# Re-evaluating the Need for Routine Maximal Aerobic Capacity Testing within Fighter Pilots

Zachary Zeigler; Anthony M. Acevedo

**INTRODUCTION:** There is a current belief in aviation suggesting that aerobic training may reduce G-tolerance due to potential negative impacts on arterial pressure response. Studies indicate that increasing maximal aerobic capacity ($\dot{V}O_2$ max) through aerobic training does not hinder G-tolerance. Moreover, sustained centrifuge training programs revealed no instances where excessive aerobic exercise compromised a trainee's ability to complete target profiles. The purpose of this review article is to examine the current research in the hope of establishing the need for routine $\dot{V}O_2$-max testing in air force pilot protocols.

**METHODS:** A systematic search of electronic databases including Google Scholar, PubMed, the Aerospace Medical Association, and Military Medicine was conducted. Keywords related to "human performance," "Air Force fighter pilots," "aerobic function," and "maximal aerobic capacity" were used in various combinations. Articles addressing exercise physiology, G-tolerance, physical training, and fighter pilot maneuvers related to human performance were considered. No primary data collection involving human subjects was conducted; therefore, ethical approval was not required.

**RESULTS:** The $\dot{V}O_2$-max test provides essential information regarding a pilot's ability to handle increased $G_z$-load. It assists in predicting G-induced loss of consciousness by assessing anti-G straining maneuver performance and heart rate variables during increased G-load.

**DISCUSSION:** $\dot{V}O_2$-max testing guides tailored exercise plans, optimizes cardiovascular health, and disproves the notion that aerobic training hampers G-tolerance. Its inclusion in air force protocols could boost readiness, reduce health risks, and refine training for fighter pilots' safety and performance. This evidence-backed approach supports integrating $\dot{V}O_2$-max testing for insights into fitness, risks, and tailored exercise.

**KEYWORDS:** fighter pilots, $\dot{V}O_2$ max, $G_z$ performance.

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The prevailing belief in the aviation community is that aerobic training will lower overall G-tolerance.[6,9] This thought is perpetuated by the notion that high levels of aerobic training may negatively impact the arterial pressure response, which governs G-tolerance. Despite this prevailing thought, research suggests otherwise. Studies show that aerobic training that increases $\dot{V}O_2$ max will not hinder G-tolerance,[14,37] and it has been found that aerobically trained subjects do not have lower G-tolerance than non-aerobically trained subjects.[23,43] For example, Bateman et al. examined over 500 attendees of a highly sustained centrifuge training program. The authors did not document a single case where excessive aerobic exercise compromised a student's ability to complete target profiles.[3]

The authors intend to provide evidence and create an argument to implement routine $\dot{V}O_2$-max testing into air force pilot protocols. A $\dot{V}O_2$-max test, also known as a maximal oxygen consumption test, measures the maximum amount of oxygen an individual can utilize during intense exercise. It is considered one of the most accurate ways to assess aerobic capacity and overall cardiovascular fitness. The authors have broken down the argument into three points. First, the $\dot{V}O_2$-max test can provide information about the pilot's readiness for duty.

From the Grand Canyon University, Phoenix, AZ.

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Address correspondence to: Anthony M. Acevedo, Ph.D., Exercise Science Adjunct Professor, Grand Canyon University, 3300 West Camelback Rd., PO Box 11097, Phoenix, AZ 85017; anthony.acevedo.5.ctr@us.af.mil.



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Second, the $\dot{V}o_2$-max test can give information about the pilot's risk for disease. Third, the $\dot{V}o_2$-max test provides information needed to create a training program tailored to improve aerobic fitness.

## METHODS

A systematic search of electronic databases including Google Scholar, PubMed, the Aerospace Medical Association, and Military Medicine was conducted. Keywords related to "human performance," "Air Force fighter pilots," "aerobic function," and "maximal aerobic capacity" were used in various combinations. Articles addressing exercise physiology, G-tolerance, physical training, and fighter pilot maneuvers related to human performance were considered. No primary data collection involving human subjects was conducted; therefore, ethical approval was not required.

## RESULTS

The $\dot{V}o_2$-max test provides essential information regarding a pilot's ability to handle increased $G_z$-load. It assists in predicting G-induced loss of consciousness by assessing anti-G straining maneuver (AGSM) performance and heart rate variables during increased G-load. Additionally, the test can identify cardiovascular risk factors like chronotropic incompetence (CI), abnormal heart rate recovery, and blood pressure (BP) responses.

## DISCUSSION

### Readiness for Duty

When discussing air force pilots and the cardiovascular (CV) system, much of the talk is around the ability of the CV system to tolerate high G. An inability to have an elevated G-tolerance can lead to G-induced loss of consciousness. An individual's capacity to withstand high G is mainly determined by his/her arterial pressure response to elevated $G_z$ load.[11] It is well-established that the arterial pressure response governs G-tolerance. At increased $G_z$-load, to maintain arterial pressure in the brain sufficiently high to avoid cerebral anoxia and hence G-induced loss of consciousness, arterial pressure at the heart level must increase to the extent that it overcomes the exaggerated hydrostatic pressure drop along the arteries from the heart.[23] The baroreflexes play an essential role in maintaining this arterial pressure sufficiency.

To help prevent G-induced loss of consciousness, modern fighters are taught to perform the AGSM, which consists of the Valsalva maneuver combined with lower-body muscle strain to avoid blood pooling in the lower extremities. Aerobic training may reduce the effects of fatigue from performing the AGSM, leading to better AGSM performance.[9] AGSM performance is one of the most significant predictors of whether a pilot experiences G-induced loss of consciousness.[41]

In addition to the optimal performance of the AGSM, researchers found many heart rate variables that may shed light on a pilot's ability to handle $G_z$-load. For example, researchers found that a more minor increase in heart rate during centrifuge training increases the likelihood of failing during high G-training.[41] Moreover, heart rate recovery has been suggested to be an essential factor in tolerating increased $G_z$-load. Subjects with a higher heart rate reserve (the difference between the maximum and minimum resting heart rate) also presented a more remarkable ability to recover from the orthostatic stress created by the $G_z$ force.[8,13,38] Heart rate and heart rate variability have been shown to help determine a pilot's mental workload.[28] Pilots who failed to increase their heart rate (less than 10%) during the first 1–5 s of 7.5 G-profile had a 10-fold higher chance of failing than those with a more considerable heart rate increase.[40] One variable of interest during an exercise test is heart rate response.

As a pilot performs a standard $\dot{V}o_2$-max test, heart rate is reviewed, and abnormalities can be detected. Peak heart rate could be one of the physiological predictors of G-tolerance during training. Indeed, the heart rate under sustained hypergravity reaches the maximum, depending on the $G_z$-load, within seconds.[19] Estimating $HR_{max}$ from prediction equations is not ideal due to individual variability. Indeed, the most common estimate equation of $HR_{max}$ is 220 − age,[16] which has been reported to have a standard deviation of 10–12 bpm.[2] Additionally, some data suggests that $HR_{max}$ decreases with aerobic training.[15,45] The proposed mechanisms for this reduced $HR_{max}$ are not entirely understood, but plasma volume expansion and enhanced baroreflex function[47] are thought to play a role. An expanded plasma volume, along with left ventricular cavity enlargement,[44] contributes to increased resting and maximal stroke volume in aerobically trained persons.[1] The decreased $HR_{max}$ is offset by increased stroke volume, thus maintaining optimal cardiac output. These adaptations would not negatively impact arterial pressure response but should function to enhance it. Thus, training for increased cardiorespiratory fitness may favorably impact heart rate response to $G_z$-loads. For example, a 12-wk conditioning program consisting of 1 h, twice a week, reduced heart rate to a given G-level,[37] suggesting a reduced CV stress. Alternative training methods have proven their effectiveness. Additionally, studies have demonstrated a quicker recovery heart rate following short-interval and high-intensity training sessions.[25] Lastly, syncope, which can occur suddenly during recovery from maximal exercise or even acute exercise, represents a failure to maintain or regulate BP and may be due to reduced muscle pump augmentation of blood return to the right side of the heart.[19] Experimental data has shown that training to increase $\dot{V}o_2$-max increases orthostatic tolerance,[29,31] mainly due to the expanded plasma volume seen from exercise training.[34] The increased orthostatic tolerance derived from increased cardiorespiratory fitness could theoretically aid in tolerating increased $G_z$-load.

### Pilots' Risk for Adverse Events

CVD is one of the most frequent causes of sudden incapacitation in flight for pilots. One study autopsied 534 pilots involved in fatal aircraft accidents from 1996–1999. Cardiovascular abnormalities were found in 44% of them.[39] Additionally, CV risk factors tend to increase throughout a pilot's career. For example, a study looking at German Air Force pilots found that as pilots age, total cholesterol, LDL, glucose, and triglycerides increase significantly.[33] Variables measured during a $\dot{V}O_2$-max test, such as heart rate and BP, have been shown to predict the health and longevity of the participant.

Heart rate response and recovery from maximal exercise provide information about potential CV risk. The need to increase heart rate when exposed to increased G-forces is of paramount importance. CI is the inability to increase heart rate commensurate with exercise demand.[20] CI can be identified during routine $\dot{V}O_2$-max testing. CI can be determined by failure to reach 80% of heart rate reserve, defined as: (observed heart rate max − heart rate rest) ÷ (age-predicted heart rate max − heart rate rest) × 100. Failure to reach 80% of heart rate reserve during a $\dot{V}O_2$-max test has been shown to be a validated method to determine CI.[26] In a study of healthy older adults, it was found that CI was extremely common and is a risk factor for morphological abnormalities of the heart, such as higher left atrium size and left ventricle mass.[24]

A slowed heart rate recovery is associated with all-cause mortality and cardiac events.[30] Heart rate is measured each minute during exercise and 1, 2, 3, and 5 min post-exercise, allowing for this assessment. An abnormal recovery heart rate is a decrease of <22 beats after 2 min of recovery.[36] Cross-sectional data show that $\dot{V}O_2$ max is positively associated with parasympathetic activity,[21] and interval training has been shown to increase parasympathetic activity and baroreflex sensitivity;[32] both could favorably affect heart rate recovery.

BP control is a key factor to pilots withstanding $G_z$-load. An exercise test can point out if there are abnormalities in BP response. For example, if exercise-induced hypotension takes place, (systolic BP decreases by >10 mmHg with increased intensity), this is a strong predictor of coronary artery disease and ventricular systolic dysfunction[18] and predicts two-year risk for adverse events.[12] On the other end, exercise-induced hypertension, defined as systolic BP > 210 mmHg and diastolic BP > 10 mmHg above resting values, predicts risk for future hypertension and CV events.[18,35] Recovery BP and heart rate also predict future CV issues, and both are assessed during a $\dot{V}O_2$-max test.[35]

Exposure to $+G_z$, particularly on a centrifuge, has been shown to cause premature ventricular contraction, bigeminy, trigeminy, and sinus bradycardia.[7,42,48] Typically, these are benign and resolve upon cessation of the $G_z$ exposure. Although fast jet aircrews are generally healthy, caution is warranted if an individual with underlying cardiac pathology is exposed to increased $G_z$. Changes in ECG morphology during a $\dot{V}O_2$-max test may indicate underlying pathology. Examples are QRS complexes that are increased, suggesting left ventricular dysfunction, or abnormal ST-segment changes, which have been the standard criteria for coronary artery disease for more than half a century.[35] Lastly, premature ventricular contractions are found in 30–40% of healthy people during an exercise test, and this has been shown to predict 5-yr mortality.[17]

Lastly, aerobic capacity is one of the strongest predictors and prognostic markers for the risk of adverse events in apparently healthy people.[10] For example, those who achieved greater than 10 metabolic equivalents (METs) during a $\dot{V}O_2$-max test have a low prevalence of coronary artery disease compared to those who had less than 7 METs.[4] Additionally, each 1-MET increase in functional capacity has been shown to lead to a 13–15% decreased rate of all-cause death and CV events.[22] As the aerobic capacity of pilots increases, so does their life expectancy and possibly their career.

**Exercise Prescription**

The assessment of $\dot{V}O_2$ max through a controlled and incremental exercise test serves as a pivotal tool in formulating precise and individualized aerobic exercise prescriptions. $\dot{V}O_2$ max reflects the upper limit of an individual's capacity to utilize oxygen during intense physical activity, providing insights into their cardiovascular fitness and endurance potential. By accurately quantifying an individual's oxygen consumption at maximal effort, exercise physiologists can delineate the optimal exercise intensity, duration, and frequency required to elicit physiological adaptations conducive to improved aerobic performance.[27] This data-driven approach facilitates the development of targeted aerobic exercise programs tailored to an individual's specific fitness level, ensuring that training regimens are both effective and safe. Resistance training has been touted as a modality that increases G-tolerance in pilots, yet some data shows no change in G-tolerance from resistance training programs.[5] A universal training modality and program concerning exercise training and the modern fighter pilot are still elusive. The prescription of aerobic exercise guided by $\dot{V}O_2$-max assessments contributes to the enhancement of overall cardiovascular health, endurance, and metabolic efficiency, thereby promoting sustainable and personalized strategies for physical fitness optimization.

The prevailing belief in the aviation community suggesting that aerobic training might lower overall G-tolerance due to potential negative impacts on arterial pressure response is contradicted by recent research findings. Studies indicate that aerobic training, particularly that which increases $\dot{V}O_2$ max, does not hinder G-tolerance, and aerobically trained subjects do not exhibit lower G-tolerance than their non-aerobically trained counterparts. Moreover, evidence from a comprehensive analysis of over 500 individuals engaged in a sustained centrifuge training program found no documented cases where excessive aerobic exercise compromised a student's ability to complete target profiles.[46] Resistance training, often touted as a means to increase G-tolerance, lacks consistent supporting data. The authors advocate for the inclusion of routine $\dot{V}O_2$-max testing in air force pilot protocols, emphasizing its potential to provide valuable information on readiness for duty, assess the risk for adverse events, and guide the formulation of precise and individualized aerobic exercise prescriptions for optimizing cardiovascular health and endurance. This evidence-based approach can contribute to the development of effective and safe training regimens tailored to the specific needs of modern fighter pilots.

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*Authors and Affiliations:* Zachary Zeigler, Ph.D., and Anthony M. Acevedo, Ph.D., LDN, CSCS, CNS, CISSN, Exercise Science Department, Grand Canyon University, Phoenix, AZ.

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