Neuroanesthesia and Intensive Care

Pressure breathing in fighter aircraft for G accelerations and loss of cabin pressurization at altitude - a brief review

[La respiration sous pression dans les avions de chasse soumis à des accélérations G et à la perte de pressurisation de la cabine en altitude - une étude sommaire]

Lars P. Lauritzen MD, John Pfitzner FRCA

Purpose: The purpose of this brief review is to outline the past and present use of pressure breathing, not by patients but by fighter pilots.

Source: Of the historical and recent references quoted, most are from aviation-medicine journals that are not often readily available to anesthesiologists.

Principal findings: Pressure breathing at moderate levels of airway pressure gave World War II fighter pilots a tactical altitude advantage. With today's fast and highly maneuvrable jet fighters, very much higher airway pressures of the order of 8.0 kPa (≡ 60 mmHg) are used. They are used in conjunction with a counter-pressure thoracic vest and an anti-G suit for the abdomen and lower body. Pressurization is activated automatically in response to +Gz accelerations, and to a potentially catastrophic loss of cabin pressurization at altitude. During +Gz accelerations, pressure breathing has been shown to maintain cerebral perfusion by raising the systemic arterial pressure, so increasing the level of G-tolerance that is afforded by the use of anti-G suits and seat tilt-back angles alone. This leaves the pilot less reliant on rigorous, and potentially distracting, straining maneuvers. With loss of cabin pressurization at altitude, pressure breathing of 100% oxygen at high airway pressures enables the pilot's alveolar PO_2 to be maintained at a safe level during emergency descent.

Conclusion: Introduced in military aviation, pressure breathing for G-tolerance and pressure breathing for altitude presented as concepts that may be of general physiological interest to many anesthesiologists.

Objectif : *Présenter l'utilisation passée et présente de la respiration sous pression, non par des patients, mais par des pilotes de chasse.*

Source : *La plupart des références historiques et récentes proviennent de journaux de médecine aéronautique qui ne sont pas facilement accessibles aux anesthésiologistes.*

Constatations principales : *La respiration sous pression à des niveaux modérés de pression des voies aériennes a été un avantage tactique en altitude pour les pilotes de chasse de la Seconde Guerre mondiale. Avec les chasseurs à réaction rapides et très maniables d'aujourd'hui, des pressions des voies aériennes beaucoup plus élevées, de l'ordre de 8,0 kPa (≡,60 mmHg), sont utilisées en conjonction avec un gilet thoracique à contre-pression et un vêtement anti-G pour l'abdomen et les membres inférieurs. La pressurisation est activée automatiquement en réponse à des accélérations +Gz et à une perte potentiellement catastrophique de la pressurisation de la cabine en altitude. Pendant les accélérations +Gz, la respiration sous pression maintient la perfusion cérébrale en élevant la pression artérielle générale, ce qui augmente le niveau de tolérance G qui est fournie seulement par l'usage de vêtement anti-G et les angles du siège inclinable. Le pilote n'a plus à réaliser des manœuvres difficiles et rigoureuses qui pourraient monopoliser son attention. Avec la perte de pressurisation de la cabine en altitude, la respiration sous pression d'oxygène à 100 % selon des pressions des voies aériennes élevées permet de maintenir la* PO_2 *alvéolaire du pilote à un niveau de sécurité pendant la descente d'urgence.*

Conclusion : *Introduite dans l'aviation militaire, la respiration sous pression pour la tolérance G et pour l'altitude est présentée de façon élémentaire. Le sujet peut attirer de nombreux anesthésiologistes intéressés à la physiologie générale.*

From the Department of Anaesthesia, The Queen Elizabeth Hospital, Woodville South, Australia.

Address correspondence to: Dr. John Pfitzner, Department of Anaesthesia, The Queen Elizabeth Hospital, 28 Woodville Road, Woodville South, SA 5011, Australia. Phone: +61-8-8222-6000; Fax: +61-8-8222-7065; E-mail: pfitznerwines@ozemail.com.au

Accepted for publication September 26, 2002.

Revision accepted December 13, 2002.

IT is often overlooked by anesthesiologists and intensivists that the first serious interest in positive pressure breathing was not for the purpose of medical applications,[1–3] but for that great catalyst of human ingenuity – war. In the present brief review the different military roles of pressure breathing are outlined, from its introduction during World War II to its current use in today's highly sophisticated fighter aircraft.

World War II

The majority of World War II fighter aircraft were not pressurized and facemask breathing of oxygen at airway pressures higher than atmospheric, together with a counterpressure waistcoat (Figure), gave pilots a tactical advantage by enabling them to fly at higher altitudes.[4,5] The practical and theoretical aspects of this so-called pressure breathing are well documented in an informative article by Gagge *et al.* from Wright Field Aeromedical Laboratory.[4] By the time this paper was published in February 1945, the authors were able to report that the practical ceiling for the breathing of pure oxygen was approximately 12.8 km (42,000 ft) for brief periods. However, by using pressure breathing at airway pressures of 2.0 to 3.3 kPa (equivalent to 15 to 25 mmHg at sea level), a few minutes at 15.2 km (50,000 ft) could be tolerated.

Today's fighter aircraft

In today's powerful fighter aircraft, although the cabin is pressurized the pilots still use pressure breathing apparatus, counterpressure thoracic vests, and anti-G suits for the abdomen and lower body. They do so for two reasons. First, pressure breathing has a contributory role in achieving the marked elevation of systemic arterial pressure[6] that is necessary to maintain cerebral perfusion and pilot consciousness and capability[7] during +Gz accelerations such as occur when the aircraft loops backwards or comes sharply out of a dive. To apply the positive airway pressure, sophisticated pressure breathing/chest counterpressure systems are used,[8,9] such as the COMBined Advanced Technology Enhanced Designed G-Ensemble (COMBAT EDGE). Use of this pressure breathing for G-tolerance (PBG) system has been shown to increase the level of G-tolerance that is afforded by the use of anti-G suits and seat tilt-back angles alone.[9] The system is automatically activated at +4Gz and the breathing pressure increases by 1.6 kPa (≡ 12 mmHg) with each +1Gz increase, to a design maximum of 8.0 kPa (≡ 60 mmHg) at +9Gz.[8,9]

Also very important in elevating systemic arterial pressure during +Gz accelerations is the pilot's performance of rigorous active straining.[9] However, it is believed that the use of pressure breathing will lessen pilot reliance on these rigorous straining practices, and so reduce the physical and mental stresses that occur during high +Gz maneuvers.[9]

FIGURE Early pressure breathing mask and waistcoat. Picture sourced from a previously "RESTRICTED" September 1952 British Admiralty/Air Ministry publication, stored in the Royal Air Force Museum, Hendon, London NW9 5LL and identified as 'Air Publication 1275G, Vol 1, Sect. 3, Chapter 8: pressure breathing equipment'. Annotations reprinted, with the wording unchanged. ©British Crown Copyright/MOD. Reproduced with the permission of the Controller of Her Majesty's Stationery Office.

Second, pressure breathing has a vital role, as pressure breathing for altitude (PBA), in the event of a sudden and potentially catastrophic loss of cabin pressurization at altitude.[10] Because an adequate alveolar PO_2 (PAO_2) requires an adequate inspired PO_2 (PIO_2), pilot oxygenation in the event of loss of cabin pressurization becomes increasingly precarious at the low ambient barometric pressures seen at high altitude. The influence of altitude on PAO_2 is summarized in the Table, for subjects breathing either air or 100% oxygen.

TABLE The influence of altitude and pressure breathing on PAO_2

Situation	*Height/ altitude (m)*	*Ambient pressure (kPa)*	*(mmHg)*	*PIO_2 (mmHg) Breathing oxygen*	*air*	*PAO_2 (mmHg) Breathing at oxygen*	*($PACO_2$) air*
Sea level	0	101	760	713	149	663 (40)	99.0 (40)
Commercial aircraft pressurized to 9,000 ft	2750	73	550	503	105	453 (40)	55.1 (40)
Mt Blanc (Switzerland)	4807	55	415	368	76.9	318 (40)	39.4 (30)
Highest human habitation	5500	50	374	327	68.3	277 (40)	43.3 (20)
Mt Kilimanjaro (Tanzania)	5895	47	354	307	64.2	257 (40)	39.2 (20)
Loss of consciousness breathing air - unacclimatized	6000	46	347	300	62.7	250 (40)	37.7 (20)
Mt McKinley (Alaska Range, USA)	6194	45.5	344	297	62.1	247 (40)	
Highest altitude for retaining consciousness during free fall without oxygen - 28,000 ft (parachute not opened)	8400	34.5	260	213	44.5	163 (40)	
Mt Everest (Nepal) - [acclimatised]	8848	33.5	253	206	43.1	156 (40)	[29.3 (11)]*
Loss of fighter aircraft pressurization above 39,000 ft -pressure breathing oxygen required	11900	19	144	97	20.3	47 (40)	
Maximum altitude for commercial aircraft - 43,000ft	13100	16	123	76	15.9	51 (20)	
Loss of consciousness breathing oxygen - unacclimatized	13700	14.5	110	63	13.2	38 (20)	
Pressure breathing oxygen at 60,000 ft -airway pressure ≡ 70 mmHg[14]	18290	7.2	54.2	77†	-	52 (20)	
Tears (at 37°C) boil	19200	6.2	47.0	very low	very low	too low	
Pressure breathing oxygen at 72,000 ft -airway pressure ≡ 80 mmHg[14]	21950	≈ 4	≈ 30	63‡	-	38 (20)	

The values given for PAO_2 have been derived using the formula, $PAO_2 = PIO_2 - (PACO_2 * 1.25)$; where $PIO_2 = (\text{Bar. Press.} - 47) * F_IO_2$. Note: the figure for $PACO_2$ used in each calculation of PAO_2 is given in brackets, e.g., (40), (30), (20) or (11). * = climbing Mt Everest without oxygen;[11] † = the figure of 77 mmHg is the sum of 54 + 70 – 47 mmHg; ‡ = the figure of 63 mmHg is the sum of 30 + 80 – 47 mmHg.

The PAO_2 values (in mmHg) were calculated using the formula, $PAO_2 = PIO_2 - (PACO_2 * 1.25)$; where $PIO_2 = (\text{barometric pressure} - 47) * F_IO_2$; and where different values for $PACO_2$ were used.

The reason that different values for $PACO_2$ were used in the Table calculations is to demonstrate the very relevant effect that hyperventilation has on PAO_2, especially at altitude. A good example is that of acclimatized mountaineers climbing Mount Everest. Without gross hyperventilation to a $PACO_2$ of the order of 1.5 kPa (≡ 11 mmHg), it would be impossible to conquer Mount Everest breathing air[11] (see Table). Even climbing Mount Kilimanjaro breathing air requires hyperventilation and a $PACO_2$ of the order of 2.7 kPa (≡ 20 mmHg).

In aircraft below 12.8 km (42,000 ft), as in commercial jets flying at about 12.2 km (40,000 ft), the ambient pressure is such that prompt use of oxygen via facemask allows consciousness to be maintained while the aircraft makes an emergency descent.[12] However, to maintain full fighter pilot capability in the event of loss of cabin pressurization, pressure breathing is used at altitudes above 11.9 km (39,000 ft).

With pressure breathing it has been shown that at an airway pressure of 9.3 kPa (≡ 70 mmHg), physiologically safe PAO_2 levels can be achieved following rapid decompression at simulated altitudes of 18.3 km (60,000 ft) and higher.[13,14] Thus, the pilot can initiate a rapid emergency descent or if necessary safely eject. The use of pressure breathing at airway pressures of the order of 8.0 kPa (≡ 60 mmHg) has enabled the approved and published ceiling of operation of planes such as the 'Eurofighter' to be increased from 15.2 km (50,000 ft) to 18.3 km (60,000 ft).

The practical use of PBA systems in emergency 'get me down' exercises has recently been assessed by Lindeis *et al.*[14] in six trained volunteers who underwent rapid pressure-chamber decompression from a simulated operational[15] altitude of 6.9 km (22,500 ft) to a simulated postemergency altitude of either 18.3 km (60,000 ft) or 21.9 km (72,000 ft). The decompression was initiated in 0.6 sec and was maintained for 180 sec in all six subjects following decompression to 18.3 km, and for 60 sec in all six subjects following decompression to 21.9 km. Only four of the six subjects were able to complete the second 60 sec of the study at the 21.9 km simulated altitude. The inspired oxygen was 100%, and the airway pressure of the PBA system was activated to either 9.3 kPa (≡ 70 mmHg) or 10.6 kPa (≡ 80 mmHg) for the two different decompression altitudes. Using a sophisticated visual-serial-choice assessment, it was found that there was a greater impairment of reaction time following a rapid decompression to 21.9 km (72,000 ft) than to 18.3 km (60,000 ft). This greater impairment of reaction time was considered to be due not to hypoxia, but rather to an impairment of vision caused by the vaporization of tears and subsequent increased tear production.[14] Vaporization, or boiling, of tears occurs at altitudes above about 19.2 km (63,000 ft), where the barometric pressure is 6.26 kPa (≡ 47 mmHg), the saturated vapour pressure of H_2O at 37°C.

With sudden loss of cabin pressurization there is also the possibility of arterial gas embolism[16] as with rapid ascent from an underwater dive,[17,18] and also a considerable risk of decompression sickness from dissolved gas coming out of solution with time.[19–21] This latter risk is very much reduced by preoxygenation to achieve denitrogenation,[15,22] as employed with high flying surveillance aircraft.[22]

Today's fighter pilots therefore operate in cabins pressurized according to a pressurization schedule,[15] they breathe up to 100% oxygen,[15] and they wear and use pressure breathing equipment. Pressure breathing, without appreciably restricting pilot mobility, improves G-tolerance and hence pilot performance, and also reduces the grave risks inherent in loss of cabin pressurization at altitude.

Elusive information

Back during World War II, the fighter planes were very much slower than today's jets, were much less maneuvrable, they flew at much lower altitudes, the cabins were mostly unpressurized, and the pressure breathing airway pressures were very much lower. Even so, pressure breathing did give fighter pilots a tactical altitude advantage and was in use in World War II. What is uncertain from the published literature, however, is the identity of the nation that first used pressure breathing apparatus in combat, and in which year. Whether or not pilots realized at the time that the use of pressure breathing reduced the risk of G-induced loss of consciousness is also unclear. Perhaps a colleague with an interest in the history of continuous positive airway pressure (CPAP) or of pressure breathing in military aircraft will be able to throw some light on this elusive information.

Conclusion

Pressure breathing has recognized roles both in fighter aircraft and as CPAP in the intensive care unit, but the indications for its use and the benefits derived are completely different in the two settings. In the intensive care unit it is used in the management of selected patients with low lung compliance and airway closure, with the object of improving alveolar expansion, reducing alveolar collapse, improving the pattern and lessening the work of breathing and, as a consequence, improving arterial oxygenation. In fighter aircraft, on the other hand, pressure breathing at airway pressures far in excess of those used in clinical practice enables highly trained pilots with healthy lungs to better tolerate +Gz accelerations and to better survive potentially catastrophic loss of cabin pressurization at altitude.

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