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EFFECTS OF WEIGHT LIFTING ON INTRATHORACIC PRESSURES GENERATED BY ANTI-G STRAINING MANEUVERS

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Commanding Officer

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ABSTRACT

The purpose of this study was to assess the effects of a physical fitness program on the ability to perform an anti-G straining maneuver (AGSM). We used intrathoracic pressure (IP) measured at the mouth as an index of effectiveness of the AGSM. We compared changes in IP in experimental subjects who performed the AGSM 5 times per week and participated in a weight-lifting exercise program to IPs in control subjects who performed the AGSM 10 times per week and did not participate in a weight training program. Initial mean IPs were 169 mmHg and 167 mmHg for the experimental and control groups, respectively. After 6 weeks of exercise and AGSM training, mean IP for the experimental subjects was 213 mmHg (26% increase). After 3 weeks of AGSM training, mean IP for the control group was 202 mmHg (21% increase). The difference in pre- and post-IPs between groups was not significant, but both groups significantly increased their IPs with training. Multiple linear regression analysis showed that pulmonary vital capacity and the strength of several muscle groups were significant predictors of IP in the experimental group. We conclude that strength and anaerobic fitness may be important for the performance of an effective AGSM. However, the AGSM training alone appeared to improve the performance of the AGSM as indicated by the increased IPs.

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INTRODUCTION

The long-term objective of the G-tolerance research program at this laboratory was to evaluate and recommend training programs for aviators that would improve their ability to perform effective anti-G straining maneuvers (AGSM) and thus expand their physiological performance envelope during tactical air combat. A straining maneuver was used by aviators in World War II to prevent loss of consciousness under high-acceleration forces (1). It was very similar to the Valsalva Maneuver described for decades in medical physiology literature as the voluntary increase in intrathoracic pressure by forcible exhalation against a closed glottis. This maneuver increases pressure in the arteries leading to the brain and, therefore, can be used to partially counter the deleterious effects of head-to-foot (+Gz) acceleration. It has been shown that +Gz acceleration can reduce eye-level blood pressure by 20-30 mmHg per 1 Gz of acceleration in a relaxed, seated aviator (2). The theoretical expectation of this phenomena would be that for every 25 mmHg increase in carotid artery pressure induced by the AGSM, the transient physiological performance envelope would be expanded by 1 G. In a series of classic studies, Wood *et al.* (3) documented that a well-trained man can increase his G-tolerance by as much as 3 Gs by using this maneuver. They demonstrated that fluid shifts to the lower body during +Gz acceleration were reduced with an anti-G suit that was inflated simultaneously with the performance of the Valsalva Maneuver. The combination of the two produced hypertension at the heart level of about 250 mmHg such that vision and consciousness were maintained during exposure to +6.5 Gz.

These basic protective measures provided the pilots with a physiological performance envelope that was reasonably compatible with aircraft performance envelopes at that time. Since then, airframe and propulsion technology have produced aircraft acceleration characteristics that exceed the corresponding physiological capabilities of pilots (2). Some of the tactical advantages offered by these aircraft cannot be realized because of physiological limitations of the crews. Part of the gap between pilot and aircraft performance envelopes has been closed with life support equipment engineering improvements, such as, faster G valve, positive pressure breathing with chest counterpressure, and a better anti-G suit. The human body cannot be redesigned, but we may be able to maximize crew performance through selection and training.

In July 1987, the Naval Aerospace Medical Research Laboratory and the USAF School of Aerospace Medicine jointly sponsored a workshop to develop a physical fitness training program that would enhance aircrew G tolerance. Conference participants were selected from professional scientific disciplines and the tactical aviation community. The attendees collectively integrated the current literature on the physiology of exercise, data related directly to G tolerance, and the practical aspects of implementing physical fitness programs in operational aviation units. The group published a special report containing physical fitness programs (4) that concentrated on whole-body strength training and anaerobic endurance training. The programs were designed to improve the strength of the AGSM and the endurance required to maintain a series of maneuvers to sustain consciousness in a typical air-to-air combat engagement. Consideration was also given to exercises that would improve tolerance to postural stress, especially on the head and neck, induced by high-G forces.

The consensus of the scientists participating in the workshop was that the conditioning programs would provide adequate training to maintain strength and anaerobic fitness and, therefore, improve tolerance to severe postural stresses encountered in high-G environments. They were less sure of its effect on the strength and endurance of the AGSM because the maneuver requires complex neuromuscular coordination of several muscle groups. Also, the sensory feedback resulting from increased pressure in the chest, neck, and head (that could provide an indication of effectiveness) is poorly defined and idiosyncratic.

Our objective was to measure the effects of the recommended exercise program on the strength and effectiveness of the AGSM. We measured strength and effectiveness as the pressure generated at the mouth with an open glottis during a forceful exhalation into an occluded system containing a pressure transducer. Our hypothesis was that the mouth pressures (MP) would increase in both experimental and control groups due to a learning effect and that the experimental group would show an additional increase in MPs because of enhanced strength from the weight lifting program. We assumed that forced exhalatory pressure with an open glottis measured at the mouth was equivalent to intrathoracic pressure (IP) generated by an AGSM against a closed or partially closed glottis.

MATERIALS AND METHODS

Eighteen male student naval aviators of the initial thirty volunteers completed the study. Each subject was thoroughly briefed on the procedures and the known risks. They were advised that they could withdraw from the project at anytime without bias or prejudice to their careers. They were encouraged to ask questions of the investigators and the medical monitor. Those agreeing to participate signed a consent form and a privacy act statement. A Navy Flight Surgeon gave each subject a physical examination and rejected or cleared them for further participation. After being cleared to participate, the subjects were randomly assigned to either the experimental or control group. A pulmonary function test to determine vital capacity (VC) was done on all subjects.

Each subject received instruction on the physiology of G-induced loss of consciousness (GLOC) and was taught to perform a correct AGSM. They also were trained on the apparatus for measuring MP. They were directed to generate maximum pressure as indicated visually to them on a pressure gauge. They were advised to avoid emphasizing the use of any specific muscle group.

The pressure measuring apparatus consisted of a mouthpiece, an aneroid pressure gauge, a pressure transducer with an amplifier that converted pressure to an electrical voltage, and a chart recorder that recorded the pressure output. The mouthpiece was fitted to an adapter that connected it to flexible tubing with an inside diameter of approximately 3 mm. This tubing was attached through a "Y" connector to the aneroid pressure gauge and the pressure transducer. The dead space of the tubing was approximately 20 ml. Both the aneroid pressure gauge and pressure transducer could measure pressures up to 300 mmHg with a resolution of 2 mmHg. Mouthpieces were sterilized with a 2% glutaraldehyde solution.

To warm-up before exerting maximal effort in an AGSM, subjects were instructed to inhale and then exhale into the mouthpiece with only enough force to generate 20 mmHg of pressure and hold it for 3 s. After 30 s of rest, they repeated this maneuver generating pressures of 40, 60, and 80 mmHg. They were allowed a short rest before attempting a maximal effort. For the maximal straining maneuver, they inhaled maximally and then forcefully blew into the mouthpiece to increase the pressure reading on the gauge as high as they could, and tried to hold that pressure for 3 s. After a minimum of 1 min of rest, they repeated the maneuver. They continued this cycle with rest periods until 5 maximal straining maneuvers were completed. The entire procedure including warmup exercises constituted one AGSM session. The experimental group completed one AGSM session each week before accomplishing the weight lifting session. The control group completed two AGSM sessions per week with at least two days separating the sessions. The major assumption underlying this study was that mouth pressures were equivalent to IPs.

The experimental subjects utilized the exercise program for "Stacked Machine Weight Equipment" recommended in the joint USAF/Navy publication "Physical Fitness Program to Enhance Aircrew Tolerance" (Crisman & Burton, 1988). This particular program consisted of a Strength Emphasis Workout and an Endurance Emphasis Workout. The Strength Emphasis Workout included the following exercises: leg press, bench press, latissimus (lat) pull, military press, arm curl, and sit-ups, and was usually performed on Mondays and Thursdays. Each set of lifts in this workout consisted of 6-8 repetitions at a weight set to enable the subject to achieve no more than 8 repetitions in good form (8 RM). The number of sets performed was dictated by the published workout. Subjects in this group were given instructions in proper weight lifting techniques.

The Endurance Emphasis Workout, consisting of leg extension, leg curl, bench press, shoulder shrug, lat pull, seated row, military press, upright row, triceps extension, arm curl, and sit-ups, was usually performed on Tuesdays and Fridays. In each set of an exercise, the number of repetitions was limited only by fatigue; a maximum of 1 min of rest was allowed between each set. No more than 3 sets of each lift were allowed, and if the average repetitions per set exceeded 10, the weight was increased at the next session. The number of sets and repetitions as well as the amount of weight were recorded. At the beginning of the first session and thereafter at the beginning of the Thursday session, the maximum weight that could be lifted only once with good form (1 repetition maximum or 1 RM) was determined. The 1 RM values were used as the criteria strength measurements for the muscle groups involved in that exercise.

Data were analyzed using the Abacus Concepts SuperANOVA software (Abacus Concepts, Inc., Berkeley, CA, 1989). Multiple linear regression analyses with repeated measures of the dependent variable, mouth pressure (MP), were computed with VC as an independent covariate. Type III sums of squares were used. This method removed the effect of all other variables in the model before testing the variable in question. With mouth pressure as the dependent variable, multiple linear regression analyses with 5 repeated measures was performed to determine which muscle groups involved in the exercise program for the experimental subjects accounted for a significant portion of the variance observed in MP. Performance on each muscle group was analyzed each week over a 5-week period. For the strength workout, the 1 RM weight was used as the measure of performance. For sit-ups, the maximum number that could be done as the last event in the strength workout was used as the measure of performance. For the endurance workout, the product of weight lifted and the number of repetitions for the first set was used as the measure of performance for each exercise. Mean MPs from each weekly session were used as the repeated measures dependent variable.

All parameters were forced into the model and computations were performed for a no-intercept model using Type III sums of squares. The partial F ratios could then be interpreted as though they were constructed from a sequential model where each variable in turn played the role of the last variable being entered into the model and was not affected by changing the order of terms in the model. The parameter having the lowest partial F ratio and a p value greater than 0.05 was then deleted and a new model computed. This sequence was repeated until all remaining parameters were significant ($p < 0.05$). Table I summarizes the results of this analysis.

Table 1. Multiple Linear Regression Model for Mouth Pressure Versus Vital Capacity and Muscle Performance.

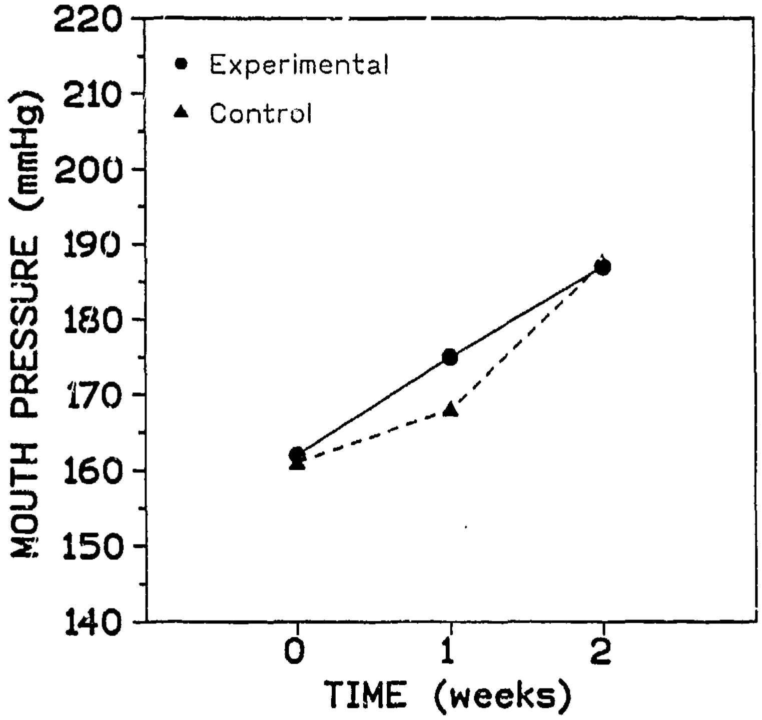
Parameter	F Value	p Value	Beta coefficient
Vital capacity (liters)	12.3	0.0009	15.080
Max lat pull (lbs)	28.4	0.0001	0.856
Sit-ups (repetitions)	5.1	0.0282	-0.145
Shoulder shrug (lbs x repetitions)	14.9	0.0003	0.012
Bench press (lbs x repetitions)	6.1	0.0168	-0.019

Model Summary: R = 0.991, Adjusted R = 0.981, F = 557.0, df = 15, $p < 0.0001$

RESULTS

Results of the first 3 weeks are shown in Fig. 1. The dependent variable for each subject is the mean of all pressures taken during that week (5 trials for the experimental group and 10 trials for the controls). The independent variable is time in weeks. These data are for 15 experimental and 11 control subjects. Each control data point is the mean of 2 sessions separated by at least 2 days during the week. The first data point for the experimental group was taken before the subjects had participated in any of the exercise sessions. Mouth pressures for both groups significantly increased ($p < 0.0001$) over the 3-week period; however, there were no significant differences in MPs between the experimental and control groups. The largest variation in mean MP at any point in time occurred in the second week, but that difference was not significant.

Figure 1. Mean mouth pressure over first 3 weeks for both groups.



Comparisons of MPs over the first 4 sessions of measurements, regardless of the time period over which they were taken, are shown in Fig. 2. Mouth pressures for both groups increased significantly ($p < 0.0001$). However, the increases were not significantly different between the experimental and control groups. The group means for corresponding data points were not significantly different for session 1 or session 2 but were significantly different for session 3 ($p = 0.001$) and session 4 ($p = 0.003$).

Figure 2. Mean mouth pressures over first 4 sessions.

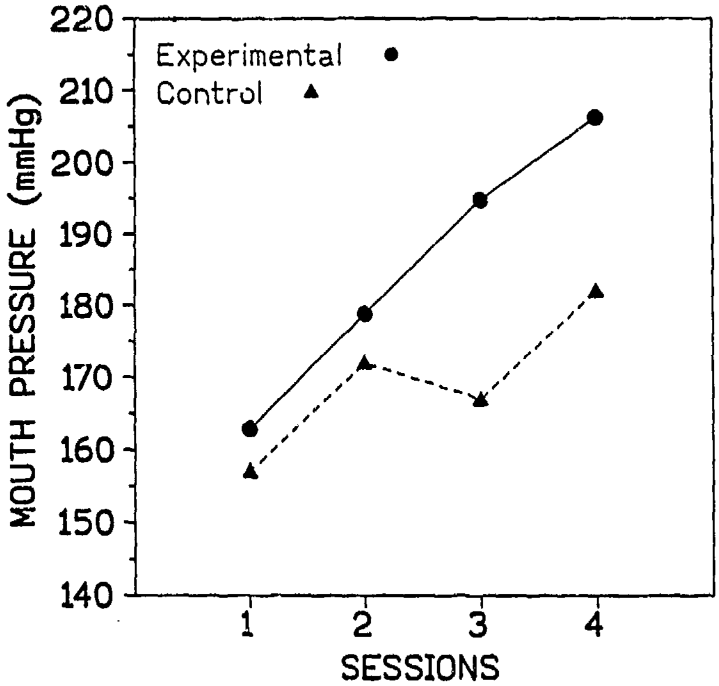
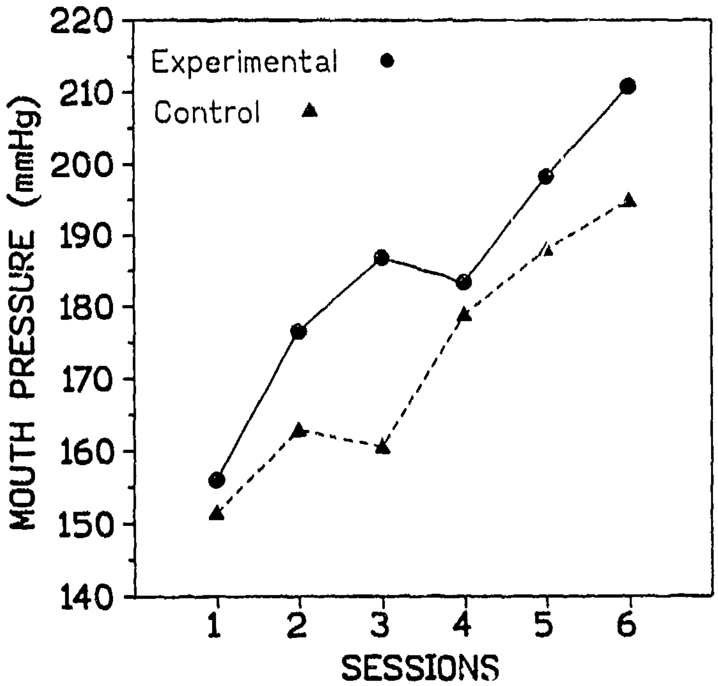


Figure 3. Mean mouth pressures over first 6 sessions.



The analysis of MPs measured during the first 6 sessions, regardless of the time period, are shown in Fig. 3. This plot is structured similar to Fig. 2, but only 8 of the original 15 experimental subjects and 10 of the 11 control subjects were able to continue for all 6 sessions. Mouth pressures for both groups increased significantly ($p < 0.0001$) over time. But again, the changes in MP between the experimental and control groups over the 6 sessions were not significant. The difference between experimental and control MP means at the sixth session was 13 mmHg, and was significant ($p = 0.04$). The initial difference at session one was 4.9 mmHg and was not significant. At session two, the differences were significant ($p = 0.0008$). At sessions 4 and 5, the differences were not significant.

Figure 4 was derived from the same data as Fig. 3 except that only the maximum pressure generated by a subject in any one of the 5 trials in each session was used to compute the group mean. The rationale for this analysis is that each subject was instructed to use maximum effort on each trial, so the best of 5 attempts should be more closely correlated with maximum strength. Maximum pressure significantly increased ($p = 0.0028$) for both groups. The difference in rate of increase between the experimental and control groups was not significant. The groups were not significantly different at any session.

Figure 4. Mean maximum mouth pressures over first 6 sessions.

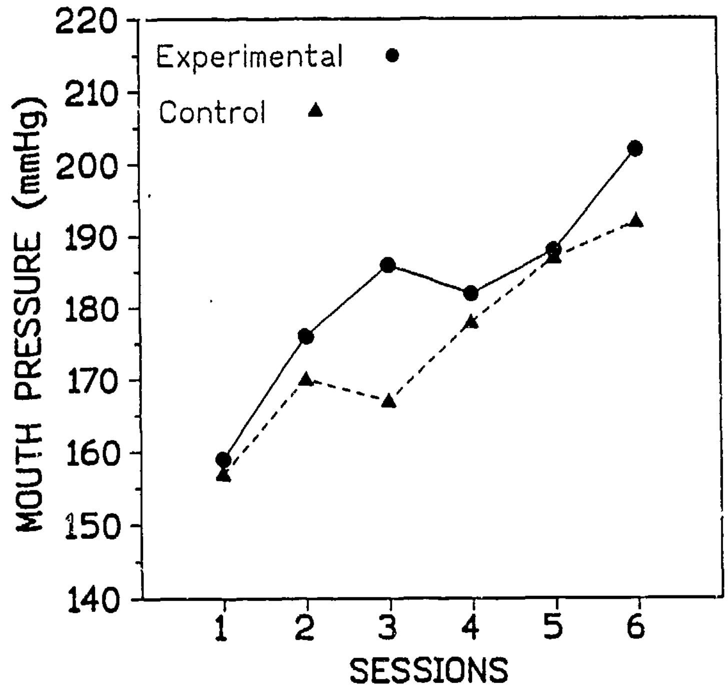


Figure 5 compares AGSM trials within each pressure measuring session. These plots were derived from the same data set as Fig. 4. Mouth pressures for each subject for each of the 5 trials within a session were averaged for the corresponding trials over 6 sessions and then used to compute the group means for each trial. Mouth pressure significantly increased from the first to the fifth trial ($p < 0.001$) for both groups. Once again, the difference in rate of increase between the groups was not significant. The group means were significantly different for trial 1 ($p = 0.007$), trial 2, ($p = 0.05$), and trial 3 ($p = 0.04$), but were not significantly different for trial 4 or trial 5.

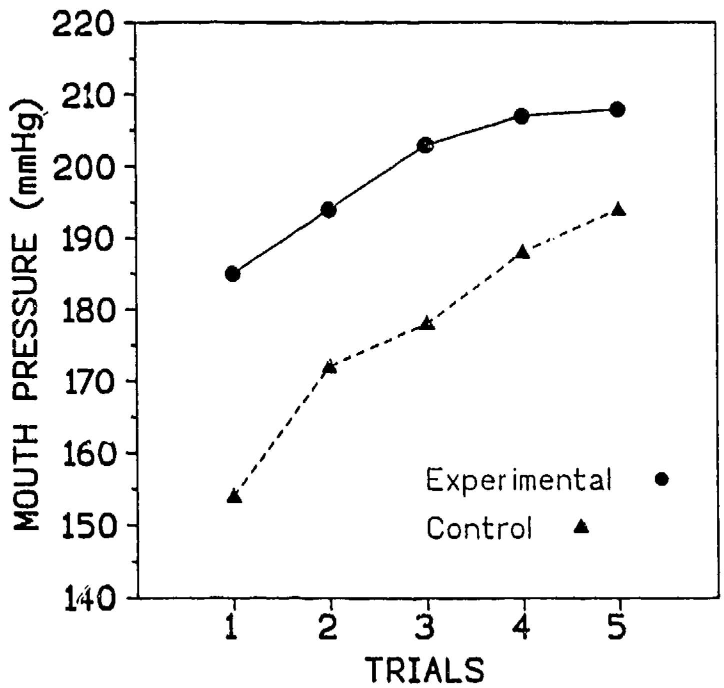


Figure 5. Mean mouth pressure per trial over 6 sessions.

DISCUSSION

We designed our experiment on the assumption that we would have 15 experimental and 15 control subjects available for at least 10 and hopefully 12 weeks. We expected the experimental subjects to increase in strength through the first 10 weeks for training. We intended to measure MP in both groups weekly over this entire period. This protocol would have allowed sufficient time for a significant increase in both strength and endurance in the experimental subjects. The resulting data would also have allowed us to observe the increase in mouth pressure associated with learning the best technique for most effectively performing an AGSM. In reality, only 18 subjects completed the 6-week study.

Another problem that was realized early in the study was attributed to the motivation of our subjects. We learned quickly that most of the volunteers wanted to be assigned to the weight lifting group to prepare themselves for aviation training. Many of the subjects did not want to participate as controls. The control group was not allowed to begin an exercise program during this period. To ensure that we would have an adequate number of control subjects, we had to modify our protocol such that the control subjects would participate in 2, rather than 1, MP-measuring sessions each week for 3 weeks, and then they could begin an exercise program. This procedure produced the same number of pressure measurements in both groups, provided an adequate comparison of the learning effect, and allowed us to evaluate the relative merits of additional straining maneuvers compared with weight lifting exercises.

Burns *et al.* (5) measured eye-level blood pressure and esophageal pressure in miniature swine performing an AGSM under positive 3, 5, and 7 Gz on a centrifuge. They found that the increase in eye-level blood pressure was 0.86 mmHg for every 1.0-mmHg increase in esophageal pressure induced by the AGSM. They also reported that the decrease in eye-level blood pressure for these animals was about 24 mmHg for every 1-G increase in Gz acceleration. This figure compared favorably with values for humans: for every +1 Gz increase there is a 20-25 mmHg decrease in blood pressure at eye level in a relaxed seated subject (2). Assuming that for head-to-heart hemodynamics miniature swine are a reasonably good model for predicting human responses, we can infer that in only 3 weeks of training our subjects increased their G tolerance approximately 1 G. In Fig. 1, the mean increase for 15 experimental subjects was 26.7 mmHg while the increase for 15 control subjects was 26.2 mmHg. Over these 3 weeks, the experimental subjects performed 15 maximal effort AGSMs plus the exercise program while the controls performed 30 AGSMs. These data suggest that any benefits provided by the exercise program in the experimental group were equivalent to 15 additional AGSMs performed by the control group. Comparing the same subjects over 4 sessions regardless of time negates the advantage the control subjects had with the additional sessions, and, therefore, emphasizes the effect of the exercise program in the experimental group. The experimental group had slightly higher MPs in the beginning, but by the third and fourth sessions, the differences were significantly greater, which indicates that the exercise was beneficial.

In Fig. 3, a similar analysis with fewer subjects revealed an unexplained decrease in trends at session 3 for the controls and at session 4 for the experimental group. The last 3 sessions suggest a diverging trend. However, the overall difference in slopes is not statistically significant, and the difference in means at session 6 is only 8.1 mmHg greater than they were at session 1. At this point, the exercise program may have had a slight beneficial effect.

Analyses using only the maximum pressure at each session rather than the mean pressure indicate even less difference between the experimental and control groups. The underlying reason for these differences in maximum pressure and mean pressure can be seen when these same data are analyzed by trial number within sessions as shown Fig. 5. The experimental subjects were clearly more consistent than the controls in their efforts over the 5 trials within sessions. Because MP measurements of the groups were converging and increasing with time, fatigue during the sessions does not provide a rational explanation for this difference. A difference in muscle tone and warm-up time rather than maximum strength seems a more plausible rationale. That would be an important reason for implementing an exercise program since a series of straining maneuvers without rest is frequently required in air combat maneuvers.

The multiple linear regression analysis summarized in Table 1 clearly indicates that VC and the strength performance of 5 muscle groups could be used in a mathematical model to predict the ability to use an AGSM to raise IP. Vital capacity is a function of anatomy that stabilizes with adulthood and cannot be significantly increased with exercise. After VC had been accounted for as an anatomical covariate, the muscle groups associated with lat pulls, sit-ups, and shoulder shrugs were positively correlated predictors of MP generated by an AGSM. It is not difficult to understand why maximum efforts to reduce thoracic volume would recruit these muscle groups. It is understandable that the other two major muscle groups identified in Table 1 associated with the leg press and the bench press might have little, if any, effect on intrathoracic pressure, but it is not clear why these groups have negative beta coefficients. which This indicates that enhanced performance of these groups would have a detrimental effect on the overall ability to perform an AGSM.

To adequately appreciate the contribution of these muscle groups, typical values of each term in the regression equation should be compared. A typical value of the VC would be 5 liters. The corresponding term in the equation would be the product of this value and the beta coefficient (5 X 15.08 = 75.4). Typical values for all the terms would be as follows:

Vital capacity	5 (liters) x 15.080 = 75.4
Max lat pull	150 (lbs) x 0.856 = 128.4
Max leg press	425 (lbs) x -0.145 = -61.6
Sit-ups	50 (reps) x 0.210 = 10.5
Shoulder shrug	3000 (lbs x reps) x 0.012 = 36.0
Bench press	1800 (lbs x reps) x -0.019 = -34.2

We do not have a good physiological explanation for the leg press and bench press having negative coefficients in this model. But if these relationships are real, it may mean that some elements of a whole-body exercise program have a detrimental effect on the magnitude of pressure that can be generated by an AGSM. One possible rationale is that strengthening the chest muscles (via the bench press) may reduce to ability to expand the chest due to increased muscle tone and therefore reduce vital capacity. Likewise, conditioning of the chest and abdominal muscles as a secondary effect of the leg press may have the same effect.

Based on physiological reciprocal inhibition between muscles and their antagonists, we can assume that there is a spinal-level inhibition between the muscle groups that are strong contributors to the AGSM and their antagonists. If the subject is not well-trained, and therefore does not have good voluntary control over the agonist muscle, reciprocal inhibition of the antagonist muscle may also be poorly conditioned. The agonist muscle cannot achieve it's maximum potential. The muscles involved in the bench press and the leg press, as opposed to the muscles used in the lat pull, are more frequently used in normal activities. These exercises are also very popular for men and women involved in recreational weight lifting. Maximal lifts on these 2 exercises are frequently cited in competition as evidence of one's prowess in the weight room. In some of our subjects, these muscle groups may have been disproportionately developed in both strength voluntary control.

The AGSM was unfamiliar to our subjects. The maneuver requires a coordinated near-maximal contraction of muscle groups that we could not adequately isolate in our conditioning program. Under such circumstances, it seems likely that our subjects would have voluntarily, and involuntarily, emphasized those muscle groups that were most developed in both strength and control. Therefore, strong contractions of muscles that had been disproportionately developed by over-emphasizing the leg press and bench press may have had a reciprocal inhibitory effect on antagonist muscle groups that could have had more involvement in effectively raising IP.

CONCLUSIONS

Our sample of Navy and Marine Corps student aviators improved their ability to increase mouth pressures by an average of 40 mmHg, which theoretically improves their G tolerance by 1.5 to 2 Gs. Some subjects improved by 100 mmHg, and most subjects did not reach a clear plateau. They achieved this increase by actively trying to maximize their pressure while doing the maneuver. The rate of increase in the exercise group was not significantly greater than the rate of increase in the control group over the 6-week period that these subjects were available to us. We therefore conclude that practicing the maneuver is very important to maximizing its effectiveness to protect the aviator from G-induced loss of consciousness.

Lung vital capacity and the strength of several muscle groups were significant mathematical predictors of MP used as a measure of effectiveness of an AGSM. We, conclude that strength and anaerobic fitness are important for the performance of an effective AGSM, but a weight lifting program should not be used as a substitute for actually performing AGSMs in training.

RECOMMENDATIONS

We recommend that aviators practice the AGSM to develop good technique and muscle tone. Practice during flight without medical supervision should be done while subjected to +Gz loads in excess of 2 Gs. We recommend that the Naval Aerospace Medical Research Laboratory develop procedures for aviators to safely practice the AGSM at 1 G under the supervision of a flight surgeon. Aviators should also maintain reasonably good strength and anaerobic fitness through a balanced exercise program such as those suggested in the USAF/USN report (1988).

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