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Expulsion Effect of the High Frequency Ventilation and its Utilization in Clinical Practice

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Introduction

High frequency jet ventilation has, apart from other positive effects, another one that it is capable to move around mobile bodies (foreign bodies, mucus, aspirate etc.) inside the tracheo-bronchial tree.

This movement can be programmed in order to achieve the required effect. Mobile body can be defined a solid, semi–solid or liquid obstruction which is not attached to the bronchial tree – mucosa. It can be an aspirated foreign body, liquid aspirate or mucus as well as the lavage solution instillated into the airways.

Under physiologic conditions, the airways are being cleaned by the muco-ciliary system and the mucus together with the trapped particles are transported to the hypopharynx where they can be swallowed.

In case of a more intense triggering of the airway mucosa, the coughing reflex is being activated and the mucus and /or foreign bodies are eliminated.

Slacking down the pace of a natural cough we can see that the coughing subject is slowly inhaling then closing his vocal cords. The expiratory musculature contracts, creating a pressure increase in the lungs. Then vocal cords quickly open and a fast air outflow leaving the airways tears down mucus (aspirate etc.) which is then expelled from the airways.

Physically can this process to be explained following way:

- during inhalation the gas flows slowly behind the “obstruction “. The gas flow is slow, thus the force affecting the obstruction is also small. The magnitude of the force affecting the obstruction equals to the time integral of the flow biquadratics.
- during the expirium (or cough), the gas flow velocity is far higher and thus the force affecting the obstruction increases by second power, causing a shift or slinging the obstruction out of the airways.

We chose natural cough to be the model for explanation of the expulsion principle. This principle is being preserved also during HFJV.

Two effects of the high frequency ventilation used to be inappropriately mixed in the literature:

1. Prevention of the secretions leaking into the patients’airways along the unsealed endotracheal tube (Klain’s effect). (Klain & co.1977).
2. The expulsion effect itself which acts in the whole tracheo–bronchial tree and which inventor was Ing. Brychta, thus it is the Brychta’s Efect. (Brychta 1985, 1993)

Klain’s effect is caused by intratracheal overpressure during the whole cycle of HFJV directing the gas stream along the endotracheal tube to the patients’ hypopharynx and mouth. This gas stream prevents leaking into the trachea.

The expulsion effect itself (Brychta’s effect) occurs in the whole bronchial tree.

The theory of the expulsion effect – a simplified mathematical model is explained in the following paragraph.

Expulsion Effect – Simplified Theoretical Model

Gas flow in airways generates a force which affects the eventual foreign body (or any other obstruction) present in the airways. This force is directly proportional to gas pressure difference (in front of and behind the foreign body) and to the cross-section area of the body in the flow direction.

Gas pressure difference in front of and behind the body is a mathematical product of the gas flow velocity square and of the gas density. This force alternates in the airways in both directions according to the phase of breathing cycle.

The effect of the force in time is called the force impulse.

If the final force impulse is greater in the inspiratory direction then the obstructing body will be pushed into the lungs. If the force impulse is greater in expiratory direction then the body moves out of lungs.

Determination of the force impulse requires a definition of the dependency of flow in time. In case that the gas flow and its velocity are changing in time then the resultant impulse can be calculated as an integral of force in time.

Expulsion effect can be evaluated as a ratio of the inpulsion IN to expulsion EX force. If IN/EX >1 then the obstructing body moves in direction into lungs.

If IN/EX <1 the body is moving out from lungs.

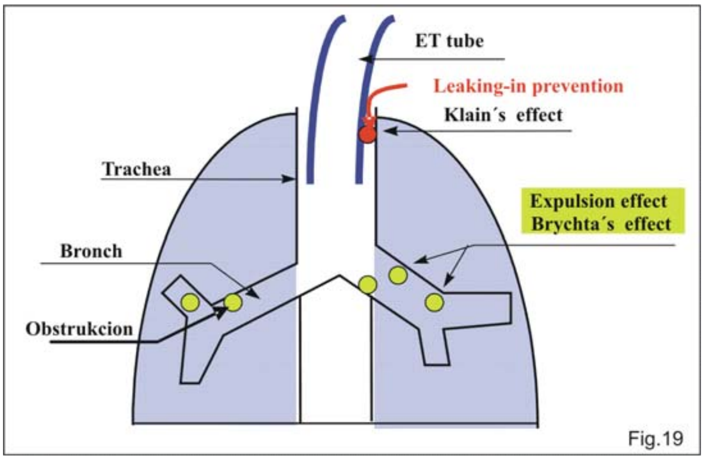
On assumption that the cross-section area of the obstructing body remains unchanged and the same is the gas density then the IN/EX ratio can be expressed as a general relation. Suppose that IN = EX (Ti = Te) there is no movement and this situation is called as neutral effect.

Qi/t/ is the inspiratory flow course in time and similarly Qe/t/ is the expiratory flow course. Ti and Te are times of inspirim and expirium.

Applied to HFJV it is possible to say in simplified way that expulsion effect occurs if the programmed inspiratory time is longer than the expiratory one. (Ti>Te). Inpulsion effect occurs if Ti<Te and neutral effect is characterized by Ti = Te.

Expulsion effect can be observed also on a branching of bronchi leading to two different lung compartments where there is an obstructing body in one of them. Different expiratory gas flow velocities bring about a local (relative) underpressure distally to the obstructing body and this elicites a force pushing the body out from lungs in direction of the expirium.

Fig.1



Expulsion effect works on all levels of the bronchial tree whereas the leak-in prevention effect acts only in trachea. The principle of Klain's effect is that there is a relative overpressure in trachea during whole ventilation cycle compared to the atmosphere and this overpressure prevents leaking in around an un-cuffed or cuffed but not inflated tracheal tube.

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Clinical Use of the Expulsion and Inpulsion Effects

The main scope of the utilization of the above-mentioned effect is lungs cleaning.
HFJV (Czecho-Slovak type) gives to a physician a potent tool capable with minimally aggressive approach to battle one of the most difficult problems of any type of ALV: the mucus retention in the airways and how to get rid of it.

The other application opportunity is airways cleaning and their intensive lavage following an aspiration of any etiology.

Caution! After aspiration and before the oncoming lavage, the expulsion should be applied first in order to avoid pushing the aspirate deeper into the airways.

Similarly, it is possible to improve lungs function in mucoviscidosis (Laho and Dluholucky 1987)

The utilization of the inpulsion itself is possible e.g. in CPR for catecholamine administration in case that there is no venous access available. It is also possible to administer some other medication by impulsion.

An interesting solution is the application of surfactant in children with IRDS.

Material and Methods

During last 6 years we have used expulsion and inpulsion effects in more than 500 patients in 2 hospitals (NsP Ruzinov - Bratislava, NsP Vranpv n.T.) and the number of single applications exceeded 6000.

A group of 141 patients with complete results available for evaluation have been chosen for appraisal.

The whole patient group can be found in tab. 3.

Tab. No. 1 Distribution by age and body weight

Patient distribution according to age and body weight			
Age (year)	**Number**	**%**	**Weight (kg)**
0-5	19	5,6	9,2 ± 2,98
6 - 15	17	5,0	15,4 ± 3,6
16 - 20	22	6,5	51,7 ± 7,1
21 - 59	121	35,5	78,5 ± 8,5
60 - 69	96	28,2	86,8 ± 8,9
70 - 79	54	15,8	82,3 ± 8,4
80 and more	12	3,5	76,1 ± 8,4
TOTAL	**341**	**100,0**	

Patients were ventilated by Paravent PAT, Chirajet NCA85, Chirolog SV Alfa – V, Beat -2 (prototype) and Vive – 2 (prototype) ventilators. Basic physiologic parameters were monitored classically. Arterial or arterialized capillary blood samples have been tested for blood gases (ABL 330 Radiometer). Lung mechanics parameters were monitored and evaluated by Dynavent 888 (Medinvex) monitor and since 2000 by Dynavent 2000 (Kalas). Invasive haemodynamic parameters were monitored by Arrow monitor using a Swan Ganz catheter. The patient group in which lung mechanics and haemodynamics were monitored, is smaller because this type of monitoring has been accomplished in Vranov only during last 4 years.

In rare, very severe cases the airway cleaning used to be helped with flexible bronchoscopy during ongoing HFJV. The patient number benefiting from this proceeding is small because it has been applied only during last 2 years in Bratislava only and in selected patients only.

The ventilation frequency was constant (f = 120c/min). Vt used to vary from 10 to 250 ml depending on the size of MNJI used and on Pin.

The efficiency of the expulsion and of the lavage has been evaluated by following criteria:

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- Presence of mucus in hypopharynx during expulsion (ejection of the foreign body after aspiration)
- Improvement of the auscultation findings
- Improvement or unchanged PaO2 / FiO2 index
- Improvement of lung mechanics parameters (Raw, Cst)
- Improved or unchanged haemodynamic parameters
- Improved or unchanged parameter of aveolo-capillary membrane gas exchange (A – a DO2, Qs / Qt)

In case of impairment of oxygenation parameters during and after the expulsion and lavage application for more than 15 minutes, we considered this fact to be an indicator of ineffective expulsion.

Planned expulsion and lavage in ventilator – dependent patients used to be prepared in advance by previous nebulisation of mucolytic substances approximately 30 – 60 minutes before starting the lavage.

It is obvious that the application of the expulsion and the lavage in patients with dry airways with thickish mucus sticked to the airway-wall can not be effective. It should be pointed out that the patient must be well hydrated and if on ALV then his airways have to be perfectly humidified.

Only ET tubes with flat cuffs have been used during lavage and expulsion in order to allow mucus to pass into the hypopharynx and patients' mouth freely.

The performance of expulsion and lavage itself

The approach to the application of expulsion and lavage using HFJV used to be differentiated according to the patient group and according to the reason leading to their need. Elective application in patients on a classical or on HF ventilation used to start in inpulsion regime with the instillation of the lavage solution into the lavage – valve (aqua pro injectione, Mistabron, F1/1), usually 1.5 ml/kg/24 hour while the single dose did not exceed 10-15ml. Inpulsion effect used to be applied for 120 seconds after lavage solution instillation.

Compliance with **the time recommendation is important in order not to allow the lavage solution to reach alveolar compartment and to wash out the surfactant.** After finishing the expulsion the ventilator was switched to expulsion regime which used to last as long as any mucus could be removed from patient's mouth by a suction catheter but usually 5 – 15 minutes.

The procedure used to be repeated 2 – 3 times subsequently if necessary.

The lavage and expulsion used to be repeated 2 – 8 times a day but in case of need even more.

In patients after aspiration, the lavage started always by a 5-10 minutes lasting expulsion application, in order to avoid the aspirate to spread distally to deeper part of lungs. The usual lavage started after this initial procedure. In case of acidic aspirate we used for lavage 2.1% NaHCO3 in a dose higher than the obvious 1.5 ml/kg/24 hours with a single dose up to 20 ml.

In patients aspirating blood, e.g. after craniocerebral injury we used to proceed same way as after acidic aspiration but the lavage liquid applied was aqua pro injectione or normal saline.

In patients permanently ventilated on HFJV, the expulsion regime used to be set up as needed.

Expiration support has always been applied during expulsion, using the expiratory support nozzle on the MNJI.

Expiration support helps to decrease 'inadvertent PEEP' occurring in the airways during HFJV and which has a tendency to increase when expirium shortened. Expiration support decreases inadvertent PEEP to the levels as they were before starting the expulsion. The above mentioned process is fully automated in Paravent PAT ventilators.

An infectious aerosol is created during the lavage and the expulsion, that's why it is necessary to wear an appropriate face – mask and to use protective gloves. This aerosol can be vented using a one-way valve and a hose attached to the proximal end of the MNJI. The end of the hose leads the infectious waste aerosol into a condensation container filled with a disinfectant solution (part of the so called 'expulsion set').

Results

Table 2 shows the patients' distribution according into diagnostic groups, number of patients who died, number of expulsion applications in particular patients' groups, evaluation of the efficiency of expulsion. Last column shows the average length of ALV application in one patient (conventional or HFJV). The average expulsion lasted 8 -10 minutes. The maximum length did not exceed 20 minutes.

The lowest efficiency used to be achieved in patients with bronchial spasm in a mixed group marked as: "other causes ". The highest efficiency has been achieved in the ARDS, pneumonia and cranio-cerebral injuries with aspiration groups.

Tab. No. 2

Diagnostic group	**No.of patients**	**No.of deaths**	**Death percentage**	**No.of expulsions**	**No. of efficient expulsions**	**Efficient expulsion percentage**	**Average single patient ALV length in hours**
Bronchiolitis	12	2	16,67	108	77	71,2	36
Pneumonia	48	7	14,58	912	843	92,4	76
ARDS	33	12	36,36	1234,2	1021	82,7	187
CCP craniocrebral trauma (CCT)	123	34	27,64	3001,2	2839	94,6	122
Aspiration in CCP	51	Including CCP		1810,5	1753	96,8	142
Acidic aspiration	22	1	4,55	396	377	95,2	54
Chest trauma (lung contusion)	29	7	24,14	1522,5	1191	78,2	210
Astma	11	1	9,09	24,2	12	51,6	11
Other causes (sepsis, shock etc.)	12	5	41,67	159	125	78,8	53
TOTAL	**341**	**69**	**20,23**	**8439,75**	**6953**	**82**	**99,00**

The expulsion was successful in approximately 90% of cases and showed excellent efficacy in approximately 84 – 87% of cases. The expulsion and the lavage were applied only after a successful secretion mobilization in the 'asthma and bronchiolitis' groups, never at the beginning of ALV, when HFJV proved to be inefficient.

Apart form other parameters, also airway resistance and lung compliance were monitored, using Dynavent 888 monitor. The results are in table No.3.

In some groups the parameters of lung mechanics improved statistically significantly after the application of a series of 3 – 5 expulsion sessions.

Tab.No 3 Changes of lungs mechanical properties after expulsion
Patient group no. = 118

Group	No.of patients	Raw (kPa/l/s)		Cst (ml/kPa)	
		Before expulsion	**After expulsion (20 min)**	**Before expulsion**	**After expulsion (20 min)**
Pneumonia / bronchopneumonia	10	0,6 ± 0,05	0,47 ± 0,05	480 ±75	560 ± 77 *
ARDS	12	0,7 ± 0,08	0,51 ± 0,07 *	380 ± 62	410 ± 65
CCP	56	0,36 ± 0,03	0,35 ±0,03	580 ±78	590 ± 80
Aspiration in CCP	21	0,68 ± 0,06	0,47± 0,05 *	426 ± 59	511 ± 71 *
Acid aspiration	19	1,18 ± 0,12	0,82 ± 0,09 **	451 ± 67	550 ± 79 *

* - Statistically significant difference p< 0,05 in paired Student's t-test
* * - Statistically significant difference p< 0,01 in paired Student's t-test

In a relatively small group of patients which had their haemodynamics monitored, changes of oxygen delivery before, during and after the expulsion were measured. The results can be seen in tab. 4. Statistically significant difference was found in PaO2 improvement and in improvement of Qs/Qt. Cardiac index changes were not substantial. Blood gases and pH were monitored regularly in a group of 167 patients during those two days when lavage was applied most frequently.

Tab.No.4 Comparison of some of haemodynamical parameters and blood gases
n=31 (Group of CCT and ARDS)

Time	CI	TPR	PVR	IDO2	Qs/Qt	pH	PaCO2	PaO2
	l/min/m2	**dyn/sec/ m-5**	**dyn/sec/ m-5**	**ml/min/ m2**	**%**		**kPa**	**kPa**
Before expulsion	3,3 ± 0,4	1510 ± 200	190 ± 15	179 ± 20	19 ± 4	7,34 ±0,04	5,1 ± 1,2	9,6 ± 2,1 +
During expulsion	3,2 ± 0,3	1580 ± 230	188 ± 12	183 ± 34	14 ± 3,8	7,36 ± 0,06	4,45 ±1,1*	14,4 ± 4,8 ++
After expulsion (20 min)	3,4 ± 0,5	1501 ± 190	177 ± 14	191 ± 33	15 ± 3,6 *	7,35 ±0,05	5,05 ± 1	11,9 ± 3,2 * +

* - Statistically significant difference p< 0,05 in paired Student t-test
\+ FiO2 during ALV before and after expulsion = 0,4 - 0,45
++ FiO2 during expulsion = 0,55

Discussion and Conclusion

During the last two decades after the implementation of high frequency ventilation into the clinical practice we saw an initial boom followed by a certain sceptisizm caused mostly by some vagueness in the theoretical field and last but not least by not the best results in the clinical practice.

In spite of the unfavourable experience emerging mostly abroad, remained the group of researchers in former Czechoslovakia working on original theories and development of new devices.

One of the main problems remained the explanation of the expulsion effect, invented by Ing. Brychta, CSc., and its clinical application (Brychta 1983, 1985).

Clinical use of the mentioned effects required a huge amount of work in theoretical but also practical field.

The practical result of this effort was the development of the Chirajet NCA high frequency ventilator for long term ventilation and Paravent P, PA and PAT for short–term ventilation outside hospitals, in surgical practice and in intensive therapy as well.

One of the positive effects of the introduction of HFJV into the clinical practice is the application of expulsion and inpulsion effects in our hospitals, which significantly changed the care of the ventilated patients especially during long-term ALV. They also brought some new elements into the emergency medicine, which are not negligible.

The efficiency of the expulsion is not 100% in all cases but a 90% efficiency of a therapeutic procedure can be considered to be very good, whilst in approximately 86% of cases were the expulsion and the lavage excellent.

Haemodynamic parameters monitoring in a small patient group showed that a switch from conventional to high frequency jet ventilation and to expulsion showed only minimal influence on the cardiac output but it did cause a decrease in peripheral vascular resistance. Lung mechanics and blood gas changes are only confirming patients' status improvement after the application of expulsion and the lavage.

In some patients the expulsion was not efficient and HFJV caused ventilatory and haemodynamic problems in terms of impaired gas exchange and blood pressure decrease. We weren't able to explain this phenomenon.

The application of HFJV using original Czecho-Slovak ventilators based on original theories with results as shown in previous chapters it is possible to allege that the developed technical equipment as well as their application possibilities are at the present up to the mark and that they are capable to push forward the standard of care of critically ill patients.

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