DCIEM-SL-1999-107

REVIEW ARTICLE

Physical Conditioning to Enhance +Gz Tolerance: Issues and Current Understanding

William A. Bateman, Ira Jacobs, and Fred Buick

Bateman WA, Jacobs I, Buick F. *Physical conditioning to enhance +Gz tolerance: issues and current understanding.* Aviat Space Environ Med 2006; 77:573–80.

Introduction: Although Canadian Forces (CF) efforts directed at developing new G-protection strategies have often raised the question of potential benefits of physical conditioning (PC) on G tolerance (GT), a fatality in a CF fighter aircraft accident, in which it was suggested the pilot may have had 'sub-optimal GT,' sparked renewed interest in this topic. ***Methods:*** A two-part review was conducted: 1) a survey of the literature on the effects of PC on GT; and 2) a determination of further research required to resolve uncertainties on the subject. ***Results:*** Five key themes surfaced: 1) GT as a concept is complex, and has different connotations for different users; 2) the term 'PC' likewise has a variety of meanings, and precise definitions are necessary to compare research results; 3) in examining the relationship between PC and GT, the roles of strength training, muscle fatigue, and aerobic fitness are not as clear as some studies seem to suggest; 4) in designing PC programs to enhance GT, issues such as palatability, efficacy, and intended target population must be addressed for the program to be operationally useful; and 5) there is a requirement for investigations that have controlled important influences such as intercurrent +Gz-stress exposure, proficiency in performing the anti-G straining maneuver, and the wide inter- and intra-individual variation for PC and GT measurements. ***Discussion:*** The effects of PC on GT are not well established. Further research with more robust experimental designs and/or analyses than those used to date must be conducted (on new or existing data) to clarify this relationship. Conducting such work with sound experimental design and controls is more complex and time-consuming than some may appreciate.

Keywords: acceleration, centrifuge, exercise, +Gz tolerance, physical conditioning, physical fitness.

THE NOTION THAT physical conditioning (PC) can be an effective modality for increasing the ability of aviators to tolerate the considerable +Gz stresses of the modern high-performance aviation environment is prevalent in both the high-performance pilot domain and the aeromedical community (18,21,42). Although it may appear intuitive that physical fitness training might have some role to play in helping an aviator tolerate such stresses, very few studies have investigated the relationship.

Ongoing efforts within the Canadian Forces (CF) directed at developing new G-protection strategies have often raised the question of potential benefits of physical exercise. However, when the investigation report of a fatal 1995 CF-18 Hornet aircraft accident suggested the pilot involved may have had 'sub-optimal G-tolerance,' the CF's Air Command gained renewed interest in this issue. Accordingly, a review was undertaken of available literature relating to the effects of PC on G tolerance (GT) in order to determine if there was an empirically supported consensus within the research community, as well as to clarify what further research (if any) would be needed to address the subject.

KEY ISSUES

In the course of this review, the following five key themes surfaced: 1) intricacies in addressing 'GT' as a concept; 2) analogous intricacies in addressing the concept of 'PC'; 3) the question of ways in which PC might influence GT; 4) the problem of designing operationally useful and acceptable PC programs proven to enhance GT; and 5) devising recommendations for future research needed to address these issues.

I. The Concept of GT

One of the problems making it difficult to separate fact from folklore in the realm of PC and GT is that although the meanings of these terms at first glimpse seem simple, they are instead rather complex concepts having different connotations with different users. In the conduct of the CF's high sustained G centrifuge training program, we have had some exposure to the spectrum of connotations that aircrew infer from the term 'G tolerance' (8). Some examples:

1) "...to be able to still see under G...";
2) "...not do the 'Funky Chicken' [we infer this to mean 'undergo G-LOC with myoclonic or seizure-like activity'] in a fight....";
3) "...to 'feel good' after doing ACMs....";
4) "...to be able to shoot HIM before he shoots YOU...";
5) "...to be able to complete the target runs [in centrifuge training] so I don't have to keep coming back for more rides....".

Although these reflect the inexactitude with which GT can be discussed, they also illustrate some impor-

---

From Defence Research and Development Canada (DRDC) – Toronto, Toronto, Ontario, Canada.

This manuscript was received for review in December 1999. It was accepted for publication in March 2006.

Address reprint requests to: Commander (Ret.) William A. Bateman, M.D., D.Av.Med., DRDC-Toronto, P.O. Box 2000, 1133 Sheppard Ave. W., Toronto, ON M3M 3B9, Canada; bill.bateman@drdc-rddc.gc.ca.

tant dimensions of the term. Example 1 refers to coping with $+G_z$ stress, the severity of which varies with its magnitude, duration, onset rate, starting G level, and frequency and duration of exposure. Both examples 1 and 2 refer to direct consequences of $+G_z$ stress (some of which may be used as endpoints for research), such as loss of peripheral visual fields, visual greyout or blackout, and G-induced loss of consciousness (G-LOC). Indirect consequences of $+G_z$ stress such as fatigue (and its attendant performance decrement) and strain injuries are raised in Example 3. A broader connotation is introduced in Example 4: operationally, the capacity to avoid $+G_z$ stress and still complete the mission may be at least as relevant, so perhaps it is equally important to consider 'G management' overtones when dealing with GT. Example 5 serves to remind us that centrifuge-based measures of GT (e.g., training target profiles) are an artificial representation of the in-flight situation that may have important limitations. Nevertheless, success or failure in completing such target profiles have become training (and sometimes selection) tools on which the operational community has come to rely.

In controlled experimental settings, GT is examined using a model of $+G_z$ stress (commonly specific runs in a centrifuge) to examine physiological strain (i.e., result or yield) in the form of some objectively measured endpoint. These models and endpoints have taken various forms, the multiplicity of which can make it hard to compare research results. Centrifuge profiles used in examining GT may assess G intensity (e.g., peak G level) or G duration. Examples of the latter have included simulated air combat maneuver (SACM) runs such as alternating 15-s plateaus at $+4.5\ G_z$ and $+7\ G_z$ (14) or $+5\ G_z$ and $+9\ G_z$ (47) to an endpoint such as limit of volitional tolerance or visual loss. The limitations of the various SACM G duration tolerance profiles in simulating the high sustained G environment have been reviewed elsewhere (47), but in essence it can safely be said that each may have different implications when used to study GT. Endpoints of GT (especially G intensity tolerance) have also been reviewed elsewhere (10) and may include the visual or fatigue endpoints as indicated above, but may also include measurements of physiological strain (e.g., changes in such recordings as ear-opacity pulse amplitude or finger-site BP). As also indicated above, other more indirect endpoints of GT such as injury or 'kill' rates may have operational relevance at least as important as physiological indices that are classically studied.

It is also critical to recognize that the term GT may be understood in a variety of different senses. For example, one may consider 'innate' GT that is attributed to anthropometric and other constitutional variables [though the validity of so doing has been questioned by at least some authors (49)], 'relaxed' GT (which presumably includes involuntary G-protective reflexes such as those of the cardiovascular system), or 'straining' GT [which includes protection afforded by executing the anti-G straining maneuver (AGSM) or equivalents such as the Qi-Gong maneuver (53)]. It has been well documented that the latter two senses of GT (i.e., 'relaxed' and 'straining') have enormous inter- and intra-individual variation that is particularly sensitive to intercurrent G exposure and non-specific learning effects (33,50). Furthermore, one must also consider the sort of GT increments found while wearing G-protective garments.

II. The Concept of PC

Like GT, PC has a variety of connotations that make comparison of experimental results difficult. We understand PC to mean the use of an exercise program to improve certain components of physical fitness. The term 'physical fitness' has metabolic (i.e., aerobic or anaerobic) and muscle strength dimensions, either of which may be viewed in terms of physical work capacity, power, or endurance (39). Furthermore, the term PC, though often used in relation to an individual's whole-body physical fitness, may sometimes only concern particular muscle groups such as axial (e.g., abdominal or chest) or peripheral (e.g., thigh and leg).

III. In What Ways Might PC Influence GT?

Few would dispute the physical demands of tolerating $+G_z$ stress (especially if the AGSM is performed): operating under $+G_z$ takes work—and fit people can do more work than less fit people. Thus, it seems intuitive that PC must somehow affect GT. In particular, muscle strength, muscle fatigue, and aerobic fitness have been surmised to play some role in GT.

The Role of Strength Training

Rationale: In a given individual there is a direct relationship between the force generated by a muscle and the increase in systemic BP (30,31). Since muscle contraction is involved in executing the AGSM, it makes sense that increases in muscle strength brought about by training should result in a reduced relative effort required to elicit the BP increase needed to tolerate a given $+G_z$ stress. Similarly, it has been shown that because strength training reduces the fraction of the maximum force-generating capacity of muscle required to produce a given absolute force, the duration for which that force level could be sustained also increases (16,40).

Also, muscle contraction causes increases in BP in an individual, the extent of which is a direct function of the force generated and the muscle mass recruited (30,31). However, increase in BP is a function of the relative intensity of exertion and not the absolute force generated during muscle contraction, nor the absolute size of the muscles used to generate that force (34). In other words, during maximal muscle contractions a weak and a strong individual should have similar increases in BP. This draws into question the whole premise of strength training to improve GT. Indeed, our literature review yielded a meta-analysis that suggests that strength training, if anything, decreases BP (25). There is, however, one study (41) that suggests strength training may result in an increased maximal BP response to maximal muscle contractions. In this study, six male subjects who weight-trained the legs 3 d · wk^{-1} for 19 wk were reported to have significant increases in peak arterial and esophageal pressure responses attained during maximal weight-lifting exercise. Higher peak arterial pressures suggest tolerance of higher $+G_z$ levels, but because of their apparent conflict with the above-cited meta-analysis, these results (and the conclusion they imply) require confirmation. If confirmed, they would support a role for strength training in increasing GT. However, it is entirely possible that such weight training realizes its benefit not simply by increasing local muscle strength, but also—or even instead—through an indirect mechanism. Weight training involves forceful muscle contractions in the chest, which could enhance the thoracic component of the AGSM (4,34). Although weight training also involves abdominal muscle contraction, specific regimens designed to achieve training effects in these groups have not produced significant improvements in GT (6).

Evidence: Five published studies have used a longitudinal design to evaluate the effects of large muscle group strength training on GT (5,12,19,20,46). A brief summary and interpretation of each study follows. All of these studies evaluated GT in a centrifuge; no reports have been found to document the effects of physical training on in-flight GT.

Epperson et al. (19) examined the effects of weight training on SACM tolerance time. They recruited 24 subjects and divided them into 3 groups: control (no training), runners, and weight trainers. Training lasted 12 wk. The GT increment in SACM averaged 4 $s \cdot wk^{-1}$ in control subjects and runners, and 15 $s \cdot wk^{-1}$ in the weight trainers. The authors concluded from these results that strength training increases GT. Thus, it appears that the rate of change in GT in the weight trainers was at least double that of the other groups. This interpretation is confounded, however, by the fact that all groups had continually increasing GT times throughout the 12 wk of the study, including the control group. In other words, all the groups were progressively improving their GT, probably simply due to their exposure to G (SACM tolerance time was measured in seven centrifuge sessions over 12 wk). Can we exclude the possibility that the subjects in the weight-training group just happened to be more predisposed to adapt rapidly to G exposure than the subjects in the other groups? Thus, it is questionable whether it is possible to dissociate the effects of the various training modalities from the effects of simply "learning" how to tolerate the G stress [cf. findings of Bulbulian et al. (12) summarized below]. This study would have been more robust had the training commenced only after all groups reached 'plateau' (i.e., showed no further increases in GT as a result of repeated exposure to G). The multiple paired *t*-tests that were employed also lacked sufficient power to conclude confidently that the apparently impressive nearly 4-fold increment in GT times found between the two groups was in fact statistically significant. A preferable analysis would have been one which enabled a repeated measures (pre, post) comparison across the various treatment groups, with the main emphasis placed on the group by time interaction. The magnitude of this interaction would answer the question, 'Was the change from pre to post the same across all three treatment groups?' Perhaps this study could realize its full potential should the authors re-analyze the original data accordingly. Although this study has often been cited as evidence for the efficacy of strength training in enhancing GT, without proper control of the "learning" factor, it provides insufficient grounds to conclude that GT is improved by strength training.

In a subsequent report, Epperson et al. (20) examined the effectiveness of specific weight training regimens on SACM tolerance. In this work, seven subjects weight trained for 12 wk, and average SACM tolerance time was found to increase by 53%. The authors attempted to correlate the changes in the strength of various muscle groups with changes in SACM tolerance time. Multiple regression analysis was used in an attempt to derive a variable representative of the combined effects of changes in the strength of more than one muscle group. Perhaps to compensate for the small sample size (seven subjects), the investigators chose to consider the pre-training and post-training data from each subject as representing two independent observations. By doing so, there is a very serious problem related to the non-independence of observations, artificially inflated degrees of freedom, and a high degree of correlation among the predictors themselves. The resulting regression equation can be unstable from one sample to the other (23). Moreover, data from a control group of subjects is not included in the statistical analysis. Thus we conclude that the statistical analysis and interpretation are not robust enough to conclude that strength training increases GT.

Tesch et al. (46) also studied the effects of weight training on SACM tolerance time. Before and after 11 wk of strength training, 11 fighter pilots were tested and mean SACM tolerance time increased by 39%. Lean body mass did not change after training in spite of increases in muscle strength. In the discussion of their results, the authors suggested that physiological alterations other than muscle hypertrophy are responsible for the gains in GT and muscle strength. The design of this study suffers from lack of a control group for comparison, and no data are presented about the reproducibility of SACM tolerance time in these subjects. This study also included artificial data inflation caused by treating repeated measurements on the same subject as independent observations. Although an uncontrolled study such as this begs the inference of a link between PC and GT, it must be borne in mind that this design overlooks other factors that may be at play. Accordingly, any conclusions must be drawn only with great caution.

Balldin et al. (5) studied 17 Finnish fighter pilots, "well-trained in the centrifuge." Although this study sought primarily to establish the usefulness of a "Rating of Perceived Exertion" index, it also implied a relationship between PC and GT. Training consisted of 1 yr of mixed strength and endurance training, but key program details (such as an index of variation among or between subjects) are not specified in the paper or its references. All subjects were tested in the same order, i.e., once before training, which represents the GT after a control period, and then again after training. A serious flaw for this experiment relates to how the two treatments (control and training) were temporally placed. A more powerful experimental design would have involved two cross-over groups, with half the subjects getting training first and half getting the control period first. However, all subjects received a control treatment first and the training treatment second, thus the effect of the training was completely confounded with time. In other words, it is not possible to tell if the improvement was due to the training or the passage of time. Also, although subjective Rating of Perceived Exertion during the SACM was lower and the mean SACM times increased after the year of training, the lack of a control group precluded comparison. Further, no flying history information (prior to or during the study) is presented. This suggests an important confounding factor that is not controlled for in the study: intercurrent G-exposure related to flying duty.

Bulbulian et al. (12) followed 14 Navy aviators divided into weight-trained and non-weight trained groups (n = 7 per group). Training duration was 10 wk using a schedule of two consecutive workout days followed by one rest day, repeated throughout the 10 wk. The first workout day was for training of strength, and the second day for training of muscle endurance. Typical free-weight exercises were used to train both upper and lower body muscle groups. SACM and gradual onset rate centrifuge profiles were used to evaluate GT before and after training (there were no intercurrent centrifuge runs, but in-flight G exposure consisted of "…similar training missions…"). Both the training and control groups increased tolerance times similarly, interpreted by the authors as demonstrating a pronounced learning effect due to simple exposure to the centrifuge profiles. The preferred statistical analysis for this study, given the experimental design, would have been a two-group repeated measures analysis of variance, with the primary emphasis placed on the group by time interaction. Instead, the statistical treatment of the data in this study involved a collection of *t*-tests (both parametric and non-parametric), which cannot be considered particularly robust given the very small sample size (i.e., seven subjects in each group). Given the small sample size, the possibility cannot be excluded that the sample size was too small to permit separation of the observed effect from what could occur merely as a result of sampling error. This study does, however, highlight the important influence of $+G_z$ stress exposure history and the poor reproducibility of SACM tolerance times. It also provides an excellent discussion of some of the difficulties in properly designing, conducting, and drawing appropriate conclusions from studies involving wide inter- and intra-individual differences such as apply for PC and GT.

One further study attempted to assess the relation between anaerobic power and tolerance to SACM, though it had cross-sectional rather than longitudinal design. Wiegman et al. (52) compared the power output generated during 30 s of supramaximal intensity leg or arm exercise (as measured by the Wingate Test) with SACM endurance time, and concluded that "…anaerobic power is an important physiological component in SACM tolerance." The correlation of their anaerobic fitness variables with SACM time was only statistically significant when expressed in absolute terms (i.e., watts of power), but not when the power was expressed relative to bodyweight or lean body mass. The emphasis the authors placed on the relationship to fitness is suspect because further analysis of their data shows that variables such as lean bodyweight and chest circumference were more highly correlated with SACM time than the anaerobic test variables. Based on the results presented, one could accept an alternative hypothesis—that lean body mass alone is directly related to GT. The significant relationship of absolute power output to SACM time could have been a function of the protocol used to establish the resistance setting during the Wingate test: it was individually set for each subject according to their absolute bodyweight. In other words, their method assigned resistance for the Wingate test based on individual subjects' weights (lean body mass, LBM). Therefore, by design, observed Wingate power output varies directly with LBM. The study cannot determine whether any of the variability found in GT is due simply to the LBM-dependent resistance-assignment protocol, or to 'true' differences in power output independent of said protocol. Their conclusion would have been more credible were there a significant relationship between power output per kilogram of lean body mass and SACM time. The interpretation of the results of this study is also confounded by an experimental design which did not control physical training or activity status (it was self-reported) or the $+G_z$ exposure history of the subjects.

Conclusions: Unfortunately each study suffers from experimental design or statistical treatment flaws which seriously confound interpretation of the results. Therefore, it is our conclusion that available research has yet to clearly demonstrate whether or not strength training affects GT. The available literature does suggest, however, that there could be indirect strength training effects on GT, mediated through established effects on the respiratory muscles, BP, or both.

The Role of Muscle Fatigue

Improvements in strength or muscle endurance (or both) of the large muscle groups recruited during the AGSM might enhance GT if fatigue of these muscles were a limiting factor in SACM tolerance time. Fatigue of specific muscle groups is accompanied by established biochemical indicators, such as the intramuscular accumulation of lactic acid to the very high concentrations associated with impairment of muscle function (15,44). Also, muscle glycogen utilization rate is directly related to relative intensity of muscle contraction and rate of muscle fatigue. Assay of muscle substrates in conjunction with performance of a SACM is technically difficult, and only one such study has been published (1). Although the rate of change in the concentrations of glycogen and lactate in the thigh muscles indicated that these muscles were recruited during the SACM, the absolute changes were not sufficient to induce muscle fatigue that would limit force generation during the SACM.

This conclusion was confirmed in a follow-up report (3), which documented that at voluntary exhaustion during SACM (the point at which a subject no longer feels able to perform an AGSM adequately to maintain consciousness), the subjects were still able to generate the same maximal leg muscle forces as they were prior to beginning the SACM. Tesch and Balldin reported that there was no correlation between the percentage of the highly fatiguable fast twitch fibers in the v. lateralis muscle and GT (45); such a relationship would be expected if muscle fatigue limited GT because of the well-established relationship of skeletal muscle fiber type composition with fatiguability during repeated maximal muscle contractions. Another report found no evidence of force-limiting fatigue in the arm, chest, leg, or abdominal musculature at the point of voluntary exhaustion (2). Contrary to other reports (e.g., 15), these suggest that fatigue of large muscle groups is unlikely to occur to such an extent that it limits the force generation required to sustain an adequate AGSM, and, therefore, GT time during a SACM.

Despite these results, there is no doubt that the repeated performance of the AGSM during a SACM results in perceived fatigue. Many subjects have reported anecdotally that their 'exhaustion' during SACM is due to a perceived inability to generate sufficient force with the chest strain or Valsalva component of the AGSM, particularly the inspiratory phase thereof. Respiratory musculature is recruited to increase intrathoracic pressure during the Valsalva maneuver and a direct attempt has been made to determine the extent of fatigue of the respiratory musculature during a SACM. Bain et al. (4) compared indices of intrathoracic pressure, respiratory function tests, and electrical activity of the respiratory musculature before, during, and after a SACM. Respiratory muscle fatigue was found to coincide with the termination of SACM.

Indeed, respiratory muscle fatigue has been implicated as a potential limiting factor in other forms of physical exertion (24). 'Unloading' of the respiratory muscles by using helium/oxygen breathing realized a 40% increase in time to exhaustion during high-intensity exercise. Such evidence suggests that respiratory muscle fatigue can limit endurance during high-intensity exercise, and a report from the diving environment (48) suggests that isolated respiratory muscle training (using normocapnic hyperpnea) can improve exercise tolerance. Unfortunately, we could find no published studies which support the value of training of the respiratory musculature to improve GT time. Confounding the issue further is the finding that an ordinary cough can yield intrathoracic pressures that significantly exceed those developed during a maximal AGSM (9). If GT time is indeed limited by, inter alia, the ability to sustain high intrathoracic pressure, then future research might attempt to focus on why pressures similar to those generated during coughing are not generated voluntarily during an AGSM.

The Role of Aerobic Fitness

One widely held tenet is that excessive aerobic fitness can reduce one's GT (13,18,21). However, in over 500 attendees of the CF high sustained G centrifuge training program, we are unable to document a single case where excessive aerobic fitness independently clearly compromised any student's ability to complete target profiles (8). Furthermore, at least three studies (28,32,51) have failed to demonstrate correlation between measures of aerobic fitness and GT. Still, one of these studies (51) suggested links between aerobic fitness and motion sickness and cardiac dysrhythmias—both of which could adversely affect GT indirectly.

On the contrary, since no one would dispute that tolerating $+G_z$ stress (especially while performing the AGSM) constitutes strenuous physical exertion, moderate aerobic training may have some indirect benefit to GT because of the improved rate of recovery from hard physical exertion that is associated with improved aerobic fitness (22,43). In summary, evidence about the relationship between aerobic fitness and GT is scant and apparently conflicting, so much about it remains to be learned (11).

IV. Requirements of an Operationally Useful Physical Conditioning Program to Enhance GT

A variety of issues must be considered to ensure a PC program can be of practical use in enhancing the GT of aircrew.

Efficacy: A PC program that imparts meaningful benefit to GT will surely motivate aircrew to follow it, and aircrew would likely measure the relative worth of such benefits against their time cost. For example, would time be better spent on a new PC program or on practicing one's AGSM technique?

Palatability: Hand-in-hand with efficacy must go palatability; the former is irrelevant without the latter. On the other hand, no matter how effectively a program may be touted to increase GT, aircrew may not choose to follow exercise programs that have poor portability, require expensive apparatus, are too complicated, or that they find too difficult or simply not 'fun.'

Specificity of conditioning: It is well established that training effects tend to be activity-specific, and that although 'dual-conditioning' is possible, the best way of improving one's performance in a given activity is to actually practice that particular activity. We have developed immense respect for the extent to which the AGSM represents a highly complex, unnatural, athletic psychomotor skill that takes a great deal of practice to learn and maintain (8). It could be that the most effective means of improving or maintaining GT is to perform the AGSM, either actually in flight or in training facilities such as centrifuges. Accordingly, aircrew need to be convinced that their time is better spent on a new PC program than on other training activities.

Target population: Any intervention such as a new PC program must be assessed in the population for which it is designed. For example, although Bulbulian et al. (12) failed to demonstrate an overall benefit for their PC interventions, they raise the question of whether there may be sub-populations in which a benefit may emerge. Sub-populations such as those having difficulty meeting centrifuge training standards may have the most to gain from new PC programs, and so may prove more motivated to follow them. The question of for how long a PC program should be followed also arises: it could be that prolonged use of a strength training program might eventually reduce GT because of attendant enhanced growth of the peripheral vascular bed (thus favoring pooling and hypotension under long-duration $+G_z$ stress).

Indirect benefits of PC: Neck strain injuries have been implicated as an important problem in fighter aircrew (17,27,35,38). PC programs might be designed to reduce such injuries, and in this sense, enhance GT. In general, regular physical training has many associated health and lifestyle benefits, some of which are reviewed elsewhere (13,18). Aircrew probably embark on exercise programs for many of these reasons, not just to improve their GT (37). Accordingly, any new PC program aimed at GT-enhancement must be compared with others that aircrew would normally follow, not only in terms of its effect on GT, but also of its indirect health benefits.

V. The Way Ahead: Recommendations for Future Work

Much research remains to be done before authoritative, evidence-based recommendations can be made about operationally viable means of enhancing GT through PC programs. Some general and specific observations follow.

General Guidance

First, as indicated in sections I and II, the terms 'G tolerance' and 'physical conditioning' represent complex concepts with a wide range of nuances that may bear different meanings for different users, so definitions and research endpoints pertaining to these terms must be carefully formulated. Second, the need for sound experimental design and statistical treatment has been previously highlighted (11): any research regarding PC and GT should include appropriate controls for potential confounding influences such as intercurrent $+G_z$ stress exposure and proficiency in performing the AGSM [indeed, it has been said that "...the AGSM remains the major determinant of an individual's G-tolerance" (49)]. Third, the methods chosen for statistical treatment of the results should be carefully chosen, keeping in mind that variables such as fitness levels and GT frequently involve wide inter- and intra-individual variations and poor reproducibility [the reader's attention is drawn to Bulbulian et al. (12) for an excellent review of these methods and associated pitfalls].

Fourth, investigators conducting centrifuge-based research should always bear in mind the limitations of such simulations. For example, few centrifuge facilities can simulate negative-to-positive ['push-pull' (7)] $+G_z$ transition, an effect that may have important implications for understanding GT and how it is influenced by PC. Also, ground-based simulators appear to lack important psychological and physiological influences seen in flight, so GT in flight is substantially greater (29). In-flight confirmation of any centrifuge-based results may, therefore, be needed. Finally, the importance of the issues raised in section IV is emphasized: no PC intervention can be considered worthwhile until the user finds it operationally acceptable.

We have great respect for the logistical problems of accomplishing dedicated, properly designed studies such as are required in PC and GT. Opportunistic studies might help surmount some of these difficulties, and may furnish cohorts of relatively highly motivated subjects. For example, large populations of aircrew undergo centrifuge training in many nations on a regular basis, with only minimal analysis of the results or of the effectiveness of various interventions. More consideration should be given to the potential to view such training as a research opportunity, although the obvious experimental design limitations of such a strategy must also be borne in mind.

Specific Research Issues

Effect of strength training on BP and cardiovascular reflexes: As indicated in section III, the results of Sale et al. (41) require confirmation. Since it has been suggested (36) that cardiovascular reflexes of fighter pilots show some evidence of adaptation, it might also be important to answer the question of whether PC influences GT through optimizing cardiovascular reflexes, or rather through its effects on some element(s) of AGSM efficacy.

Muscle endurance (aerobic fitness) and GT: As indicated in section III, much remains to be learned about this relationship. Studies must carefully control for indirect influences.

The role of respiratory muscle training: There is a requirement for properly designed studies of the GT effects of exercise programs designed to produce PC effects in the musculature of the respiratory system. These programs might consist of, for example, clinical exercises designed originally for improving respiratory function ("chest physio"), other simple maneuvers like following metronomes and using partial rebreathers to achieve normocapnic hyperpnea (48), or other means of reproducing the chest strain component of the AGSM (e.g., simple exercises like pushups). However, because lung volume is a major determinant of the ultimate pressure developed during AGSM (9), training must address both the inspiratory and expiratory musculature. Indeed, both aircrew and experimental subjects often report that fatigue in the inspiratory component of the AGSM is the limiting factor in their GT, so it is possible that the inspiratory musculature plays at least as important a rôle in overall GT as does the expiratory.

Comparison with other strength training programs: Any GT benefits realized through respiratory muscle PC programs should then be compared with those arising from strength training programs aimed at other muscle groups.

Neck strain injury and PC: Since neck strain injury may limit GT (at least in the respects noted in section I), the role of PC programs using exercises aimed at reducing neck strain injury should be investigated.

The relative importance of AGSM technique enhancement: Centrifuge training seems to have an important role to play in enhancement of aircrew GT by means of improving AGSM technique (8). Also, other interventions like the 'statoergometer' (26) have been advocated as having promising roles to play in enhancing GT. Such 'AGSM trainers' as the statoergometer (or indeed, the centrifuge) may enhance GT through improving AGSM technique, through PC effects, or both. In order to evaluate the relative worth of different training interventions like these, it must be recalled that they may impart different balances of AGSM technique and PC benefits, so different populations, or even individuals, may incur different GT effects. It is important to settle this question of relative PC vs. AGSM technique benefit of any new GT training intervention in order to properly advise operators on its relative worth in the target population or individual.

Means of quantifying $+G_z$ *exposure:* As suggested above, proper research design must include proper measurement of experimental and intercurrent exposure to $+G_z$ stress. However, at present there exists no validated means of quantifying and logging this exposure. Although at first glimpse a time-weighted $+G_z$ stress integral might make sense, it would equate, for example, exposures of $+3\ G_z$ for 30 s and $+9\ G_z$ for 10 s; the physiological consequences of these two exposures are surely quite different. Such a simple model also fails to take into account other potential determinants of the physiological consequences of $+G_z$ stress such as onset rate, negative-to-positive $+G_z$ transitions, and cumulative peaks in one exposure session. Furthermore, the notion of some threshold, exposures below which impart no training benefit, is intuitively appealing (perhaps this threshold might be the point at which AGSM becomes necessary). Non-linear means of quantification would be needed to account for this.

Interaction of AGSM and G-protective ensembles: Even though AGSM is sometimes suggested as a means to augment GT increments afforded by G-suits and other G-protection ensembles, very little data exists about how (or even if) their effects are as additive as they would intuitively seem. There may actually be circumstances where an AGSM might reduce GT if used in the setting of G-protective ensembles—particularly malfunctioning ones. This whole area, and the role of PC in this relationship, warrants closer investigation given that these are often used together.

THE BOTTOM LINE: RECOMMENDATIONS FOR AIRCREW

There are data in the peer-reviewed literature that suggest certain types of PC (i.e., strength training) may enhance GT. However, based on our critical review, it is possible that more robust experimental designs and/or statistical analyses may not support the relationship between PC and GT. Without such experiments and analyses, it may be difficult to suggest to aircrew that convincing data exist to support the notion that any specific exercise program is known to favorably influence any element of their GT. Therefore, any change in training policy of the Canadian Forces (or, indeed, other agencies) may not be supported. Nevertheless, such a conclusion certainly does not preclude advocating that improved physical fitness will likely confer operational advantages to a pilot in meeting the physical demands of their occupation, and to realize other health-related benefits. We add the caution that alleged benefits directly or indirectly related to G tolerance may seem intuitive but remain to be proven. Further research with more robust experimental designs and/or statistical analyses must be conducted on new or existing data to clarify the GT effects of any PC program, and operators should be made aware that such research is more complex, time-consuming, and potentially costly than one might at first imagine. Nevertheless, we feel that soundly conducted research into the effect of PC on GT as indicated above will yield crucial insight into GT enhancement, and so should be given due consideration.

REFERENCES

1. Bain B, Jacobs I, Buick F. Effect of simulated air combat maneuvering on muscle glycogen and lactate. Aviat Space Environ Med 1992; 63:505–9.
2. Bain B, Jacobs I, Buick F. Electromyographic indices of muscle fatigue during simulated air combat maneuvering. Aviat Space Environ Med 1994; 65:193–8.
3. Bain B, Jacobs I, Buick F. Is there central fatigue during simulated air combat maneuvering? Aviat Space Environ Med 1995; 66: 1–5.
4. Bain B, Jacobs I, Buick F. Respiratory muscle fatigue during simulated air combat maneuvering (SACM). Aviat Space Environ Med 1997; 68:118–25.
5. Balldin UI, Kuronen P, Rusko H, et al. Perceived exertion during submaximal G exposures before and after physical training. Aviat Space Environ Med 1994; 65:199–203.
6. Balldin UI, Myhre K, Tesch PA, et al. Isometric abdominal muscle training and G tolerance. Aviat Space Environ Med 1985; 56: 120–4.
7. Banks RD, Grissett JD, Turnipseed GT, et al. The "push-pull effect." Aviat Space Environ Med 1994; 65:699–704.
8. Bateman WA. Centrifuge training in the Canadian Forces - The first six years' experience. In: Selection and training advances in aviation. Neuilly-sur-Seine, France: NATO Research and Technology Organisation; 1996:26–1 to 26–7. AGARD-CP-588.
9. Buick F, Hartley J, Pecaric M. Maximum intra-thoracic pressure with anti-G straining maneuvers and positive pressure breathing during +Gz. Aviat Space Environ Med 1992; 63:670–7.
10. Buick F, Wood E, Pecaric M, et al. Methods for measuring physiological responses and protection in man exposed to high +Gz. In: Current concepts on G-protection research and development. Neuilly-sur-Seine, France: North Atlantic Treaty Organization; May 1995:8–1 to 8–15. AGARD-LS-202.
11. Bulbulian R. Physical training and +Gz tolerance reevaluated. Aviat Space Environ Med 1986; 57:709–11.
12. Bulbulian R, Crisman RP, Thomas ML, et al. The effects of strength training and centrifuge exposure on +Gz tolerance. Aviat Space Environ Med 1994; 65:1097–104.
13. Burton RR. Simulated aerial combat maneuvering tolerance and physical conditioning: current status. Aviat Space Environ Med 1986; 57:712–4.
14. Burton RR, Shaffstall RM. Human tolerance to aerial combat maneuvers. Aviat Space Environ Med 1980; 51:641–8.
15. Burton RR, Whinnery JE, Forster EM. Anaerobic energetics of the simulated aerial combat maneuver (SACM). Aviat Space Environ Med 1987; 58:761–7.
16. Clarke DH. Adaptations in strength and muscular endurance. In: Wilmore JH, ed. Exercise and sport sciences reviews. New York: Academic Press; 1973:73–102.
17. Coakwell MR, Bloswick DS, Moser R Jr. High-risk head and neck movements at high G and interventions to reduce associated neck injury. Aviat Space Environ Med 2004; 75:68–80.

18. Crisman RP, Burton R. Physical fitness program to enhance aircrew G tolerance. Pensacola, FL: Naval Aerospace Medical Research Laboratory, NAS and Brooks AFB, TX: USAF School of Aerospace Medicine; 1988. Report No. NAMRL-1334/USAFSAM SR-88-1.
19. Epperson WL, Burton RR, Bernauer EM. The influence of differential physical conditioning regimens on simulated aerial combat maneuvering tolerance. Aviat Space Environ Med 1982; 53:1091–7.
20. Epperson WL, Burton RR, Bernauer EM. The effectiveness of specific weight training regimens on simulated aerial combat maneuvering G tolerance. Aviat Space Environ Med 1985; 56:534–9.
21. Ernsting J, King P, eds. Aviation medicine, 2nd ed. London: Butterworths; 1988.
22. Hartley LH, Saltin B. Reduction of stroke volume and increase in heart rate after a previous heavier submaximal work load. Scand J Clin Lab Invest 1968; 22:217–23.
23. Howell D. Fundamental statistics for the behavioural sciences. Boston: Druxberg Press; 1985.
24. Johnson BD, Aaron EA, Babcock MA, et al. Respiratory muscle fatigue during exercise: implications for performance. Med Sci Sports Exerc 1996; 28:1129–37.
25. Kelley G. Dynamic resistance exercise and resting blood pressure in adults: a meta-analysis. J Appl Physiol 1997; 82:1559–65.
26. Khomenco MN, Vartbaranov RA, Migachyov SD. Prognostication of the flyer's +Gz-tolerance on the basis of muscular strength endurance. Physiologist 1992; 35(1,Suppl.):S126–30.
27. Kikukawa A, Tachibana S, Yagura S. G-related musculoskeletal spine symptoms in Japan Air Self Defense Force F-15 pilots. Aviat Space Environ Med 1995; 66:269–72.
28. Klein KE, Bruner H, Jovy D, et al. Influence of stature and physical fitness on tilt-table and acceleration tolerance. Aerosp Med 1969; 40:293–7.
29. Lambert EH. Comparison of the physiologic effect of positive acceleration on a human centrifuge and in an airplane. J Aviat Med 1949; 20:308–35.
30. Lind AR, McNicol GW. Muscular factors which determine the cardiovascular responses to sustained and rhythmic exercise. Can Med Assoc J 1967; 96:706–15.
31. Lind AR, Taylor SH, Humphreys PW, et al. The circulatory effects of sustained voluntary muscle contraction. Clin Sci 1964; 27: 229–44.
32. Ludwig DA, Convertino VA, Goldwater DJ, et al. Logistic risk model for the unique effects of inherent aerobic capacity on +Gz tolerance before and after simulated weightlessness. Aviat Space Environ Med 1987; 58:1057–61.
33. Ludwig DA, Krock LP. Errors in measurement of +Gz acceleration tolerance. Aviat Space Environ Med 1991; 62:261–5.
34. MacDougall JD, McKelvie RS, Moroz DE, et al. Factors affecting blood pressure during heavy weight lifting and static contractions. J Appl Physiol 1992; 73:1590–7.
35. Newman DG. +Gz-induced neck injuries in Royal Australian Air Force fighter pilots. Aviat Space Environ Med 1997; 68:520–4.
36. Newman DG, White SW, Callister R. Evidence of baroreflex adaptation to repetitive +Gz in fighter pilots. Aviat Space Environ Med 1998; 69:446–51.
37. Newman DG, White SW, Callister R. Patterns of physical conditioning in Royal Australian Air Force F/A-18 pilots and the implications for +Gz tolerance. Aviat Space Environ Med 1999; 70:739–44.
38. Oksa J, Hamalainen O, Rissanen S, et al. Muscle strain during aerial combat maneuvering exercise. Aviat Space Environ Med 1996; 67:1138–43.
39. Research Study Group on Physical Fitness. NATO Defence Research Group Panel on the Defence Applications of Human and Bio-Medical Sciences. Brussels: Research Study Group on Physical Fitness; 1986. Report No.: AC/243-D1092.
40. Sale DG, Jacobs I, MacDougall JD, et al. Comparison of two regimens of concurrent strength and endurance training. Med Sci Sports Exerc 1990; 22:348–56.
41. Sale DG, Moroz DE, McKelvie RS, et al. Effect of training on the blood pressure response to weight lifting. Can J Appl Physiol 1994; 19:60–74.
42. Scully SP. Pumping up nature's G-suit. Flying Safety 1988; June: 7–11.
43. Shephard RJ. The prediction of maximum oxygen intake from post-exercise pulse readings. Int Z Angew Physiol 1967; 24: 31–8.
44. Tesch P. Muscle fatigue in man. With special reference to lactate accumulation during short term intense exercise. Acta Physiol Scand Suppl 1980; 480:1–40.
45. Tesch PA, Balldin UI. Muscle fiber type composition and G tolerance. Aviat Space Environ Med 1984; 55:1000–3.
46. Tesch PA, Hjort H, Balldin UI. Effects of strength training on G tolerance. Aviat Space Environ Med 1983; 54:691–5.
47. Tong A, Balldin UI, Dooley JW, et al. Tactical vs. other simulated aerial combat maneuvers. Aviat Space Environ Med 1998; 69: 525–7.
48. Warkander DE, Leddy J, Boutellier U. Respiratory muscle training improves divers' submaximal cycle endurance. Undersea Hyperb Med 1999; 26(Suppl.):30.
49. Webb JT, Oakley CJ, Meeker LJ. Unpredictability of fighter pilot G tolerance using anthropometric and physiologic variables. Aviat Space Environ Med 1991; 62:128–35.
50. Whinnery JE, Jackson WG, Jr. Reproducibility of +Gz tolerance testing. Aviat Space Environ Med 1979; 50:825–8.
51. Whinnery JE, Parnell MJ. The effects of long-term aerobic conditioning on +Gz tolerance. Aviat Space Environ Med 1987; 58:199–204.
52. Wiegman JF, Burton RR, Forster EM. The role of anaerobic power in human tolerance to simulated aerial combat maneuvers. Aviat Space Environ Med 1995; 66:938–42.
53. Zhang SX, Guo HZ, Jing BS, et al. Experimental verification of effectiveness and harmlessness of the Qigong maneuver. Aviat Space Environ Med 1991; 62:46–52.