/23, korpus, 5, kv. 8.; **Alexandr Gustavovich Traxler,** ul. Pravdy 7/9, kv. 188, all of Moscow, U.S.S.R.

[22] Filed: **Aug. 18, 1972**

[21] Appl. No.: **281,772**

[52] **U.S. Cl.**..... **261/47,** 128/188, 261/DIG. 65, 261/102, 261/104, 261/153

[51] **Int. Cl.**..... **B01d 1/06**

[58] **Field of Search** ..... 128/188, 187, 186, 194, 128/196, 197, 209, 210; 261/104, 105, 47, 63, 107, 102, 104, 153, DIG. 65

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Primary Examiner—Andrew R. Juhasz
Assistant Examiner—W. R. Briggs
Attorney, Agent, or Firm—Eric H. Waters

[57] **ABSTRACT**

An evaporator for liquid narcotics, comprising a straight-flow by-pass duct, wherein provision is made for a shutter and a control slide which, when in one of the extreme positions, interacts with the shutter to close gas admission into the by-pass duct, and an evaporating chamber. The latter is made as a circular straight-flow channel embracing the by-pass duct and is provided with capillary-structure evaporating elements arranged inside the chamber lengthwise the gas flow lines, and with an effuser provided at the outlet of the chamber concentrically to the shutter so as to establish an annular gap therebetween. The control slide, when in the other extreme position, interacts with the effuser to shut up gas issue from the evaporating chamber.

3 Claims, 2 Drawing Figures

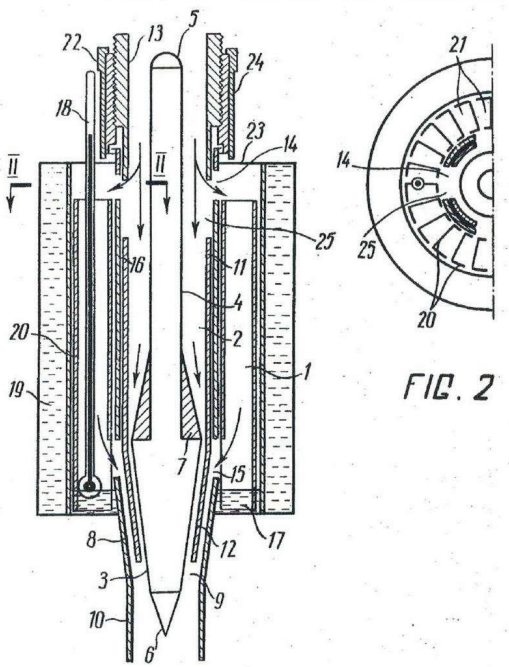

FIG. 2

Fig. 21. "Anestezist-2" vaporizer. US Patent 3836129, 17/09/1974

the limits of the scale error when the gas consumption was below 2 L/min (in this construction “heavy” anesthetics “flow” out of the chamber into the gas stream). When the vaporizer is placed horizontally, the concentration stabilizes even with a smaller gas flow rate.

The work was “for love” from 8 am to 8 pm in the paradise of the village Ginot - Shomron (in “Shomron Gardens” there are flowering trees around the house and along the street).

Models in the spirit of “bioengineering” allowed to improve the main characteristics of analogs (including the own vaporizer “Anestezist -2”) several times (by weight and concentration stability).

The first mini-vaporizer model on a new idea (from a can of tuna with a diameter of 60 mm) became in 5 times smaller than the best analogs. At the “MAY” firm in Haifa (after the names of its founders and principal performers - Mikael, Aria, Yakov) they made the main details of new “Pocket” (300 g) and then “Universal” (5 times more powerful) “MINIVAP” vaporizers.

For the rest of the money we had educational trips to the leading AM firms Drager (Germany, **[15]**) and Penlon (England, Attachment **8.4**).

The 2-nd part of the story practically ended in 2005 before the wall of impossibly expensive (in the “West” - more than $ 1 million) tests for the certification of a medical device.

Part 3. Engineering Renaissance in Russia

In 2006, I applied for support to Russian colleagues - anesthetists and engineers - and received effective assistance.

Professor Nikolai Burov, the famous Russian anesthesiologist gave his “ideological” support. He first breathed himself through a new vaporizer, and then showed it to Professor Igor Molchanov, the chief anesthesiologist of Russia, in the next office of the Botkin Hospital.

It is clear that the process of developing prototypes, state technical and medical tests and industrial development stretched out (for 7 years as it turned out). The first samples of "pocket" vaporizer were produced at the "home" plant by Alexander Pyshnov, Ph.D (see our website www.minivap.net, section "Teachers and Participants"). Then the process was successfully continued, thanks to the financial support of the State Innovation Fund (the competitive 3-stage program 2007-2014 with quarterly reports of 200 pages).

In 2011, it was possible to raise the anesthetic concentration up to 6% in a pocket "MINIVAP-20/I" (by 1.5-2 times), due to the improvement of the concentration control and the "licking" of the vapor chamber (additional evaporation surfaces, exclusion of "stagnant" zones).

During 2011-12, at the second stage of the state contract with the Fund, new models of portable AM "Colibri" were constructed and tested for small hospitals and specialized clinics. Thus, we found a promising market niche for mini-AM that corresponds to the basic contingent of patients (children and pets: dogs, cats, mice and birds).

A batch of pocket vaporizers from non-magnetic Titanium was prepared for Magnetic Resonance Imaging (MRI). At the same time it was possible to develop and produce samples of 5 times more powerful (in terms of anesthetic concentration and gas flow) "MINIVAP-20/S" vaporizer in order to surpass the best "western" analogs.

Still, we found an effective heat carrier with a melting point of 18 °C (due to the help of Boris Raiderman with his friend Mikhail Mitrofanov).

Throughout the entire Russian epic, small (filigree soldering of the first thin-walled cases and micro-bellows) and large (factory technology and production) problems were solved by wise prompts and hands of Ph.D. Alexander Yushkin (universal as Leonardo da Vinci, www.minivap.net).

The final chords were made in the spring of 2014, when I **reformed** the last hundreds pages of the scientific and technical report of the state innovation project, **received** the last portion of money (50 new vaporizers were made then) and promptly **healed** (left-sided hernia) in the Botkin Hospital thanks to the anesthetist Lev Leonid Nikolaev ("double Leo") - my Teacher and co-author of the patents.

The next "super problem" remained unresolved - the penetration into the world niches that are promising for our portable AM: emergency and military medicine, pediatric anesthesiology (including dentistry), district hospitals and veterinary medicine.

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8. Attachments

8.1. Presentation at the Exhibition MEDICA 2012

MEDICA® 2012

small size, big power

Scientific & Manufacture Venture Firm
miniVAP Ltd.

Vaporizers & Anesthesia Machines

Advantages

- can be used in either DRAW-OVER (with Air) and plenum modes (OUT of circle)
- delivered concentration is virtually independent of:
  - » flow rate (0.2 ÷ 10 l/min)
  - » ambient temperature (15 ÷ 35 °C) and atmosphere pressure (70 ÷ 110 kPa)
  - » positions (vertical and overturned)
  - » anesthetic level (from 5 ml)
- minimal weight of "MINIVAP-20" (0.4 kg)
- maximum concentration (12 vol.%) and anesthetic output (0.12 x 20 L/min) of "MINIVAP-200"
- body material: Stainless Steel, Titan (for magnetic resonance tomography)

Fields of Application

- general & district hospitals
- pediatric
- stomalogy
- veterinary
- remote areas
- ambulance & emergency situations
- military & disaster areas

Co-operation Proposal

A – Supply AM elements & units (mini- O2 , CO2 and anesthetic analyzers; mini- O2 generators (oxygenates) and CO2 absorbers (preferably membrane mode); mini-ventilators; Ambu elements & units, adapters etc.)

B – Penetration of our mini-vaporizers in a world anesthesia market (veterinary, urgent situations & remote areas, military, district hospitals)

C – patent licenses, manufactor cooperation (micro-bellows, testing and certification) and R&D novel mini-Vaporizers & Anesthesia Machines.

miniVAP Ltd. was established in March 2007 and is a scientific successor of „Laminar Technology" Ltd. (2001-2003 Israel)

Scientific & Manufacture Venture Firm
miniVAP Ltd.
Russia: 127273, Ostradnaya Str. 1/76 Moscow
Israel: 44855, Kley Shir Str. 5/8 Karney Shomron

Director:
Alexander Berlin **aleberlin@mail.ru**

Contact Germany:
Julia Berlin berlinjulia@gmx.de

www.minivap.net

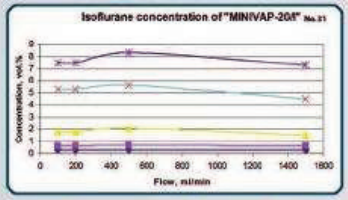
miniVAP Ltd.

Technical Data Sheet

MINIVAP 20

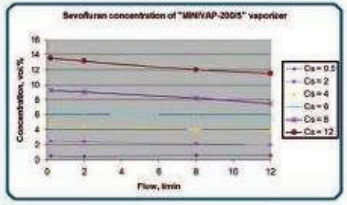
left - parts of "MINIVAP-20/I» vaporizer, right - "MINIVAP-20/S» assembly

MINIVAP 200



Output concentration of "MINIVAP-20" vaporizer at the mini- and low carrier gas flow

Technical Data	"MINIVAP-20"	"MINIVAP-200"
Concentration Range of S or I or H or E, vol.%	0 – 6	0 – 12
Gas Flow Range, L/min	0.2 – 10	0.2 – 20
Resistance to flow 10 L/min, mm H_2O	~ 10 (20 for S)	~ 5
Temperature Range, °C	5 – 35	15 – 35
Atmosphere Pressure Range, kPa	70 – 110	70 – 110
Anesthetic volume, ml	50	150
Wick Anesthetic Volume, ml	3	3
Maximum Angle of Tilt during operation (1/2 anesthetic volume)	180°	90°
Weight, kg	0.4	1.5
Inlet/Outlet	15F/15M	22F/22M



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Vaporizers & Anesthesia Machines

Advantages

- can be used in either DRAW-OVER (with Air) and plenum modes (OUT of circle)
- delivered concentration is virtually independent of:
  - » flow rate (0.2 ÷ 10 l/min)
  - » ambient temperature (15 ÷ 35 °C) and atmosphere pressure (70 ÷ 110 kPa)
  - » positions (vertical and overturned)
  - » anesthetic level (from 5 ml)
- minimal weight of "MINIVAP-20" (0.4 kg)
- maximum concentration (12 vol.%) and anesthetic output (0.12 x 20 L/min) of "MINIVAP-200"

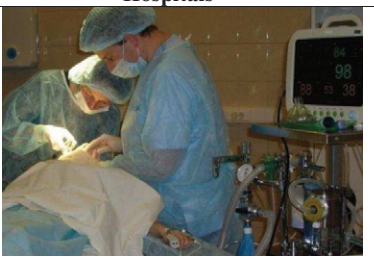
Fields of Application

- general & district hospitals
- pediatric
- stomalogy
- veterinary
- remote areas
- ambulance & emergency situations
- military & disaster areas

8.2. Prospect. PORTABLE AM «COLIBRI» & VAPORIZERS «MINIVAP»

Hospitals

Vaporizers «MV-20/I» (to the right) and «MV-20/S» Stainless steel or Titanium



Vaporizer «MV-20/S» **OUT** of circuit AM "MK-110", Japan (Maxillofacial Surgery)

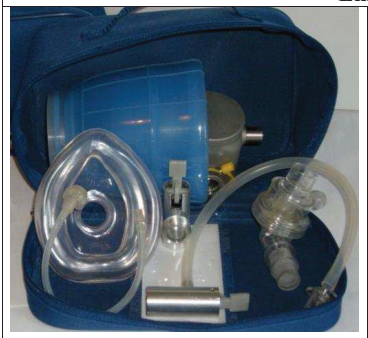
Vaporizer «MINIVAP» **IN** circuit of Ventilator

Veterinary

AM «Colibri», vaporizer «MINIVAP-20/I» **OUT** of circuit

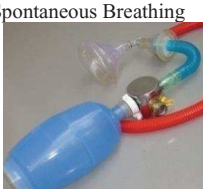
AM «Colibri» for small animals, vaporizer «MV-20/I» **IN** circuit

Emergency & Military field



AM «Colibri» for Emergency & Military field:

Spontaneous Breathing

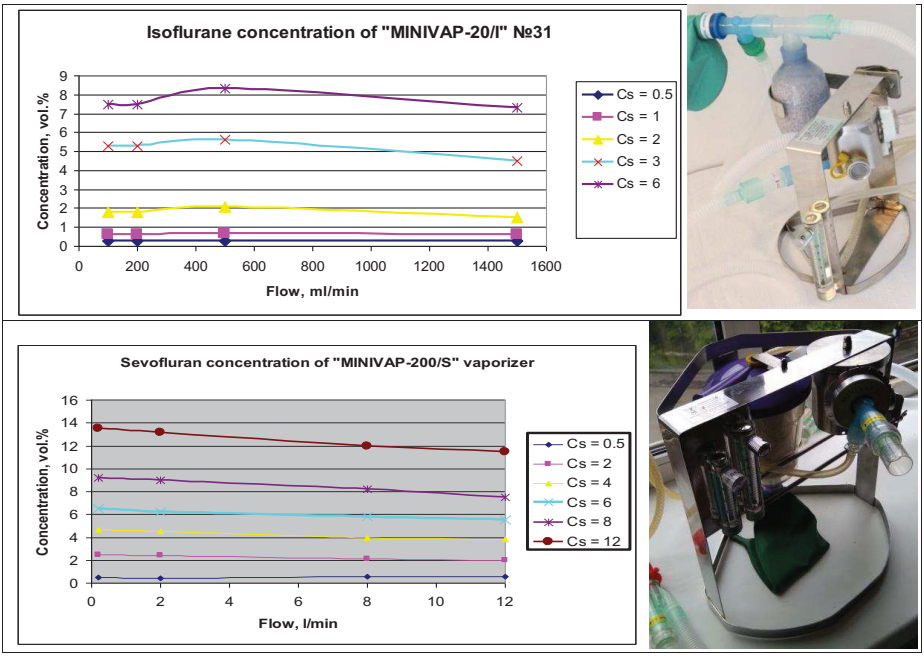


Artificial Ventilation with bag Ambu

AM «Colibri» with Mapleson A breathing circuit

- **Universal** (work on compressed gas or ambient air with any anesthetics and any breathing circuits)
- **Effective** (provide 10 MAC for the mouse at a gas rate of 0.1 L/min, and for a horse - at a rate of 20 L/min) and **economical** (10 times less the working anesthetic minimum and the residue after draining)
- **Miniature** (vaporizer "MINIVAP-20/I» less mask)
- **Compatible** with any Automatic Ventilator and O_2 Concentrators (Armed, AirSep)
- **Safe** (vaporizer "MINIVAP-20/I» works at any tilt)
- **Stable** when changing the gas flow rate (from 0.1 L/min), temperature and pressure

AM «Colibri» intended for inhalation anesthesia in **hospitals** as well as in the **military field, emergency and veterinary medicine**.



Outlet anesthetic concentration of vaporizers «MINIVAP-20/I» (above) & «MINIVAP-20/S»

Technical Data of "MINIVAP" vaporizers

Parameters	«MB-20/I»	«MB-20/S»
Dial setting range, vol.%	0 - 6	0 - 10
Temperature range, ^{o}C	5 - 35	15 - 35
Atmospheric pressure, kPa	70 – 110[1)]	70 - 110
Gas flow range, L/min	0,2 - 10	0,2 - 15
Pressure drop at 10 L/min, mm H_2O	≈20	≈10
Anesthetic volume, mL	40	100
Wick volume, mL	3	5
Angle of tilt, degrees	180^{o}	90^{o}
Mass, kg	0,4	1,5
Input/Output	15F/15M	22F/22M

[1)]3 km above sea level

Literature

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RU Certificates № ФСР 2010/06696, № РОСС RU.ИМ18.Д00129 16.09.2016

Manufacture «МІТК-М» - Moscow, + (495) 962 0175 / **mitk-m@telemost.ru** / **www.mitk-m.ru**

S&M Firm «MINIVAP» - Moscow, + (499) 907 2872 / **aleberlin@mail.ru** / **www.minivap**

Atachment 8.3

MANUAL ANAESTHETIC CIRCUIT + HALOTHANE VAPORIZER, type OMV50

EHOEANAE1H-

Gross weight/unit :	*1.7 Kg*
Volume/unit :	*10.8 dm³*
Indicative price/unit :	*2,523.17 €*
Justification code :	*P*

Definition

The OMV (Oxford Miniature Vaporiser) is a partially temperature compensated and calibrated vaporiser. The low internal resistance allows ambient air to be used as the carrier gas (draw-over anaesthesia).

The OMV can be used on anaesthetic machines with continuous compressed gas flow.

Description

Closed article.

Components

Article supplied with accessories:

- OMV 50
- Self-inflating bag
- T-piece for adding oxygen
- 2 male connectors for tubing 22 mm
- 2 female connectors for tubing 22 mm
- 1 corrugated rubber tube, 30 cm
- 2 corrugated rubber tubes, 106 cm
- One-way expiratory valve

- Anaesthetic mask, n°4 (adult size)
- Spare O-ring
- Maintenance and user information

Technical specifications

- Height: 150 mm
- Width (inlet to outlet): 139 mm
- Diameter of the main body: 50 mm
- Weight: 1.3 kg
- Capacity: 50 ml
- Direction of gas flow: right to left
- Connections: 22 mm
- Calibration: 0.5% - 4% halothane
- Internal resistance: less than 1 cm H2O at 40 litres/minute
- The output concentration is constant at flow rates between 4 and 8 litres/minute

Instructions for use

For use in draw-over anaesthesia without N2O.
Oxygen can be added either from a cylinder or from an oxygen concentrator.
Assisted or controlled ventilation is easy with the Oxford Inflating Bellows.
Must be used with a one-way anaesthetic valve in order to avoid inspiration of ambient air.
For the MSF use, the vaporiser is calibrated for halothane. Other agents can also be used, as chloroform, trilene, enflurane, isoflurane.
WARNING: DO NOT USE ETHER!
Basic maintenance can be performed by the anaesthetist. It is recommended to calibrate the OMV every year or 2 years.

MSF requirements

The OMV vaporiser is both robust and simple to use. It requires very little maintenance.

Fr
EHOE
2004 - Medical Cat. Vol.2

Draw-over anaesthesia is economic. There is little wastage of anaesthetic vapours and oxygen.
Suitable for missions in precarious conditions, as it does not require a supply of compressed gases.
It is virtually impossible to administer a hypoxic mixture to the patient.
Mainly known and used in English-speaking countries.
Portable equipment, not too cumbersome.
NB: The OMV is the vaporiser of choice for draw-over anaesthesia in MSF.

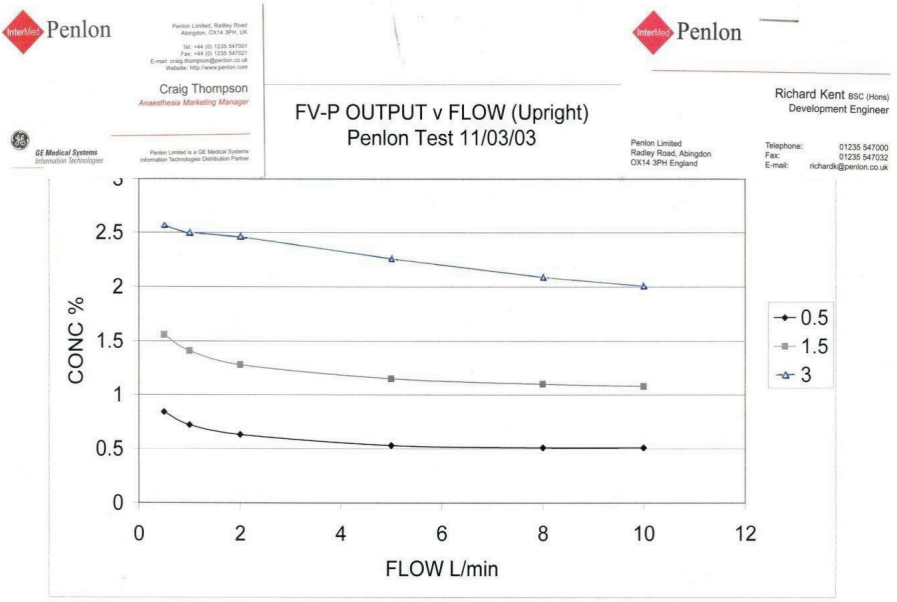
Article to be justified

Reserved for surgical missions with experienced anaesthetist.

Advices for local purchase

Not to be purchased locally.
Manufacturer: PENLON.

Attachment 8.4



PENLON Test «Output Halothane Concentration – Gas Flow»
of the «MINIVAP» laboratory sample
(Development Engineer Richard Kent - 11/03/2003)

Attachment 8.5

TEST RECORD

1. TEST OBJECT

Laboratory sample of Low Resistance Pocket Vaporizer **FLOWVAP-P**
Developed and Manufactured by Laminar Technology Ltd. (LTL)
Time of the test December 2002 – January 2003.
Scene of the test:

- Laboratory of LTL
- Anesthesia Department of Assaf Harofeh Hospital

2. TEST PROGRAM

2.1. Leakage.
2.2. Resistance.
2.3. Anesthetic concentrations at Continuous flow range.
2.4. Anesthetic concentrations at Intermittent Flow.
2.5. Anesthetic concentrations at "back Pressure".
2.6. Anesthetic concentrations at different Temperatures.
2.6. Anesthetic concentrations at angle of Tilt.
2.7. Anesthetic Volume of chamber and wicks.
2.8. Mass and dimensions of the vaporizer.

3. TEST EQUIPMENT

3.1. **Riken** anesthetic indicator.
3.2. **Dwyer** flow meters from.
3.2. **Dwyer** manometers and diffmanometers.
3.3. **Dwyer** barometer, thermometer and psychrometer of ambient air.
3.4. **Becker** air blower.
3.5. Balance and sliding calipers.
*3.6.***NEWPORT HT50** Ventilator (Flight Medical) No.1298003 *(Hospital)*
3.7.**Datex Engstrom** Monitor No.493572 *(Hospital).*

4. TEST RESULTS

4.1. **Leakage** of the vaporizers at pressure 300 mm H_20 is 0.3 L/min.
4.2. **Resistance** of the vaporizers at t=20°C, p=101,6 kPa; humid=65%

Table 1

Air flow, L/min	25	20	15	10	5	2,5
Resistance, mm H_2O at **Off**	61.5	42.5	27.5	14	5	1.5
Resistance, mm H_2O at **3%**	49.5	34	22	11	3.5	1

4.3.**Anesthetic concentrations at Flow range 0. 5 – 15 L/min** is submitted in **Fig.1**.

Maximum Concentration **Deviation** from scale mark, % vol.:

Scale mark of **Halothane**	0.5	1.5	3
Deviation	0.2 / 0	0.1 / -0.4	-0.17/-0.8

4.4. Anesthetic concentrations at **Intermittent Flow**

4.4.1. Halothane concentrations, % vol. at **Intermittent air flow by hand** (t = 22 °C, p = 100.3 kPa, humid = 57%, from 20 up to 7 ml halothane are in its chamber)

Table 2

Scale concentrations	0.5	3
Concentration at intermittent flow **4** L/min, **15** cycles/min, I:E ratio of 1:2	0.4	2.4
Concentration at continuous flow **4** L/min	0.45	2.05
Difference	- 0.05	0,35
Concentration at intermittent flow **12** L/min, **15** cycles/min, I:E ratio of 1:2	0.3	1.8
Concentration at continuous flow **12** L/min	0.4	2
Difference	- 0.1	- 0,2

4.4.2. Halothane concentration at **Intermittent** air flow by **NEWPORT HT50 Ventilator***

Table 3

Mode	Vaporizer Scale, % vol.	Minute Volume, L/min	Pressure max / min, Cm H_2O	f, min^{-1}	I / E	Halothane Concentration, % vol.
1	0.5 1.5 3	10	0 / 30	10	1 / 2	0.6 1.3 2.8
2	0.5 1.5 3	5	0 / 15	20	2 / 3	0.65 1.3 2.7

*See Respirator and Anesthetic Concentration Record

4.5. Halothane concentrations, % vol. at **Intermittent Outlet Pressure ("back pressure") by hand** (t=22 °C, p = 100.3 kPa, humi = 57%; from 20 up to 7 ml halothane in the chamber)

Table 4

Scale concentrations	0,5	3
Concentrations at "back pressure" **2 kPa (200 mm H_2O), 15** cycles/min, I:E ratio of 1:2 , flow **2 L/min**	0.65	3.2
Concentration at flow **2 L/min** without "back pressure"	0,5	3.35
Deviation	0.15	- 0.15
Concentrations at "back pressure" **5 kPa (500 mm H_2O), 15** cycles/min, I:E ratio of 1:2 , flow **8 L/min**	0.45	2.2
Concentration at flow **8 L/min** without "back pressure"	0,4	2,3
Deviation	0.05	-0.1

4.6. Anesthetic concentrations at different **Temperatures** and Intermittent flow by Ambu resuscitator (minute ventilation ~10 L/min = 0.7 x 15 min^{-1})

Table 5

Halothane Scale, % vol.	Outlet concentration at temperature **13°C**	Outlet concentration at temperature **26°C**
3	3.0	2.9
1.5	1.6	1.5
0.5	0.7	0.5

4.7. Halothane concentrations at angles 0 and 180°of **Tilt** and **Intermittent** flow by **NEWPORT HT50 Ventilator***

Table 6

Mode	Vaporizer Scale, % vol.	Minute Volume, L/min	Pressure max/min, Cm H_2O	f, min^{-1}	I / E	Halothane Concentration, % vol.
1 **Tilt 0°**	0.5 1.5 3	6	0 / 20	10	1 / 2	0.65 1.3 3.1
2 **Tilt 180°**	3 1.5 0.5	6	0 / 20	10	1 / 2	3.2 1.5 0.7

*See Respirator and Anesthetic Concentration Records.

4.8. Anesthetic **Volume** of chamber and wicks:
- Maximum anesthetic volume is about 30 ml;
- About 5 ml of anesthetic are retained in the evaporating chamber after draining.

4.9. **Mass** of the vaporizer – 0.46 kg.
Dimension ~80x100x50mm.

5. CONCLUSIONS

5.1. Vaporizer data except mass correspond to Prospect Demands.
5.2. Constructive defects:
- Uncomfortable field of view for concentration scale and absence of its zero stop;
- Outward appearance;
- Surplus mass (0.46 kg instead of 0.3 kg).

These defects will be removed on completion of the pilot model up to preproduction model FLOWVAP-P.

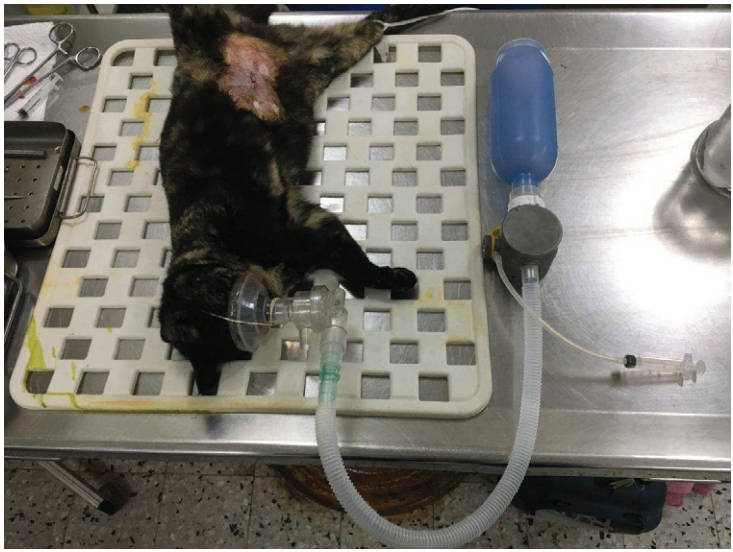
Attachment 8.6 E-mail Letter

26/1/2017

Good afternoon.
I report on the experience of using the miracle machine «Colibri». There were some pretty surmountable problems. But now everything is working well. It very facilitates, simplifies and speeds up the work.
I always work alone and for me portability and simplicity of this machine are of primary importance. In the photo the device is in actual operation.
If the surgery is short and the patients are few attach the device to the animal without special sealing.
If I want more tightness to reduce the anesthetic consumption and pollution of the atmosphere, I use a «collar» in the form of a surgical glove.
The average fuel consumption of Isoflurane in the cat up to 5 kg (45 min in the «S» scale position «4») is 3 ml.
I obtained the necessary anesthesia depth only at the «4» Sevoflurane position (about 6 vol.% Isoflurane). If the plane of anesthesia becomes too light, I squeeze Ambu bag several times to increase the inspired anesthetic concentration.
For dogs over 5 kg I use intravenous anesthetic and some Isoflurane, if there is a suitable mask. I strongly reject intubation. I am looking for a suitable shape and size of the masks. Those that are in stock are extremely inconvenient.

In short, thank you very much for such a wonderful device!

Yours faithfully,
Dr. Elly Berchanskaya
Nahariya, Veterinary Clinic «Beethoven»
ellynaharia@gmail.com
054-5743818



Isoflurane Anesthesia with portable AM «Colibri»

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Attachment 8.7. Hydrodynamic calculation of the curvilinear vaporizer chamber

А. З. Берлин, И. Ф. Зенков

Гидродинамический расчет испарительной камеры в виде криволинейного канала

Испарительная камера наркозного аппарата должна обеспечивать максимальное насыщение парами анестетика проходящего через нее потока газа-носителя при ограниченных сопротивлении и габаритах. С учетом указанных требований, предложена испарительная камера в виде криволинейного канала [3], геометрия которого выбирается так, чтобы обеспечить ламинарное безотрывное течение газа. В статье предлагается методика гидродинамического расчета криволинейного канала, составленная на основе приближенного решения уравнений пограничного слоя.

Рассмотрим установившееся стабилизированное изотермическое ламинарное течение вязкой несжимаемой жидкости (воздуха) в криволинейном канале прямоугольного поперечного сечения (рис. 1). Примем $B \ll h$, $B \ll R_{кр}$, $\rho = \text{const}$, $\mu = \text{const}$, где B, h и $R_{кр}$ — соответственно полуширина, высота и радиус кривизны канала, ρ — плотность жидкости, μ — динамический коэффициент вязкости. Такое течение описывается системой уравнений движения в пограничном слое [7].

Известно [8], что в криволинейных каналах под действием центробежных сил инерции возникают вторичные циркуляционные потоки, направленные перпендикулярно к главному потоку. Вследствие неразрывности течения вторичный поток может оказать существенное влияние на основной поток, и, в частности, вызвать смещение максимума скорости к внешней вогнутой поверхности канала и отрыв пограничного слоя от внутренней выпуклой поверхности. Поэтому будем рассматривать течение в криволинейном канале в виде суммы основного потока, направленного вдоль канала и состоящего из двух сомкнувшихся пограничных слоев (толщиной δ_1 на выпуклой поверхности и δ_2 — на вогнутой, причем, $\delta_1 + \delta_2 = 2B$), и перпендикулярного ему вторичного потока, состоящего, в свою очередь, из двух циркуляционных течений (см. рис. 1).

Для определения величины скорости вторичного потока положим, что оси циркуляционных течений расположены в плоскости раздела пограничных слоев основного потока и на расстоянии δ_2 от торцевых поверхностей канала. Сопоставляя, подобно Прандтлю [5], силы давления, обусловленные центробежными силами инерции, и силы трения, возникающие при движении вторичного потока вдоль поверхностей канала, найдем следующее приближенное значение скорости в центральной полосе вторичного потока:

$$v_ц = (3/32)\,\bar{u}\,\mathrm{Re}\,\delta_2^3/R_{кр}(4B+h)(h-2\delta_2), \qquad (1)$$

где

$$\mathrm{Re} = \bar{V}/h\nu,\ \nu = \mu/\rho,\ \bar{u} = \bar{V}/2Bh;$$

"Новости медицинской техники", 1979, вып. 5.

$\dot{V}$ — объемный расход жидкости через канал;

$\bar{u}$ — средняя продольная скорость.

Следует заметить, что при выводе формулы (1) трение, в отличие от работы [5], рассчитывалось по формуле для течения в плоской щели шириной δ_2.

Для определения скорости основного потока воспользуемся интегральным соотношением импульсов для пограничного слоя со вдувом на выпуклой и отсосом на вогнутой стенках [1, 2]:

$$\frac{d\delta^{**}}{dx}+\frac{1}{u_0}\cdot\frac{du_0}{dx}(2\delta^{**}+\delta^{*}-\delta)=$$
$$=\frac{1}{\rho u_0^2}\left(\delta\frac{dp}{dx}+\tau_{ст}+\rho v_ц u_0\right), \qquad (2)$$

Раскрывая τ через u, получим после интегрирования

$$u(\xi_1,x)=\frac{B}{\mu}e^{-0{,}5\,\mathrm{Re}_ц(1-\xi_1)^2}\int_0^{\xi_1}e^{0{,}5\,\mathrm{Re}_ц(1-\xi)^2}\times$$
$$\times(1-\xi)F(\xi,x)\,d\xi, \qquad (5)$$

где

$$F(\xi,x)=\tau_{ст}(1+\xi)+\delta(dp/dx)\xi,\ \mathrm{Re}_ц(x)=v_ц B/\nu.$$

На оси канала при $\xi_1=1$

$$u_0(x)=\frac{B}{\mu}\int_0^1 e^{0{,}5\,\mathrm{Re}_ц(1-\xi)^2}(1-\xi)F(\xi,x)\,d\xi. \qquad (6)$$

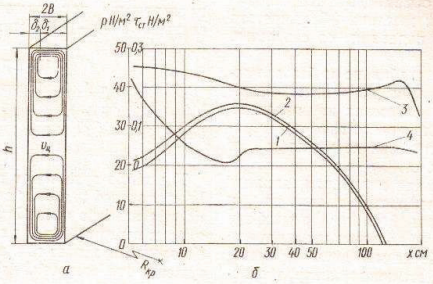

Рис. 1. Геометрические (*а*) и гидродинамические (*б*) характеристики криволинейного канала:
1, 2 — кривые давления p на выпуклой и вогнутой стенках;
3, 4 — кривые трения $\tau_{ст}$ на вогнутой и выпуклой стенках

где

$$\delta^{*}(x)=\delta-\int_0^{\delta}(u/u_0)\,dy,\ \delta^{**}(x)=\int_0^{\delta}\frac{u}{u_0}\left(1-\frac{u}{u_0}\right)dy;$$

$\delta(x)$ — толщина пограничного слоя;

$u(x, y)$ — составляющая скорости вдоль оси $0x$;

$u_0(x)$ — значение скорости на границе пограничного слоя;

$p(x)$ — давление в пограничном слое;

$\tau_{ст}(x)$ — касательное напряжение на стенке.

Сделаем обычные допущения для стабилизированного течения [1] (последующие расчеты подтвердили их справедливость):

$$\delta^{**}/\delta=\mathrm{const},\ \frac{1}{u_0}\cdot\frac{du_0}{dx}=-\frac{1}{\delta}\cdot\frac{d\delta}{dx}.$$

Тогда уравнение (2) примет следующий вид:

$$\frac{d\delta}{dx}\left(1-\tilde{\delta}^{*}-\tilde{\delta}^{**}\right)=\frac{1}{\rho u_0^2}\left(\delta\frac{dp}{dx}+\tau_{ст}+\rho v_ц u_0\right), \qquad (3)$$

где $\tilde{\delta}^{*}=\delta^{*}/\delta$, $\tilde{\delta}^{**}=\delta^{**}/\delta$.

Чтобы решить уравнение (3), необходимо знать профиль скорости по поперечному сечению пограничного слоя. Найдем этот профиль из выражения для касательных напряжений, которое зададим, по аналогии с работой [2], в виде

$$\tau(\xi,x)=(1-\xi^2)\tau_{ст}+\delta\frac{dp}{dx}\xi(1-\xi)+\rho v_ц u(\xi)(1-\xi), \qquad (4)$$

где $\xi=y/\delta$, $0\leqslant\xi\leqslant1$.

Используя формулы (5) и (6), получим выражения для $\tilde{\delta}^{*}$ и $\tilde{\delta}^{**}$. Подставляя последние в выражение (3) и используя формулу (6), выведем после преобразований следующее уравнение для пограничного слоя:

$$\frac{d\delta}{dx}\int_0^1\left\{e^{-0{,}5\,\mathrm{Re}_ц(1-\xi_1)^2}\int_0^{\xi_1}e^{0{,}5\mathrm{Re}_ц(1-\xi)^2}(1-\xi)\times\right.$$
$$\left.\times\left[\tau_{ст}(1+\xi)+\delta\frac{dp}{dx}\xi\right]d\xi\right\}^2 d\xi_1=$$
$$=\frac{\mu^2}{\rho\delta^2}\left\{\frac{dp}{dx}\delta+\tau_{ст}+\mathrm{Re}_ц\int_0^1 e^{0{,}5\mathrm{Re}_ц(1-\xi)^2}(1-\xi)\times\right.$$
$$\left.\times\left[\tau_{ст}(1+\xi)+\delta\frac{dp}{dx}\xi\right]d\xi\right\}. \qquad (7)$$

Аналогично из формулы (6) и соотношения

$$\dot{V}_\delta(x)=u_0 h\delta\left(1-\tilde{\delta}^{*}\right),$$

где $\dot{V}_\delta$ — расход через пограничный слой, получим еще одно уравнение:

$$\int_0^1 e^{-0{,}5\,\mathrm{Re}_ц(1-\xi_1)^2}\left\{\int_0^{\xi_1}e^{0{,}5\,\mathrm{Re}_ц(1-\xi)^2}(1-\xi)\times\right.$$
$$\left.\times\left[\tau_{ст}(1+\xi)+\delta\frac{dp}{dx}\xi\right]d\xi\right\}d\xi_1=\frac{\mu}{h}\frac{\dot{V}_\delta}{\delta^2}. \qquad (8)$$

Уравнения (7) и (8) содержат четыре неизвестных: $\delta(x)$, $p(x)$, $\tau_{ст}(x)$ и $\dot{V}_{\delta}(x)$. Если подставить в них сначала параметры слоя на выпуклой стенке, $\delta_1, p_1, \tau_{ст1}, \dot{V}_{\delta 1}$, а затем — на вогнутой стенке, $\delta_2, p_2, \tau_{ст2}, \dot{V}_{\delta 2}$, то получим систему из четырех уравнений для восьми неизвестных. Чтобы замкнуть систему, добавим к ней следующие четыре уравнения:

$$\dot{V} = \dot{V}_{\delta 1} + \dot{V}_{\delta 2} \qquad (9)$$

(уравнение расхода),

$$\dot{V}_{\delta 1}/\delta_1 \left(1 - \tilde{\delta}_1^*\right) = \dot{V}_{\delta 2}/\delta_2 \left(1 - \tilde{\delta}_2^*\right) \qquad (10)$$

(равенство скорости u_0 на границах пограничных слоев),

$$p_2 - p_1 \approx \left(\rho\, u_0^2/R_{кр}\right)\left(2B - \delta_1^* - \delta_2^* - \delta_1^{**} - \delta_2^{**}\right) \qquad (11)$$

(перепад давлений между стенками за счет центробежных сил инерции),

$$\delta_1 + \delta_2 = 2B \qquad (12)$$

(сумму толщин пограничных слоев).

Система уравнений (7)—(12) позволяет определить изменение давлений и касательных напряжений на стенках вдоль канала, причем $\mathrm{Re}_{ц}$ по уравнению (1) на выпуклой стенке больше, а на вогнутой — меньше нуля (соответственно для вдува и отсоса). На рис. 1 представлены результаты гидродинамического расчета на ЭЦВМ[1] криволинейного канала, состоящего из последовательно соединенных криволинейного диффузора по ширине, спирального канала постоянного сечения и криволинейного диффузора по высоте.

Расчет проводился для следующих параметров: высота канала $h=20$ мм, ширина диффузора на входе $2B_0=1$ мм, угол раскрытия диффузора по ширине $2\theta=1°$, ширина спирального канала $2B=4$ мм, угол раскрытия диффузора по высоте — 1,5°, число $\mathrm{Re}\approx 850$, расход $\dot{V}=0{,}25$ л/с, рабочая среда — воздух при нормальных условиях, радиус кривизны $R_{кр}$ на входе — 55 мм и на выходе — 15 мм.

Начальный участок диффузорной части определяли из работы [6]:

$$L_{ц} = (B_0/\mathrm{tg}\,\theta_0)\left(e^{0{,}18\cdot\theta_0\,\mathrm{Re}} - 1\right). \qquad (13)$$

Как видно из рис. 1, касательные напряжения на выпуклой стенке стабилизированного участка входного диффузора быстро падают до нуля на длине 20 см. Поэтому для предотвращения отрыва пограничного слоя при $x>18$ см переходим на спиральный канал постоянного сечения. Тогда профиль скорости стабилизируется, касательные напряжения на стенках остаются постоянными, а давление монотонно падает вниз по течению.

Рассмотренная методика расчета была использована при проектировании испарительной камеры (рис. 2) в виде описанного выше криволинейного канала. Из сопоставления параметров предложенной камеры с серийной камерой испарителя «Анестезист-1», выполненной в виде лабиринтного канала [4], следует, что обе камеры имеют одинаковые массообменные характеристики при расходе газа $\dot{V}=0{,}1$ л/с, но первая камера имеет меньшее гидравлическое сопротивление, что позволяет в 2,5 раза увеличить верхний предел расхода газа через испаритель.

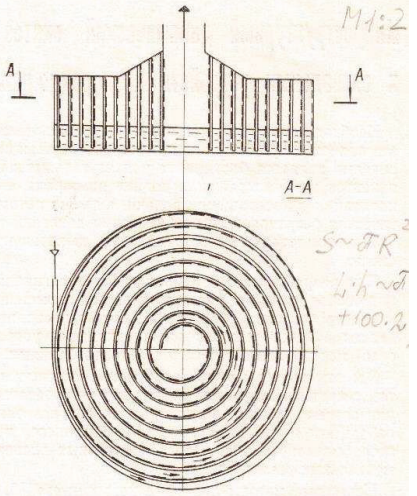

Рис. 2. Испарительная камера в виде криволинейного канала

[1] Совместно с сотрудниками института В. И. Колодиным и Ю. И. Стребковым.

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Summary

Laminar air stream ($\mathrm{Re}\sim 10^3$) in a flat curvilinear channel has been studied. Approximate solution of the equations for boundary layer was obtained on the basis of integral relationship of the pulses taking into consideration the centrifugal secondary flows.

Geometry of the curvilinear channel comprising a diffuser and a spiral channel with constant cross section was computed. This curvilinear channel is an effective vaporizing chamber for an anaesthetic apparatus.

8.8. «ANESTEZIST-1» vaporizer

Рис. 2. Испаритель «Анестезист-1».

Кран байпаса должен стоять в одном из крайних положений.

При неправильной установке флажка крана байпаса шкала не наденется на ось регулирующего крана.

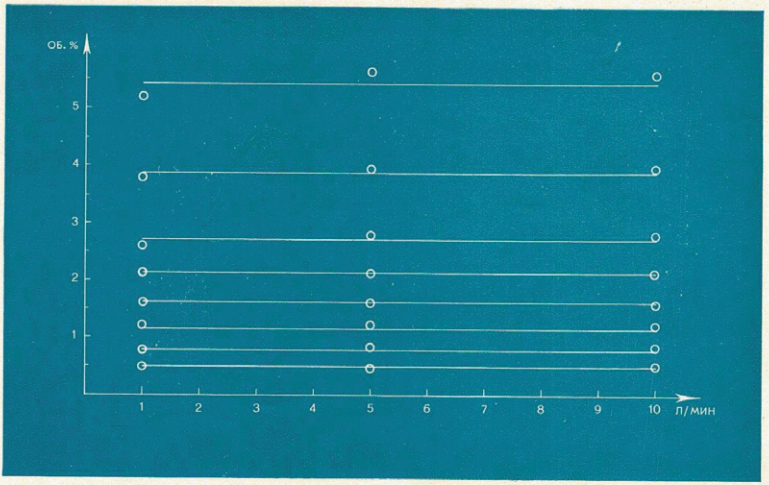
Анестетик заливается в камеру через горловину в количестве от 50 до 100 мл, а сливается через кран практически без остатка. Количество анестетика в испарителе контролируется через смотровое стекло. Установив шкалу на нуль, можно доливать анестетик, не прекращая подачи газа в дыхательный контур.

Конструкция и размеры испарительной камеры рассчитаны так, чтобы обеспечить без применения фитилей полное насыщение парами анестетика газа-носителя, проходящего через нее.

Перед заливкой нового анестетика необходимо продуть испаритель.

Продувка испарителя осуществляется потоком газа 10 л/мин в течение 3—5 мин при установке шкалы на наибольшую концентрацию и открытом кране слива анестетика.

Испаритель стабильно дозирует анестетик в широких диапазонах расходов газа (от 1 до 10 л/мин) и температур (от 15 до 30°С) при барометрическом давлении 750±30 мм рт. ст. Как видно из экспериментальных данных, изменение концентрации анестетика (фторотана) в зависимости от расхода газа не превышает ±5% от диапазона шкалы (рис. 3).



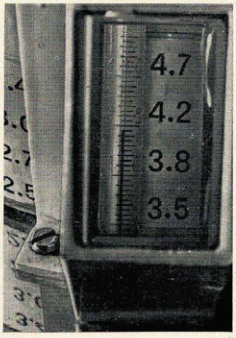
Концентрация фторотана на выходе испарителя в зависимости от расхода газа

Испаритель имеет 12 (включая нулевую) фиксированных установок концентраций. Шкалу концентраций необходимо устанавливать только в положения, определяемые фиксатором. О правильности установки свидетельствует характерный щелчок.

Требуемая концентрация анестетика устанавливается подведением соответствующего числового значения шкалы испарителя к концу столбика жидкости термометра. Значение концентрации считывается с помощью оптической призмы. Первый снизу ряд значений концентраций шкалы испарителя соответствует температуре 15°, второй 20°, третий 25°, четвертый 30°С. Если столбик жидкости термометра остановился между рядами, то концентрация на выходе испарителя находится интерполированием.

Пример. Столбик жидкости, как видно из рисунка, остановился на отметке температуры 24,5°С между отметками 3,8% (20°С) и 4,2% (25°С) шкалы эфира. Тогда концентрация равна:

$$3{,}8 + \frac{24{,}5 - 20}{25 - 20}(4{,}2 - 3{,}8) = 4{,}16$$



Определение выходной концентрации анестетика

8.9. Portable AM «NARKON-2»

ПЕРЕНОСНОЙ АППАРАТ «НАРКОН-2»

— предназначен для ингаляционного наркоза при проведении операций в полевых условиях и в работе скорой помощи;
— обеспечивает проведение наркоза любыми испаряющимися анестетиками в смеси с воздухом, кислородом, закисью азота;
— сконструирован на базе универсального испарителя низкого сопротивления «Анестезист-2»;
— имеет инжектор для подсоса воздуха и экстренную подачу кислорода;
— укомплектован пневматическим аппаратом ИВЛ «Пневмат-1».

Дозирование испаряющихся анестетиков, об %:

фторотана	0—6
метоксифлурана	0—2
эфира	0—20
трихлорэтилена	0—3
хлороформа	0—4
Дозирование кислорода и закиси азота, л/мин	1—10
Регулирование минутного объема дыхания, л/мин	3—12
Дыхательные контуры	открытый, полуоткрытый, полузакрытый, маятниковый
Сопротивление аппарата дыханию при вентиляции 8 л/мин, мм вод. ст.	не более 10
Масса аппарата (без ИВЛ и редукторов), кг	не более 15

PORTABLE ANESTHETIC APPARATUS «НАРКОН-2»

— provides for inhalation anesthesia administered to patients operationally treated under field conditions or admitted to ambulance service facilities. Any vapourizable anesthetic mixed with air, oxygen or nitrous oxide can be used.

Constructionally, the «НАРКОН-2» is based on the universal low-resistance vapourizer «АНЕСТЕЗИСТ-2». An injector is provided to draw the air and deliver emergency oxygen.

The apparatus comes with lung ventilator «ПНЕВМАТ-1».

Proportioning of vapourisable anesthetics, per cent by volume:

fluothane	0—6
methoxyfluran	0—2
ether	0—20
trichloroethylene	0—3
chloroform	0—4
Proportioning of oxygen and nitrous oxide, l/min.	1—10
Adjustment of minute respiratory volume, l/min.	3—12
Breathing circuit	open, semi-open, semi-closed, pendulum
Respiratory resistance of the apparatus at a ventilation of 8 l/min., mm H_2O	10, max.
Mass (lung ventilator and reducers not included), kg	15, max.