EVALUATION OF A PITOT TYPE SPIROMETER IN HELIUM/OXYGEN MIXTURES

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ABSTRACT. Objective. Mixtures of helium and oxygen are regaining a place in the treatment of obstruction of the upper and lower respiratory tract. The parenchymal changes during the course of IRDS or ARDS may also benefit from the reintroduction of helium/oxygen. In order to monitor and document the effect of low-density gas mixtures, we evaluated the Datex AS/3 Side Stream Spirometry module with D-lite® (Datex-Engstrom Instrumentarium Corporation, Finland) against two golden standards. **Methods.** Under conditions simulating controlled and spontaneous ventilation with gas mixtures of He (approx. 80, 50, and 20%)/O_2 or N_2(approx. 21 and 79%)/O_2, simultaneous measurements using Biotek Ventilator Tester (Bio-Tek Instr., Vermont, USA) or body plethysmograph (SensorMedics System, Anaheim, USA) were correlated with data from the spirometry module. Data were analyzed according to a statistical regression model resulting in a best-fit equation based on density, voltage, and volume measurements. **Results.** As expected, the D-lite (a modified Pitot tube) showed density-dependent behaviour. Regression equations and percentage deviation of estimated *versus* measured values were calculated. **Conclusion.** Measurements with the D-lite using low-density gases are satisfactorily contained in best-fit equations with a standard deviation of less than 5% during all ventilatory modes and mixtures.

KEY WORDS. Gas density, helium, oxygen, venturimeter, measurement, tidal volume.

INTRODUCTION

The use of helium/oxygen mixtures in the treatment of airway obstruction was introduced in the mid-thirties with the work of Barach [1]. Due to a shortage in the helium supply in the pre-war period and the introduction of β-stimulants and steroids, the interest in the clinical potential of low-density gas mixtures faded towards mid-century.

Recently, helium/oxygen mixtures experienced a renaissance in the treatment of respiratory disease in the ICU. The use of helium/oxygen mixtures as a supportive therapy in severe, conventionally treated asthma has recently been detailed by Kass [2], Manthous [3], and Gluck [4]. Clinical investigations using low-density gas mixtures in lung disease dominated by changes in compliance are under way Petros [5].

Monitoring respiratory volumes requires equipment which must be adapted to low-density gas mixtures. We have evaluated the Datex AS/3 SSS (side stream spirometry) with D-lite using low-density gas mixtures of helium, nitrogen, and oxygen under conditions of con-

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trolled (volume and pressure) ventilation in a bench test and spontaneous breathing in a body plethysmograph in order to ascertain its accuracy in the ICU. The use of a modified Pitot tube has been previously described in pediatric intensive care by Wolf [6] and during gas flow measurements during exercise by Porszasz [7]. The tube used here is described in Meriläinen [8].

MATERIALS AND METHODS

Spirometric measuring apparatus

The Datex AS/3 includes the D-lite and a side stream spirometry (SSS) software module calculating pressure, flow, and volume based on the principle of a turbulent flow-inducing restrictor.

The Datex SSS D-lite and spirometry module calculates volume on the basis of pressure difference as follows: on inspiration, gas moves from the ventilator to the patient passing point A where total pressure is measured. Simultaneously, pressure at point B is measured as the static pressure. A disposable double-lumen tube of fixed length conducts the pressure difference to the spirometry module. The static pressure at B is subtracted from the total pressure at A resulting in dynamic pressure. The square root of dynamic pressure is proportional to the linear velocity of a gas mixture. Linear velocity multiplied by the cross-sectional area of the D-lite equals volume velocity (flow rate). Integrated over time, volume velocity equals volume. The D-lite is designed to work bidirectionally; during expiration, the process is reversed. This arrangement method implies that there is no gas flow in the double-lumen tube, hence no humidity problems [9]. The aerodynamic principle of the D-lite is based on the Bernoulli principle, see appendix for mathematical equations. The software handling the signals from the D-lite contains an algorithm that calculates the density of the mixture on the basis of the identification of gases sampled at C, Figure 1. Oxygen is detected, as are carbon dioxide, nitrous oxide, and five of the halogenated anaesthetics. The balance – as presumed by the software – is made up of nitrogen. When using the D-lite with other gas mixtures, the algorithm requires modification. The AS/3 D-lite reports linear velocity or flow based on **p**resumed density (ρ_p): linear $V_p \propto \sqrt{(\Delta P/\rho_p)}$. To calculate the compensation between V_p and $V_a \propto \sqrt{(\Delta P/\rho_a)}$, linear velocity based on **a**ctual density ρ_a, the relation V_a/V_p is transformed to $V_a = \sqrt{(\rho_p/\rho_a)} \cdot V_p$. (See Appendix for a complete derivation of the correction factor.) Furthermore, it may be noted that calculation of flow is based on turbulent flow in the D-lite. At low

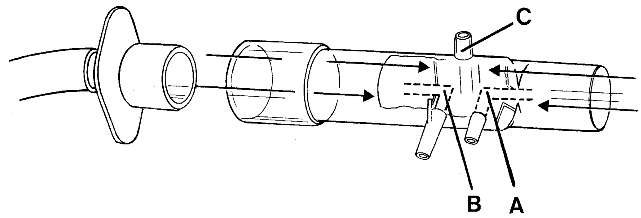

Fig. 1. The Datex D-lite. Reproduced with permission. (A) and (B) measuring pressure, (C) sampling for gas analysis.

linear velocity, laminar flow reigns and the software resorts to tabulated values. At laminar flow, the pressure difference is calculated according to Poiseuille's law using viscosity rather than density. Mixtures of oxygen and nitrogen show a linear relationship, increasing approx. 0.3 μP/%O_2 in the range 20–80% (183–200 μP), whereas mixtures with helium/oxygen behave according to a peculiar curvilinear relationship; the difference in viscosity over the therapeutic range of FIHe varies between 210 and 212 with a maximum at FIO_2 0.4 of 215 μP [10, 11]. These factors are of minor importance and are not incorporated in the present evaluation of the D-lite.

For the comparison of controlled ventilation in the bench test, we used the *Biotek Ventilator Tester* as the golden standard.* We used a *body plethysmograph* for the measurements of spontaneous breathing in human volunteers.

Testbench

The testbenches for controlled and spontaneous ventilation are shown in Figures 2 and 3.

PROCEDURE

Two situations were simulated.

- Controlled (pressure and volume) ventilation in a lung model (PC/VC).
- Human volunteers, spontaneous breathing in a body plethysmograph (SB).

* The Biotek Ventilator Tester 1B complies with the American National Standards Institute standard Z79.7 concerning compliance, resistance, and measurement of pressure volume, and flow.

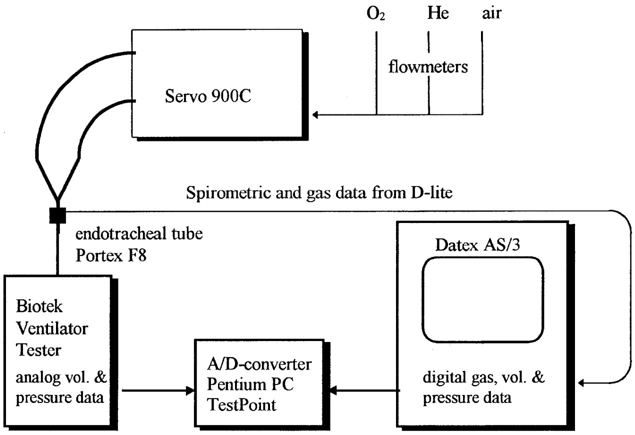

Fig. 2. Testbench for simulated controlled ventilation.

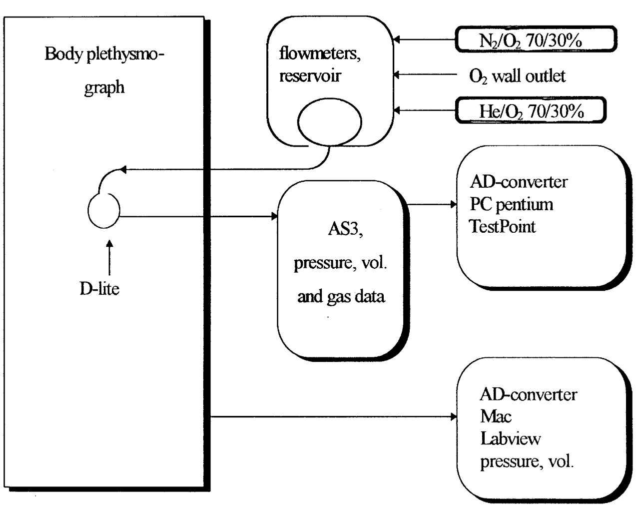

Fig. 3. Setup for the calibration of spontaneous respiration.

Controlled ventilation in a lung model, BVT-1

For the controlled ventilation, the following procedure was used. A Servo Ventilator model 900C was fed with oxygen and helium or oxygen-enriched air. The helium supply was connected to the flowmeter normally designated for nitrous oxide (conversion factor approx. 2 $Lmin^{-1}$ He/$Lmin^{-1}$ N_2O was used on an empirical basis). Helium and oxygen flows were set in such combinations that F_IO_2 was represented at low (approx. 21%), medium (approx. 50%), and high (approx. 80%) levels. Reciprocally, the F_IHe was high (79%), medium (50%), and low (20%). Two concentrations of oxygen in air were used, 21% and 89%. Keeping the frequency constant, the minute volume was changed to vary tidal volume from low (approx. 400 mL) to high (approx. 800 mL) levels. These procedures were used to test pressure-controlled as well as volume-controlled ventilation.

Tidal volumes from the pressure- and volume-controlled situations were measured simultaneously with the Biotek Ventilator Tester Model 1B and Datex AS/3 SSS with D-lite and sampled by an A/D converter (DI-220, Keithley, Taunton, USA) connected to a personal computer (AST 950N, AST Research Inc., USA) equipped with a data-acquisition program, TestPoint v. 3.2b (Capital Equipment Corporation, Burlington, USA).* Sampling frequency was 20 Hz. The AS/3 and BVT-1 were both zeroed, calibrated, and programmed with relevant information concerning barometric pressure, relative humidity, and temperature. All measurements were performed at ambient temperature and pressure, dry (ATPD).

All data were visually inspected and analyzed with respect to inspiratory minimum and maximum values of AS/3 voltage, BVT volume, and F_IO_2. From these were calculated ΔV BVT and Δvoltage AS/3, corrected with the factor $V_p \cdot \sqrt{(\rho_p/\rho_a)}$ when applicable, see above. All values were saved and analyzed in EXCEL (Microsoft Corporation®).

Spontaneous breathing – human model†

The evaluation of the D-lite during spontaneous respiration was performed as follows. Four healthy nonsmoking adults of normal stature (3 females, 1 male) were comfortably placed – one by one – in the body plethysmograph and temperature equilibration was accomplished in approx. three minutes. The person then adapted to a mouthpiece which was connected externally to either a 10–15 L/min flow of N_2/O_2 (70/30%) or He/O_2 (70/30%, 50/50%) through a one-way system of low-resistance valves. The D-lite was mounted outside the body plethysmograph. The person breathed the N_2/O_2 (70/30%) mixture for approximately three minutes and measurements were made during a three-minute period. The gas mixture was then switched to He/O_2 (70/30%) and wash-in to equilibration was performed for three minutes. In accordance with Kety [12], this is the approximate time needed to reach $F_A/F_I = 1.0$ with normal lung function. This was verified using a mass spectrometer (unpublished observations). A three-minute measurement period followed.

* The data acquisition and analysis programs are available as runtime from the author.

† The study has been approved by the Local Ethics Committee 12.12.94.

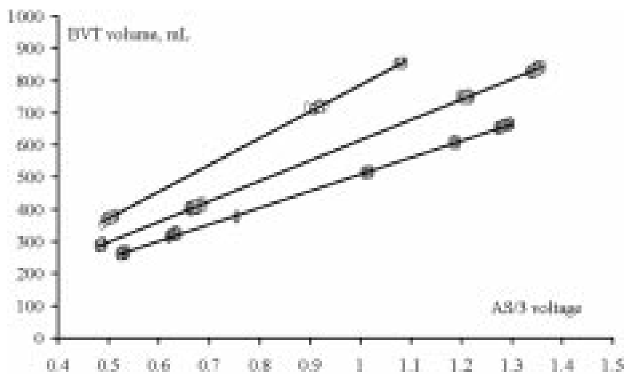

Fig. 4. Relationship between AS/3 voltage, BVT volume, and three mixtures of He/O$_2$ (FiHe 81, 52, 17%) from top to bottom. Measurements from volume- and pressure-controlled modes are grouped together for each density. For the sake of clarity, N$_2$/O$_2$ measurements are omitted.

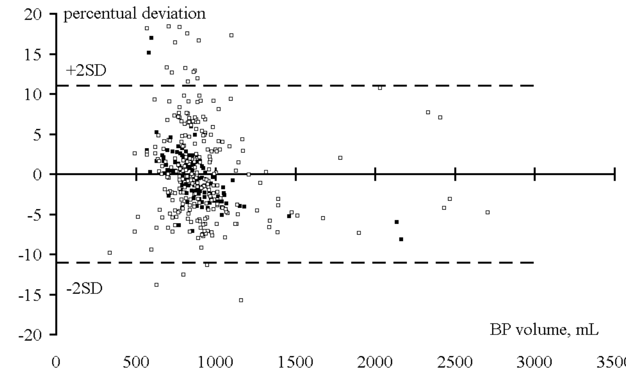

Fig. 7. Percent deviation of AS/3 volume values during spontaneous respiration. He/O$_2$ (open symbols) and N$_2$/O$_2$ (solid symbols) vs. body plethysmographic volume. ± 2 SD lines for the complete measurement.

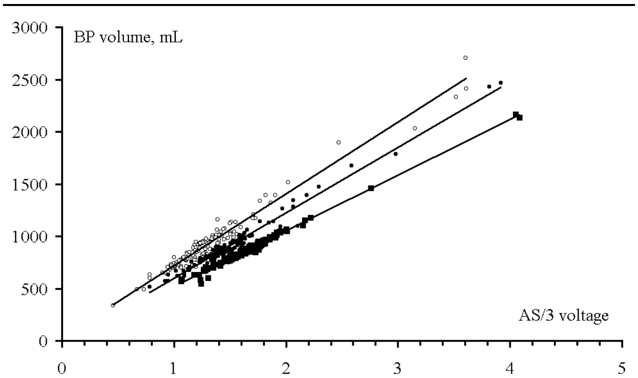

Fig. 5. Relationship between AS/3 voltage, BP, and three mixtures of He/O$_2$ (FiO$_2$ 30% (open circles), 50% (solid circles)) and N$_2$/O$_2$ (FiO$_2$ 30% (solid squares)).

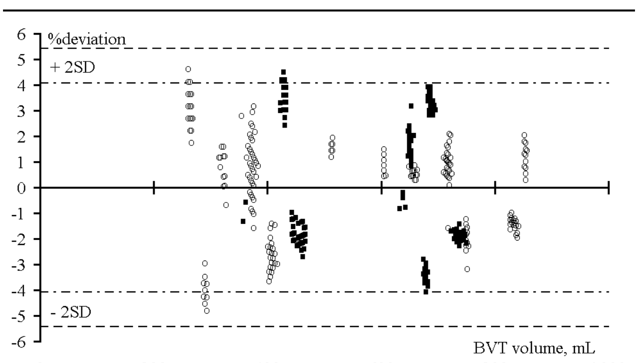

Fig. 6. Percent deviation of the estimated tidal volume PC/VC He/O$_2$ (density corrected) and N$_2$/O$_2$ vs. BVT volume. Black squares, dashed line: N$_2$/O$_2$. Open circles, dashed-dot line: He/O$_2$.

The helium/oxygen mixture was adjusted to 50/50% and another three-minute equilibration was performed before the three-minute measurement period. Data collection thus comprised 3×3 minutes of fully FA/FI-equilibrated breathing with N$_2$/O$_2$ (70/30%), He/O$_2$ (70/30%), and He/O$_2$ (50/50%) and consisted of voltage signals from AS/3 D-lite and volumetric data from the body plethysmograph. As data collection was performed with two different programs (TestPoint and LabView, National Instruments, USA), it was synchronized with an initial vital capacity breath. This was easily recognized later during data analysis.

After synchronization of data from the Mac and personal computer, measurements were analyzed using inspiratory minimum and maximum values of voltages and volumes. The reason for using inspiratory values stems from the fact that characterizing inspiratory density and viscosity in a two-gas mixture gas is much simpler than handling the mixture of five gases during expiration (O$_2$, N$_2$, CO$_2$, water vapour, He).

Analysis

The purpose of simultaneous measurement and analysis of the relationship between either the Biotek Ventilator (BVT)-tidal volume (TV) or body plethysmograhic (BP)-TV, AS/3-volume signal (volt) and density is the establishment of an equation for the calculation of patient-tidal volume (substituting the Biotek Ventilator or body plethysmograph) from corrected AS/3 voltage, FiO$_2$, density, and ventilatory mode.

Calculating the linear estimate from these figures and graphing measured *versus* estimated values revealed a dependency on density that would not have been included in the correction of the voltage signal alone. On an empirical basis, therefore, density was included in the linear estimate as an independent variable for measurements including helium:

PC/VC (He/O_2 mixtures):

$$\text{BVT ("true volume")} = \text{corrected AS/3 voltage} \cdot k_1 + \rho \cdot k_2 + k_3$$

SB (He/O_2 mixtures):

$$\text{BP ("true volume")} = \text{corrected AS/3 voltage} \cdot k_1 + \rho \cdot k_2 + k_3$$

The voltage signal of the AS/3 was in no need of correction for measurements including oxygen-enriched air, as the software assumed an N_2/O_2 mixture. The equation then simplifies to:

$$\text{PC/VC}: \text{BVT ("true volume")} = \text{AS/3 voltage} \cdot k_1 + k_2$$
$$\text{SB}: \text{BP ("true volume")} = \text{AS/3 voltage} \cdot k_1 + k_2$$

This relationship was calculated for all measurements. Measurements were assembled in categories according to gas composition and ventilatory mode (spontaneous vs. pressure- controlled/volume-controlled).

Statistics

The percent deviation of estimated values from measured values was calculated for all series of measurements and frequency tables were constructed. From these, the mean, SD, and 95% confidence level of the deviations were extracted.

RESULTS

All significant results are given in Table 1.

The D-lite produced excellent results when measurements were grouped in controlled ventilation modes He/O_2 vs. N_2/O_2.

In order to obtain the optimum foundation for utilising the estimating equations in data-sampling applications, four equations were set up for the Datex D-lite covering

(i) controlled ventilation He/O_2:

$$\text{volume } He/O_2 = \text{corrected AS/3 voltage} \cdot 481 + \rho \cdot 68 - 74$$

(ii) spontaneous breathing He/O_2:

$$\text{volume } He/O_2 = \text{corrected AS/3 voltage} \cdot 466 + \rho \cdot 65 - 39$$

(iii) controlled ventilation N_2/O_2:

$$\text{volume } N_2/O_2 = \text{AS/3 voltage} \cdot 517 - 18$$

(iv) spontaneous breathing N_2/O_2:

$$\text{volume } N_2/O_2 = \text{AS/3 voltage} \cdot 532 - 11$$

Table 1. Categories of ventilatory modes and densities with statistical measures

Gas mixture and ventilatory mode		k_1	k_2	k_3	r^2	SD % dev.	95% CM
He/O_2	VC & PC	481	67.5	−73.5	99.8	2.3	0.20
	SB	466	65	−39	96.9	5.6	0.68
N_2/O_2	VC & PC	517	−18		98.4	2.7	0.35
	SB	532	−11		98.7	3.4	0.61

Abbreviations: VC – volume-controlled; PC – pressure-controlled; SB – spontaneous breathing; CM – confidence of the mean.

DISCUSSION

The AS/3 D-lite with Datex side stream spirometry module was evaluated with different mixtures of helium/oxygen and oxygen-enriched air in an *in vitro* and *in vivo* experimental setup. After analyzing the digital voltage signals related to volume, gas mixture, and density, four equations were established relating analog tidal volume signals (BVT, BP) in controlled and spontaneous breathing to gas mixture. Regression equations concerning helium/oxygen reached better precision when density was included as an independent variable.

The construction of the D-lite SSS (Figure 1) is based on the Bernoulli equation. The pressure-sensing points are placed opposite each other and in concave sensing areas, resulting in an increased pressure difference between measuring points. The pressure measurement is possible during in- and expiration. The construction of the D-lite provokes a turbulent flow across a constriction with a short distance to uniform the flow profile. The sensors of the AS/3 measure O_2, CO_2, N_2O, and anaesthetic agent and calculate density on the assumption that the balance is N_2. Datex AS/3 uses a paramagnetic principle which is undisturbed by the presence of helium (this is in contrast to the measurement of CO_2 based on extinction of infrared wavelength).

The present evaluation deviates from these presuppositions: using He/O_2 mixtures lowers resistance in the D-lite, thus converting a turbulent flow into a laminar one. Under measuring conditions using "normal" gases, the software implements tabulated flow values when the pressure difference was low and flow expectedly laminar. This algorithm, naturally, is also involved when using low-density gas mixtures and the more so as a greater proportion of flow states is laminar. This may explain the success of adding density to the linear estimate. This was, however, without effect when tried on data from spontaneous breathing. Nevertheless, it may be assumed that, to a greater extent, quiet breathing generates small pressure differences and laminar flow states and the effect of adding density independently may be obscured by these circumstances. Spontaneous breathing entails much greater biological variation per se compared to controlled ventilation. Thus, the Equation stated above for "He/O_2 spontaneous breathing" does not impart any greater precision than a formulation *without* density as an independent variable. The present formulation is maintained for reasons of symmetry.

Analysis proceeded from minimum and maximum values of the *inspiratory* limb assuming a density correction based on the exchange of He for N_2. In the lung model, composition of in- and expiratory gas is unchanged, but – theoretically – the *in vivo* use of inspiratory values (based on a two-gas mixture) introduces an error when they are used for the calculation of expiratory volumes since the AS/3 corrects density including F_ECO_2. The error, however, is infinitesimal.

According to manufacturer's specification, measurement of tidal volume has a precision of ±6% in the Datex D-lite. In the present evaluation, we achieved a SD of less than 5%. It may be noted that the correlation between the equation for controlled ventilation with N_2/O_2 and the scaling from the manufacturer showed a correlation of 99.3%.

APPENDIX

The Bernoulli principle states that total pressure equals the sum of *potential*, *kinetic*, and *gravitational* energy:

$$P_o = p + (1/2)\,\rho\,V_1^2 + \rho\,g\,z \tag{1}$$

The gravitational element ($\rho g z$) in this context is negligible. From this linear velocity can be isolated:

$$V_1 = \sqrt{(p_{stagnation} - p_{static})/\rho}\ , \tag{2}$$

Multiplied by the cross-sectional area of the conducting tube, volume flow and integrated over time volume are calculated.

Calculation of corrected volume signal

$V_{AS/3}$	Datex AS/3 flow signal
$V'_{AS/3}$	corrected Datex AS/3 flow signal in helium/oxygen mixtures
$k_{1,2,3}$	constants
ΔP	pressure difference
$\rho_{presumed}$	density of gas mixture of N_2 and O_2 as assumed by AS/3
ρ_{actual}	density of gas mixture of He and O_2
ρ_{He}	0.1571 kg/m^3, 1ATA, 37 °C
ρ_{N_2}	1.101 kg/m^3, 1ATA, 37 °C
ρ_{O_2}	1.258 kg/m^3, 1ATA, 37 °C
F_{O_2}	fraction of oxygen

$$V_{AS3} = k \times \sqrt{\frac{\Delta p}{p_{presumed}}} \Rightarrow \Delta p = (V_{AS3})^2 \times \rho_{presumed} \times \frac{1}{k^2}$$

$$V'_{AS3} = k\sqrt{\frac{\Delta p}{\rho_{actual}}}$$

Inserting ΔP

$$V'_{AS3} = k\sqrt{\frac{(V_{AS3})^2\rho_{presumed}}{k^2\rho_{actual}}} = V_{AS3}\sqrt{\frac{\rho_{presumed}}{\rho_{actual}}}$$

$$\rho_{presumed} = F_{O_2}\rho_{O_2} + (1 - F_{O_2})\rho_{N_2} = F_{O_2}(\rho_{O_2} - \rho_{N_2}) + \rho_{N_2}$$

$$\rho_{actual} = F_{O_2}\,\rho_{O_2} + (1 - F_{O_2})\rho_{He} = F_{O_2}(\rho_{O_2} - \rho_{He}) + \rho_{He}$$

Thus

$$V'_{AS3} = V_{AS3}\sqrt{\frac{F_{O_2}(\rho_{O_2} - \rho_{N_2}) + \rho_{N_2}}{F_{O_2}(\rho_{O_2} - \rho_{He}) + \rho_{He}}}$$

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