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Year: 2014

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DOI: <https://doi.org/10.1111/aas.12374>

Posted at the Zurich Open Repository and Archive, University of Zurich

ZORA URL: <https://doi.org/10.5167/uzh-98532>

Journal Article

Accepted Version

Originally published at:

Biro, P (2014). Calculation of volatile anaesthetics consumption from agent concentration and fresh gas flow.

Acta anaesthesiologica Scandinavica, 58(8):968-972.

DOI: <https://doi.org/10.1111/aas.12374>

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How to calculate the consumption of volatile anaesthetics from agent concentration and fresh gas flow

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Short Title: Calculation of volatile anaesthetics consumption

Conflict of interests: none.

How to calculate the consumption of volatile anaesthetics from agent concentration and fresh gas flow

Background: The assessment of volatile agents' consumption is usually performed by weighing vaporisers before and after use. This method is technically demanding and unavailable for retrospective analysis of anaesthesia records. Therefore a method based on calculations from fresh gas flow and agent concentration is presented here.

Methods: The herein presented calculation method enables a precise estimation of ongoing or past anaesthesias when average fresh gas flow and average volatile agent concentration throughout the whole time period of anaesthetic gas delivery is known. Additionally, the vapor amount deriving from 1 ml fluid volatile agent has to be known. The necessary formulas for these calculations are presented herein for four agents and exemplary calculations simulating clinical dosages are performed.

Results: The calculation of volatile agent vapour deriving from 1 ml of fluid agent is presented: halothane 229 ml, isoflurane 195 ml, sevoflurane 184 m and desflurane 210 ml. These constants are used in 4 fictitious clinical cases to exemplify the calculation of volatile agent consumption in daily routine.

Conclusions: By application of the presented specific volatile agent constants and equations, it becomes easy to calculate volatile agent consumption if the fresh gas flows and the resulting inhaled concentration of the volatile agent are known. By this method both is possible, to extract data about volatile agent consumption both ways: a) retrospectively from sufficiently detailed and accurate anesthesia recordings, as well as b) by application of this method in a prospective setting. Therefore, this method is a valuable contribution to perform pharmaco-economical surveys.

Key Words: consumption, volatile anaesthetics; pharmacoeconomics

Introduction

The knowledge about the consumption of volatile agents during anaesthesia and its pharmacoeconomical implications gains increasing relevance and attention.^{1,2} The easiest way to assess the consumption of volatile anaesthetics is to weigh the vaporiser before and after anaesthesia and to take the difference (plus the eventually added refilled volumes during the ongoing anaesthesia) as the consumed amount. This method has been widely used for various drug consumption and pharmaco-economic investigations.^{3,4} A certain technical problem derives from the necessity for a very precise balance that has a wide range of measurement. Usually the larger the measurement range, the less is the resolution for small differences between the measured objects. A vaporiser weighs up to 5 kg, while the differences produced by the prevailing levels of its volatile anaesthetic content remains in the range of a few grams. Besides this technical limitation, this method can be only adopted if the assessment is planned in advance and one has the opportunity and necessary time to

perform pre- and post-anaesthesia measurements. Due to the limited availability of the mentioned equipment as well as the necessity to plan the measurements individually in advance, this weighing method remains limited to a reduced number of cases.

However, since roughly two decades we have a reliable method for the assessment of volatile agents consumption that can be applied if a few basic data of the already carried out such as the settings for both, the fresh gas flow (FGF) and the volatile agent concentration in the fresh gas, as well as the time course of these parameters.^{5,6} Additional concomitant conditions that have to be taken into consideration are the average temperature of the vaporiser during the procedure, and the specific amount of anaesthetic vapor that can be maximally drawn from 1 ml of fluid agent; the calculation of the latter for 4 volatile agents under standard conditions is presented further down. The vaporiser temperature can be approximated to be roughly 2°C below the prevailing room temperature, while the amount of anaesthetic vapor at complete saturation of the fresh gas is a constant that can be obtained by a few preparatory calculations. In the following, the calculation of volatile anaesthetic consumption from anaesthesia records is demonstrated.

Methods

As being an investigation based on physical principles and calculations without involvement of patients and/or personnel, there is no need for approval by an Ethical Committee. The herein presented assessment of volatile anaesthetic consumption relies on the assumption, that if the amount of fresh gas and its content of volatile anaesthetic is known, one can calculate how much of the volatile anaesthetic in its original fluid form has been drawn from the vaporiser. The first step is to determine the amount of anaesthetic vapor at complete saturation for each specific volatile agent. For this purpose, this equation has to be applied:

$$\text{Fluid VA (ml)} = \frac{\text{specific weight}^1 \cdot \text{Avogadro's gas constant}^2 \cdot (273 + \text{temperature})^3}{\text{molecular weight}^4 \cdot 273}$$

¹ Specific weight for volatile anaesthetics in g/ml is as follows: halothane 1.87, isoflurane 1.49, sevoflurane 1.53, and desflurane 1.47.^{7,8}

² Avogadro's gas constant states that at a standard atmospheric pressure of 760 mmHg (at sea level) and at a temperature of 0°C = 273 °K one mole of any gas consists of 6.023 x 10²³ molecules which in turn occupy a volume of 22'400 ml. This is the same for all gases at STPD conditions, and also in the case of all volatile anaesthetics. STPD means "standard temperature, standard pressure, dry", which is given for a volume of gas at 0° C and 760 torr, and that contains no water vapor.

³ The temperature of the vaporiser is close to room temperature. Due to the loss of energy during evaporation there is a tendency of cooling of the vaporiser, which is counteracted by its inbuilt high

temperature conductivity. It's reasonable to subtract 2°C from the prevailing room temperature (personal experience), then the result is to be added to 273°K.

⁴ Molecular weights for volatile anaesthetics are as follows: halothane 197, isoflurane 184, sevoflurane 200, and desflurane 168.^{7,8}

Having these four items (and assuming a room temperature of 22°C and a vaporiser temperature of 20°C), we obtain the saturated vapor volumes from the evaporation of 1 ml fluid volatile anaesthetics:

$$\text{Halothane vapor volume} = \frac{1.87 \cdot 22'400 \cdot (273 + 20)}{197 \cdot 273} = 229 \text{ ml}$$

$$\text{Isoflurane vapor volume} = \frac{1.49 \cdot 22'400 \cdot (273 + 20)}{184 \cdot 273} = 195 \text{ ml}$$

$$\text{Sevoflurane vapor volume} = \frac{1.53 \cdot 22'400 \cdot (273 + 20)}{200 \cdot 273} = 184 \text{ ml}$$

$$\text{Desflurane vapor volume} = \frac{1.47 \cdot 22'400 \cdot (273 + 20)}{168 \cdot 273} = 210 \text{ ml}$$

After obtaining these constants, the next step is to include these values into a formula that considers the settings for the FGF, as well as for the volatile agent concentrations that have been used throughout the course of the investigated anaesthesia. For volatile agent concentrations, measured values are to be preferred⁹, but if these are unavailable, the vaporiser settings can be used as well, albeit with a lesser degree of precision, since usually the output of vaporisers is lower than the set level¹⁰. Finally, for our calculations we need average FGF and anaesthetic agent concentrations. Usually, during an anaesthesia, both, FGF and even more so the volatile agent concentrations are subjected to multiple changes, which may happen independently of each other. Therefore, first the whole anaesthesia time duration has to be broken down into segments with constant settings, and their resulting products must be cumulated to obtain the average values of the entire anaesthesia. To illustrate this measure, here come 4 examples of fictitious (but realistic) inhaled anaesthesia applications which in the "Results" section will be used to exemplify the calculation of the ensuing volatile agent consumptions:

Case A.

A halothane anaesthesia of 40 minutes duration. The FGF settings (in L/min) and their durations (in min) were: 12 for 15 min, and 6 for 25 min. The concentration changes (in Vol%) were: 2 for 10 min, 1.2 for 20 min, 0.8 for 10 min.

Case B.

An isoflurane anaesthesia of 60 minutes duration. The FGF settings (in L/min) and their durations (in min) were: 6 for 5 min, 3 for 20 min, 6 for 5 min, and 2 for 30 min. The concentration changes (in Vol%) were: 2.8 for 10 min, 1.6 for 15 min, and 2 for 35 min.

Case C.

A sevoflurane anaesthesia of 90 minutes duration. The FGF settings (in L/min) and their durations (in min) were: 10 for 10 min, 3 for 20 min, 4 for 10 min, and 1.5 for 50 min. The concentration changes (in Vol%) were: 2.5 for 5 min, 1.8 for 15 min, 1.2 for 50 min, and 0.9 for 20 min.

Case D.

A desflurane anaesthesia of 120 minutes duration. The FGF settings (in L/min) and their durations (in min) were: 7 for 10 min, and 0.5 for 110 min. The concentration changes (in Vol%) were: 8 for 5 min, 6 for 100 min, and 1 for 15 min.

The usual high FGF settings at the end of anaesthesia with the scope of rapid removal of the residual volatile agent from the body are here ignored since during this measure no volatile agent consumption from the otherwise closed vaporiser occurs anymore. The hereby removed agent has already been included into the consumption calculation while it was delivered into the circuit. The time courses of the FGF and volatile agent setting examples are illustrated in Fig. 1.

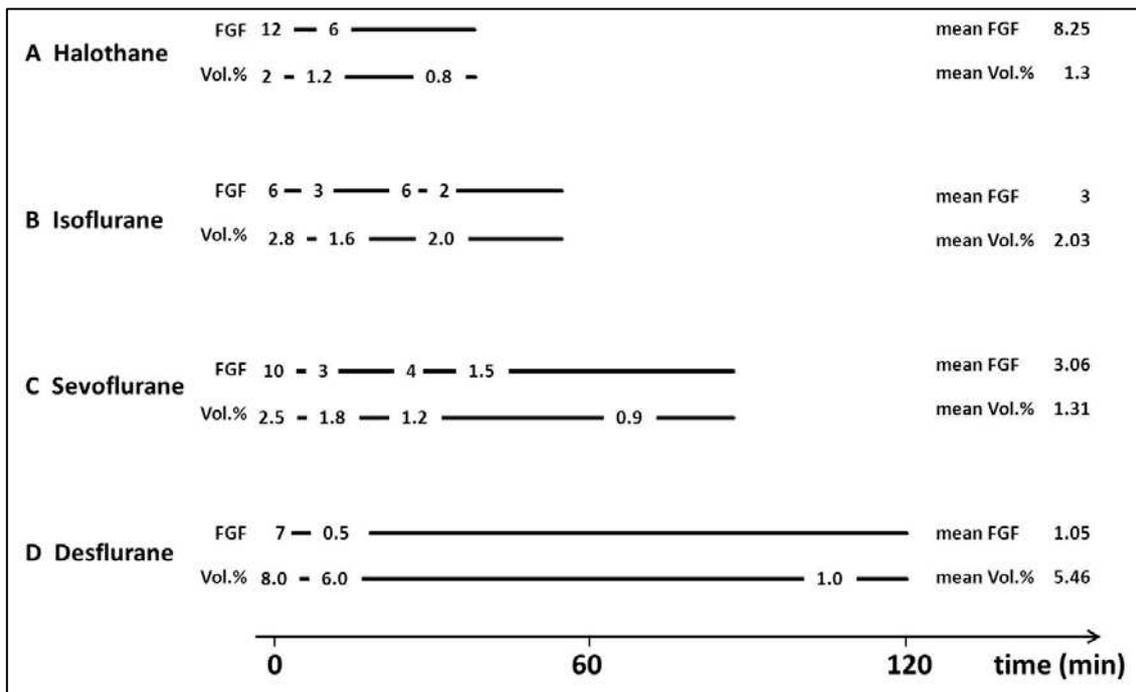


Fig. 1. Visual display of the time courses for fresh gas flows (FGF) and volatile agent concentrations in four different examples as they usually appear in anaesthesia records. Such displays are sufficient to

extract the necessary data for the calculation of mean FGF and volatile agent concentrations. On the right margin the resulting average values are included.

Results

The calculation of mean FGF and volatile anaesthetic concentrations for each case follows here. First the product of FGF (in Liters) and its time segment (in minutes) is obtained.

Case A (stepwise calculation as example):

Total FGF: $(12 \times 15) + (6 \times 35) = 330$ L; Divided by the total duration of 40 min, we obtain a mean FGF by having $330 : 40 = 8.25$ L/min

This is followed by the product of agent concentrations (in Vol%) and their time segment (in minutes):

Total Vol%: $(2 \times 10) + (1.2 \times 20) + (0.8 \times 10) = 52$. Mean Vol% results from $52 : 40 = 1.3$ Vol%.

Analog calculations for the other three agents result in:

Case B

Mean FGF = 3 L/min

Mean Vol% = 2.03 Vol%

Case C

Mean FGF = 3.06 L/min

Mean Vol% = 1.31 Vol%

Case D

Mean FGF = 1.05 L/min

Mean Vol% = 5.46 Vol%

These mean values for FGF have to be converted into milliliters/min, and inserted together with the mean volatile agent concentrations (Fig. 1), the duration of anaesthetic gas delivery (min) and the specific constants for saturated gas for each volatile anaesthetic into this equation:

$$\text{Fluid volatile agent} = \frac{\text{mean FGF (ml/min)} \cdot \text{mean agent conc. (Vol\%)} \cdot \text{Anaesth. duration (min)}}{\text{Saturated gas volume (ml)} \cdot 100 \text{ (Vol\%)}} = \text{ml}$$

This is presented for all four exemplary cases:

Case A

$$\text{Halotane fluid consumption} = \frac{8250 \text{ ml/min} \cdot 1.3 \text{ Vol\%} \cdot 40 \text{ min}}{229 \text{ ml} \cdot 100 \text{ Vol\%}} = 18.7 \text{ ml}$$

Case B

$$\text{Isoflurane fluid consumption} = \frac{3000 \text{ ml/min} \cdot 2.03 \text{ Vol\%} \cdot 60 \text{ min}}{195 \text{ ml} \cdot 100 \text{ Vol\%}} = 18.8 \text{ ml}$$

Case C

$$\text{Sevoflurane fluid consumption} = \frac{3060 \text{ ml/min} \cdot 1.31 \text{ Vol\%} \cdot 90 \text{ min}}{184 \text{ ml} \cdot 100 \text{ Vol\%}} = 19.6 \text{ ml}$$

Case D

$$\text{Desflurane fluid consumption} = \frac{1050 \text{ ml/min} \cdot 5.46 \text{ Vol\%} \cdot 120 \text{ min}}{210 \text{ ml} \cdot 100 \text{ Vol\%}} = 32.7 \text{ ml}$$

Having the consumed fluid volatile anaesthetic volumes, it's easy to calculate the costs. In contrast to i.v. anaesthetics where the unused remnant has to be discarded, the residual content of vaporisers is no waste and can be used for the next patient. We only need to know the expenditure and price of the evaporated agent. In Table 1 the volatile agent market prices for Switzerland (as obtained from the hospital's pharmacy in November 2013) are included and the resulting costs of the four examples are displayed.

Time segment	1	2	3	4	5	6	7
Duration	5	5	10	10	10	30	20
GF flow (ml/min)	10'000	10'000	3'000	3'000	4'000	1'500	1'500
VA conc. (Vol%)	2.5	1.8	1.8	1.2	1.2	1.2	1.2
VA consumption	6.8	4.9	2.9	2.0	2.6	2.9	2.0

Table 1. Results from the costs calculations considering the actual volatile anaesthetic prices and their application on the presented cases A to D (as given in November 2013 in Switzerland. Currency conversion rates were at the same time: 1.00 CHF = 1.10 US\$ = 0.81 EUR).

Discussion

The consumption of volatile anaesthetics can be precisely estimated from anaesthesia records if these essential data are available: a) the choice of the volatile anaesthetic, b) the applied FGF (with knowledge about the durations of its setting variations), and finally c) the applied concentration of the

chosen volatile anaesthetic - again with knowledge about the durations of each concentration setting. The total anaesthesia time is identical with the sum of the recorded FGF or volatile agent concentration time segments. Considerations of uptake of the volatiles into the body or losses through leaks in the breathing circuit are irrelevant for this kind of cost calculations since what counts in this respect is only the extracted amount from the vaporizer, which is the composition and amount of the FGF.

The herein presented approach by calculation from FGF and (preferably) from measured exhaled volatile agent concentrations has the big advantage to be applicable without the necessity to have sophisticated equipment such as a very precise balance with a large measurement range. Additionally, one can assess volatile agent consumptions retrospectively, provided that the recordings are accurate and detailed enough. By this it's theoretically possible to extract data from an unlimited number of cases resp. from archived records.

A certain disadvantage of this calculation based method is the initially laborious assessment of the mean FGF and agent concentrations by summing up their individual time segments. However, this work can be considerably facilitated by using a suitable matrix in a spreadsheet (e.g. in Excel, Microsoft, Seattle USA) where one only has to enter the relevant numbers into the matching cells. To illustrate such a table, a screenshot from the calculation for the case D is included in Fig. 2.

Sevoflurane							
FGF		10	3	4	1.5		
time	90	10	20	10	50	Sum	mean
		100	60	40	75	275	3.06
Vol%		2.5	1.8	1.2	0.9		
time	90	5	15	50	20	Sum	mean
		12.5	27	60	18	117.5	1.31
		Duration	FGF	VA conc.	Cons.	Cons.	
		min	ml/min	Vol%	ml/min	ml	
		90	3060	1.31	0.22	19.58	

Fig. 2. Example for a calculation matrix for case C (sevoflurane anaesthesia) as used in Excel (Microsoft, Seattle, USA) to obtain the mean fresh gas flow (FGF) and mean volatile agent concentration over the total anaesthesia time. In the bottom row are calculated the consumption per min and the total consumed volume of the volatile agent.

Another – thanks to this work by now not anymore existing – handicap is to obtain the constants for the specific amounts of the most familiar volatile agents indicating the gas volume that result from evaporation of 1 ml of each agent. These values have been obtained from known physical attributes such as the molecular as well the specific weight of these compounds, and finally by applying

Avogadro's universal gas laws. The resulting constants for the four most widespread volatiles are here available: halothane 229 ml, isoflurane 195 ml, sevoflurane 184 m and desflurane 210 ml. However, for the sake of accuracy is to be stated, that these constants are valid for "low lands" only (which for practical reasons may be acceptable for locations up to 500 m above sea level). For anaesthesia practiced at higher altitudes, the figures have to be calculated with altered parameters.

Conclusions

The professional audience has been offered a suitable tool to make precise and relevant pharmacoeconomical calculations in their daily business. The hereby presented method is also well suitable to estimate the impact of various FGF settings in order to optimise the consumption parameters for the involved inhaled anaesthetics and of related equipment.³ An interesting and useful expansion of the here stated method would be the simultaneous measurement of inhaled and exhaled volatile anaesthetics and to compare the obtained uptake with the calculated delivered amount of that agent.^{2,11} By comparing these parameters, one can deduct the magnitude of unused anaesthetic gas and will be able to take measures for minimizing waste and pollution.

Conflicts of interests

None.

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