# Air flows during anti-G straining manœuvres (AGSM)

**Mohan B Dikshit, Sunil K Chhabra**
(with the technical assistance of HK Vats)
*Department of Cardiorespiratory Physiology, Vallabhbhai Patel Chest Institute, University of Delhi,*
*PO Box No. 2101, Delhi 110 007, India*

*Air flows generated during anti-G straining manœuvres are not well documented. We trained 9 male volunteers (age 28 ± 5 yr; ht. 168.7 ± 5 cm) to do the AGSM manœuvre in the laboratory. The subjects then performed an acceptable maximal expiratory flow volume (MEFV) curve manœuvre into a computerized lung function system (Med Science). They then did 3–4 AGSM manœuvres into the same equipment. The AGSM recording was repeated while using a low-resistance breathing mask and tubes system to simulate an aircraft oxygen breathing system. The volume intake during AGSM (3.68 + 0.69 (SD) litres was significantly lower ($P < 0.001$) than the FVC (4.30 ± 0.62 l). The PEFR during AGSM was higher (9.84 + 1.03 lps AGSM vs 9.54 + 0.95 lps; $P < 0.05$). The peak inspiratory flow (PIFR) during AGSM (8.87 ± 0.92 lps) was significantly more ($P < 0.01$) than the MEFV PIFR of 7.73 ± 1.57 lps. With the mask and tubing on, the volume intake did not change during AGSM, but the PEFR and the PIFR reduced significantly ($P < 0.01$) to 8.77 ± 0.97 lps and 7.93 ± 1.65 lps, respectively. The results indicate that fairly high flow rates are generated during the AGSM manœuvre. Aircraft oxygen equipment in current use may not cater to such high flow rates.*

*In another group of 6 subjects, the $VO_2$ consumption at rest (0.207 ± 0.013 (SEM) lpm) increased to 0.336 ± 0.014 l at the end of 10 continuous AGSMs, which took an average of 27.1 s to perform. This amounts to a $VO_2$ of 0.749 ± 0.03 lpm, a near 3.5-fold increase. The equivalent energy utilization was 1.03 ± 0.07 kcal/min, which increased to 1.69 ± 0.07 kcal during the AGSMs (3.78 ± 0.16 kcal/min). The mean volume intake/AGSM was 3.49 + 0.16 l while the best AGSM effort of these subjects when measured separately was slightly greater (3.98 + 0.31 l). This suggests that repeated AGSMs, if required to be done in aerial combat, may reduce the efficacy of the manœuvre, and thus may compromise flight safety. We, therefore, advocate respiratory muscle training to improve AGSM performance.*

**Keywords:** +Gz; $\dot{V}_{max}$; PIF; PEF

New-generation fighter aircraft can generate +Gz stress to the extent of +9 Gz for a few seconds at a time [1]. The incidence of G-induced loss of consciousness in the IAF was reported by Malik *et al.* [2] to be about 11%. A number of measures are being introduced to enable the pilot to maintain functional control of the aircraft during such manœuvres, one of them being the anti-G straining manœuvre (AGSM) [1, 3].

In essence, the AGSM consists of a maximum tensing of all skeletal muscles (abdominal, chest, calf, thigh), and a respiratory effort (rapid inspiration for ~1 s, followed by rapid expiration for 1.5–2 s) [4] which is likely to generate high flow rates, particularly during inspiration. Information on this issue is generally lacking, and needs investigation because, anecdotally, pilots undergoing high sustained +Gz (HSG) training on the human centrifuge have expressed reservations about being able to perform the AGSM effectively while using aircraft oxygen-breathing systems during combat manœuvres involving HSG. It is possible that the breathing equipment impedes the physiologically effective performance of AGSM as it may not cater to the high flow rates which are likely to be generated, and thus may contribute to affecting flight safety adversely. We have, therefore, undertaken this study in the laboratory to try and determine the air flows that are produced while performing the AGSM.

## Material and methods

Nine healthy male volunteers (mean age 28 ± 2.9 (SD) yr; height 168.7 ± 5.3 cm; weight 60.4 ± 5.7 kg) were recruited for the study, which had ethical approval. Their fitness for undertaking the experiment was ascertained after taking a clinical history, and doing a clinical examination, with particular emphasis on the cardiovascular and respiratory systems. None of the subjects were military personnel, nor had they had the occasion to perform the AGSM at any point of time. Each subject was demonstrated the AGSM as per Whinnery and Murray [4] by one of the authors (MBD), with a slight modification that the manœuvre was performed with a semi-closed glottis. The subject then did the AGSM himself to the satisfaction of the observer(s) and was then ready for the experiment.

### *Recording of MEFV and AGSMs: volume and flow rates*

To begin with, the subject performed a classical forced expiratory manœuvre into a dry, wedge spirometer (Med Science) and the output was processed through an APPle IIe computer and Epson Pulmonary Software programme which converted the spirometer output into a flow volume curve. A standard maximal expiratory flow volume (MEFV) curve was thus obtained. After a rest, the subject performed about 3–4 AGSMs continuously into the same spirometer for the output to be analysed by the computer system in the same fashion as he did the MEFV. In this manner, all the respiratory details of the AGSM, which was, in fact, converted into an expirogram, could be obtained, viz. the volume intake (interpreted by the computer as the FVC), the peak expiratory and inspiratory flow rates, and other data, all of which could be printed out at will. The MEFV and the AGSM curves were also superimposed in order to compare the assets of the two expirograms from a fixed point (at TLC). However, the computer was programmed to print out only the 'best' of the efforts made, and hence data for the *best* MEFV and the AGSM efforts were made available.

After a brief rest, the AGSM experiment was repeated while using a breathing system to simulate an aircraft breathing equipment. This consisted of a polyvinyl mask with a rubber mouthpiece, into which were fitted low-resistance inspiratory and expiratory valves. The valves were connected by wide-bore breathing tubes to the wedge spirometer through a wide-bore y-tube connected. The length of this combination was adjusted so that it was similar to the length of the original spirometer tube through which the initial MEFV and the AGSM manœuvres were made. In a separate series of tests on a few volunteers, it was ascertained that the characteristics of the MEFV curve with and without the double-breathing tube system (without the mask) was similar. The system was calibrated frequently using a calibration syringe (Med Science) and the internal calibration of the machine. After the main tests, the subjects' MVVs were also recorded on the computerized spirometer, with and without the breathing equipment.

### *Oxygen consumption and energy expenditure during AGSM*

In a separate series of experiments, the oxygen cost of ground simulation of AGSM was measured in 6 subjects. For this each subject was connected to a ventilation measurement system and $CO_2$ and $O_2$ analysers with an incorporated cardiac monitor (Magna 901 MK 2-PK Morgan) through a low-resistance breathing valve so that the inspired minute ventilation and respiratory rate and a single-lead (CM5) ECG could be monitored directly. He was asked to breath quietly, and when a steady state was reached, the expired air was collected into a polyvinyl bag (100 l) for 2 min. Simultaneously, the minute ventilation and heart rate (ECG monitor) were noted. The collected expired air was then passed through the gas analysers, and the readings noted when they had stabilized. Permanent recordings could not be done.

At the end of this stage, the gas collection bag was again attached to the expiratory valve, while the subject once more settled into a steady-state breathing pattern for about 10 min. At this point, he was asked to begin the AGSM manœuvres, and connected to the recording system after he had taken 2–3 AGSM breaths. The data were collected over the following 10–11 breaths, at the end of which he was disconnected from the system. The time taken for these breathing efforts was noted using a stop watch. The expired air was analysed for the percentages of $O_2$ and $CO_2$. The whole experiment was repeated after a rest of about 10 min. In this manner, we were able to obtain two sets of data for each subject in one sitting. The inspired minute ventilation for the tidal breathing was converted to expired ventilation volume, and the $VO_2$ and $VCO_2$ were calculated to obtain RER. The metabolic cost of resting ventilation was calculated (1 l of $O_2$ consumed is equivalent to 4.87 kcal for RQ value of 0.8, and 5.04 kcal for RQ of 1 and more [5]. The oxygen cost of AGSM was similarly calculated, but only for the actual ventilation recorded (not converted to l/min). Some of the subjects reported symptoms of hyperventilation (faintness, tingling sensations in the peripheries, dryness of mouth) but completed the AGSM breaths effortlessly.

### *Measurement of airway conductance and the effect of using a breathing system on it during tidal breathing, and while performing the AGSM*

In a different set of experiments, we measured specific airway conductance (sGaw) of 6 volunteers in a whole-body constant volume plethysmograph using the method described by Agarwal [6]. In brief, the principle of the method is that at FRC (no flow), as there is no volume change, the box signal is entirely related to the change in air flow. Accordingly, if the change in air flow (on the *Y* axis) and the change in pressure (on the *X* axis) are recorded during tidal breathing in a body box, then the airway conductance may be directly read off as the slope of the flow/pressure relationship described on the oscilloscope. To obtain this, the subject breathed quietly (tidal breathing) into a Fleisch-type pneumotachgraph (no. 4) after he was enclosed inside the body plethysmograph (Warren Collins). The output of the pneumotach was measured using a differential air pressure transducer (Validyne MP 45-16-871) and was suitably amplified through a carrier amplifir (Hewlett Packard 8805 B) and displayed on to the *Y* axis of a storage oscilloscope (Tektronix 5116). The pressure change in the body box was measured using another differential pressure transducer (Validyn) and displayed after amplification on to the *X* axis of the oscilloscope. The oscilloscope was programmed so that two cursors could be placed on the ascending limb of the tracing (inspiratory) to obtain the best-fit slope (viusually). The tangent was then directly displayed on the screen as $\delta V/\delta P$. The system was calibrated for box pressure in terms of volume (5 ml/div) and air flow (0.5 lps/div) to obtain a calibration factor of 0.1. The experiment was repeated while the subject breathed through an oxygen mask and tube assembly (which was slightly different from that used for MEFV curves, as the length of the tubing attached to the mask had to be modified so that it could be used in the confines of the body box). After this experiment, the subjects performed the AGSM in the body box with and without the mask assembly. (The sensitivity of the carrier amplifiers was suitably rearranged for this part of the data collection.)

**Table 1.** The FVC during MEFV and during AGSM manœuvre (l) and the peak inspiratory (PIF, lps) and peak expiratory flow (PEF, lps) in 9 subjects. The values represent mean ± SE. *d* = difference between the two variables

| | MEFV | AGSM | *d* | *P* |
|---|---|---|---|---|
| FVC | 4.30 ± 0.21 | 3.68 ± 0.23 | −0.62 ± 0.10 | < 0.01 |
| PIF | 7.73 ± 0.52 | 8.87 ± 0.31 | 1.13 ± 0.25 | < 0.01 |
| PEF | 9.54 ± 0.32 | 9.84 ± 0.34 | −0.30 ± 0.21 | > 0.05 |

**Table 2.** The volume/AGSM (l) the peak inspiratory and expiratory flows (PIF, PEF; lps) without the breathing equipment (A), and with the breathing equipment (B). Values represent mean ± SE. *d* is the difference between the two variables. *n* = 9

| | A | B | *d* | *P* |
|---|---|---|---|---|
| Volume intake | 3.68 ± 0.23 | 3.65 ± 0.16 | 0.03 ± 0.17 | > 0.05 |
| PIF | 8.84 ± 0.41 | 7.93 ± 0.55 | 0.91 ± 0.23 | < 0.01 |
| PEF | 9.80 ± 0.34 | 8.44 ± 0.32 | 1.36 ± 0.31 | < 0.01 |

### *Statistical analysis*

Paired *t* test was used in stages to compare the variables given in Tables 1 and 2. Similarly, the effect of using a mask and tube system on sGaw during tidal breathing was analysed separately from the sGaw measurements during AGSMs. This was done as the volume history for each set of measurements was different.

## Results

*Volume and flow rate measurements.* The 'FVC' measured during the MEFV and the AGSMs was taken as volume intake per breath. The AGSM volume was significantly lower ($P < 0.01$) than the maximal effort of FVC (Table 1). It was about 85% of the FVC. On the other hand, the peak inspiratory flow (lps) generated by the AGSM efforts was significantly greater ($P < 0.001$), while the PEF (lps) though greater during AGSM was not significantly so (Table 1).

The comparative figures for the volume intake, PEF, PIF for AGSMs without and with breathing equipment are given in Table 2. Though the breathing equipment did not reduce the volume intake significantly, the flow rates were affected.

In an earlier trial, we had measured the volume in 6 subjects during MEFV and AGSMs. In this group too, the AGSM volume of 3.12 ± 0.44 l was about 81% of the FVC volume recorded (3.84 ± 0.32 l). Therefore, it is deduced that the volume intake during AGSM approaches about 81–85% of the FVC.

*MVV.* The use of the breathing equipment reduced the MVV significantly from 151.4 ± 10.9 (SEM) lpm to 127.8 ± 11.4 lpm ($P < 0.01$).

*$O_2$ consumption and energy expenditure.* In this part of the study in 6 subjects, 5 of whom had participated in the volume and flow experiments, the resting oxygen consumption was 0.207 ± 0.013 lpm (SEM). At the end of a mean duration of 27.1 + 1.6 s of the 10 AGSMs, this had increased to 0.336 + 0.014 l (or 0.749 + 0.03 lpm).

The energy utilization at rest was 1.03 ± 0.07 kcal/min, while the 10 AGSMs increased it to 1.69 ± 0.07 kcal for 27.1 s (or 3.78 ± 0.16 kcal/min).

There was a considerable degree of $CO_2$ washout as the RER increased from a resting value of 0.91 ± 0.02 to 1.70 ± 0.08. Even though some subjects reported symptoms of hyperventilation (tingling sensation in the peripheries with numbness, dryness of mouth), none abandoned the AGSM effort of 10 breaths over which the measurements were made.

The mean volume intake of the 10 AGSMs was 3.49 ± 0.16 l. The same subjects had the best effort of 3.98 ± 0.31 l when they had made just 3–4 efforts while recording the flow volume loops on the computer. Therefore, an extended AGSM effort brings down the volume intake per breath (though not significantly so) in this small group examined.

*Airway conductance.* The conductance (sGaw lps/cm$H_2O$) measured during tidal breathing (0.219 ± 0.037 SEM) decreased to 1.49 ± 0.022 when the mask and tube assembly was used ($P < 0.05$). During AGSM, the sGaw was 0.134 ± 0.043 without the breathing equipment, and 0.124 ± 0.028 with it ($P > 0.05$).

## Discussion

Quantitative data on ventilatory needs of pilots flying high-performance aircraft has been made available [7]. During mock aerial combat, the mean ventilation recorded was 26 lpm. It was estimated that the maximum ventilation which may be required to be sustained in flight for periods more than 30 s would be about 55 lpm [8]. However, the quantification did not take into account the ventilatory effort which has to be made during AGSMs. This was probably because the performance of the aircraft then was not high enough to demand such rigorous methods of +Gz tolerance.

While using low-resistance $O_2$ equipment, Harding [9] recorded peak inspiratory flow rate of the order of 350 lpm (5.8 lps). In the present investigation, the peak inspiratory and expiratory flows recorded are greater in magnitude (Table 1). It may be argued that while Harding's data were recorded in flight, ours were done in the laboratory under +1 Gz conditions. It is not clear whether the former data are from AGSMs performed in the air. The data generated during the present set of experiments suggest that AGSMs are likely to generate peak flow rates of the magnitude of 540–600 lpm, which reduce significantly to 450–500 lpm while using the $O_2$ mask and tube. Pyszczynski *et al.* [10] recorded MEFV curves in 6 subjects exposed to +3 Gz stress on a human centrifuge and reported that the PEFR achieved (about 10 lps) was not affected by the exposure. Their subjects did not use the oxygen mask and tube assembly. These authors did not measure the inspiratory part of the flow volume loop. Also, the acceleration (+3 Gz) was of a low magnitude. It is conceded that it is difficult to say as to whether similar peak flow rates are achievable during high sustained +Gz (HSG). Experiments need to be done on the human centrifuge to confirm this. Nevertheless, the observation that even low-resistance $O_2$ mask and tube equipment used by us in this study reduces air flow generation significantly is confirmed by the significant reduction of the MVV from 151.4 ± 10.9 (SEM) lpm to 127.8 ± 11.4 lpm ($P < 0.01$). Therefore, what Harding may have recorded in flight using the low-resistance breathing system may, in fact, have been a representation of impeded max air flow. The anecdotal apprehension of fighter aircrew that while in the air the AGSM efforts may be impeded may have a sound reason.

When a more sensitive index (sGaw) was used, the breathing system used by us produced an impediment to tidal breathing (sGaw reduced significantly). The sGaw during AGSMs was lower than that recorded during tidal breathing, though no statistical comparison was made (sGaw during tidal breathing is measured at FRC, while during AGSMs this was done at a volume closer to RV). The disadvantage of measuring sGaw during AGSM is that, being a forced respiratory effort, dynamic compression of airways and alteration in the airway smooth muscle tone may limit the measured values, as also the interpretation of the result [11]. However, the redeeming features of AGSM are that neither RV nor TLC are reached. Even then, the explanation for this anomaly may be that in the body box we were forced to use a breathing tube which was shorter in length compared to that used during AGSMs recorded on the computerized spirometer because of space restriction. As a corollary, shortening the length of the breathing tubes of aircraft $O_2$ systems and use of man-mounted regulators may be a step in the right direction *vis à-vis* a successful AGSM.

As expected, the $O_2$ consumption (and hence the energy utilized) increased by about 3-fold during the AGSMs. During exposure to HSG in the centrifuge or during simulated air combat, this is likely to increase still further. This increase in $O_2$ consumption is understandable as considerable muscular effort needs to be generated to perform a successful manœuvre. This also involves the main respiratory muscles. Though the oxygen cost of breathing is only about 1–2% of the baseline oxygen consumption [12], this equation may not hold good during the AGSM, where efficiency of the respiratory effort goes a long way in producing a successful protective manœuvre. No data are available on this subject. It is reported that repeated AGSMs are fatiguing [3]. Respiratory muscles can be trained for better strength and endurance by doing static maximal inspiratory and expiratory manœuvres against obstructed airways [13]. Perhaps, aircrew of the state-of-the-art high-performance aircraft should be imparted such training.

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