A Medical Review of Fatal High-G U.S. Aerobatic Accidents

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INTRODUCTION: Exposure to high G force is a known safety hazard in military aviation as well as civilian aerobatic flight. Tolerance to high G forces has been well studied in military pilots, but there is little research directed at civilian pilots who may have medications or medical conditions not permitted in military pilots.

METHODS: In this case-control study, we identified 89 fatal high-G aerobatic accidents and 4000 fatal control accidents from 1995 through 2018 from the NTSB accident database and the FAA autopsy database. We retrieved medications and medical conditions from the FAA's pilot medical databases. Logistic regression models were used to explore the associations of drugs, medical conditions, height, and medical waivers with high-G accidents.

RESULTS: Seven drugs (alprazolam, clonidine, ethanol, meclizine, phentermine, triamterene, and zolpidem) reached statistical significance in our models, but had such small case counts that we consider these findings to be uncertain, except for ethanol, which was found in seven cases. Of these, only triamterene was known to the FAA. Statistically significant medical predictors included only alcohol abuse (seven cases) and liver disease (only two cases).

DISCUSSION: Our analysis found that the drug ethanol and the condition alcohol abuse are significantly associated with high-G accidents. Seven other factors were statistically significant, but should only be considered as hypothesis generating due to very low case counts. Our study does not suggest that restricting pilots with otherwise permissible medications or medical conditions from aerobatics is warranted.

KEYWORDS: G force, safety, medications, drugs, pilots.

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The effect of G force was recognized as a hazard to flight safety by at least WWI when "fainting in the air" was described.[28] The responsible force is that which pushes the pilot down into the seat when he pulls up from a dive and is now known as positive G or $+G_z$. This $+G_z$-induced loss of consciousness is known as G-LOC. As much higher performance aircraft were introduced in WWII, it was recognized that G-LOC countermeasures were required to use these fighters to their potential. This consisted of anti-G straining and inflatable anti-G suits. Advanced anti-G countermeasures are used with all modern high-performance military aircraft with improved anti-G suits that add positive pressure breathing and other features.

High-performance civilian aircraft, mainly intended for aerobatics, can also produce high G forces similar to many military aircraft, but typically do not support military-type G-LOC countermeasures. Examples are the Extra 200/300 (±10 G), Yak 50/55 (+9/−6 G), and newer Pitts Specials (+9/+7.5 G). Even older civilian aerobatic aircraft were frequently rated at +6/−5 G. G force effects may be an under-recognized safety risk for these aircraft. One experiment demonstrated that typical aerobatics in a Bellanca Decathlon (+6 G/−5 G) are capable of inducing G-LOC.[2] The larger studies concerning the effects of G forces have been performed almost exclusively on young healthy military pilots, which leaves us with an incomplete understanding of the effects on G tolerance of factors seen only in civilian pilots. Civilian pilots may be much older and have medical conditions and/or medication use that would be disqualifying for military pilots.

Some factors that reduce G tolerance, such as fatigue, alcohol sequella, illness, and sedentary lifestyle, have been recognized

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for many years in military aviation medicine.[3] There has been speculation about other disease and medication-related factors that may reduce G tolerance. These would primarily affect civilian pilots since most of these factors would be disqualifying for military pilots of high-performance aircraft. These factors include medications that can precipitate hypotension, advanced cardiac disease, diseases such as Parkinson's that are associated with hypotension due to autonomic dysfunction, and advanced age. The goal of this study was to test a number of these factors for association with civilian aerobatic accidents where high G forces were likely present.

There is a large amount of research regarding G force effects in military aviation.[28] Most of it is centrifuge based and much of the research was performed using modern anti-G force countermeasures that are typically not used by civilian pilots. Relatively recent studies by Whinnery and Forster in unprotected subjects quantitate parameters for loss of consciousness due to G force and for regaining consciousness.[31,32] This updated the pioneering work by Stoll.[25] These transitions between the loss of consciousness and regaining it do depend on level and rate of onset of G loads, but at the rapid onset of G loading typical of aerobatic flight, they converge to relatively constant times. Times to loss of consciousness is 5 to 7 s, with the time to first arousal taking about 12 s followed by an additional 12 s of relative incapacitation before the pilot is fully functional. G-LOC for healthy men in the unprotected state with rapid G onset may occur around +4 G_z, which is well within what is experienced in civilian aerobatic maneuvers. Furthermore, a phenomenon known as the push-pull effect can lead to G-LOC at much lower levels of G force. For example, after exposure to −3 G for 10 s, tolerance for an immediately following G-LOC event declined from +4.85 G to as little as +2.8 G.[27] Another adverse effect of +G exposure well defined by Shender et al. and Sinha and Tyagi is near-loss of consciousness (A-LOC).[23,24] Experimental studies have documented impairment in a wide constellation of motor and cognitive functions sufficient to result in an accident with short pulses of less than 4 s at +6 G with impairment often lasting over 10 s.

Several articles quantitate the G force levels experienced in various standard aerobatic maneuvers.[12,17] A typical 15-s loop requires two 1-s exposures to +3.5 G. A 6-s aileron roll reaches a maximum of +2.5 G. Inside snaps take about 3 s and pull +2.5 to +3 G. The pullout from a three-turn spin involves +3.5 G for 3 s. An inside square loop takes 24 s and contains two +4.2 G exposures, which will result in G-LOC in an unprepared person. A vertical "8" takes 35 s and has four high +G exposures from 3.5 to 4.5 that frequently result in brief G-LOC in aerobatic pilots. This maneuver invokes the push-pull effect mentioned above since the upper loop is preferred to be an outside maneuver. Professional aerobatic pilots report G loads during an aerobatic show range from −5 G to +7 G with rapid changes between negative and positive Gs. For inexperienced pilots, errors while executing the above maneuvers may result in much higher and more prolonged G loads than that cited above for properly performed maneuvers.

A case-control study that included 78 G-LOCs in U.S. Air Force pilots found that having flown three previous sorties the same day was a risk factor for G-LOC mishaps, possibly due to fatigue or complacency. The only personal risk factor for G-LOC in these fighter aircraft was lack of experience.[22]

A centrifuge-based study exploring civilian tolerance to G force profiles associated with commercial spaceflight included 86 subjects with various medical conditions and medications.[5] This included a number of the cardiac diseases (i.e., coronary artery disease, valvular disease, dysrhythmias) and medications (i.e., beta blockers, alpha blockers, ACE inhibitors) of interest for aerobatic flight. Although some expected effects of the medications were observed, all of the subjects tolerated 3.5-G_z exposures.

Textbook theory predicts that taller persons are at increased risk of G-LOC. Two centrifuge and observational studies did not find that height made a significant difference in G tolerance.[11,22] Another experimental study of 1300 pilots found height had a statistically significant association, but the effect was so small as to not have any practical significance.[30]

There are a number of nonfatal in-flight misadventures that are known to have resulted from G-LOC. Impairment due to G-LOC or A-LOC also appears likely to have been involved in several fatal aerobatic accidents. In 1999, as a result of three of these accidents, the NTSB issued two safety recommendations.[9] These recommended adding an operational limitation prohibiting aerobatic flight to medical certificates of pilots with significant cardiac disease or who take medication that could reduce G tolerance. The Federal Aviation Administration (FAA) assessed the National Transportation Safety Board (NTSB) recommendations by carrying out a study of 38 accidents from 1993 to 1999 that involved aerobatic flight.[8,29] They looked at odds ratios (ORs) for special issuance (SI) waivers (OR = 5.67, $P = 0.284$), hypertension (OR = 1.69, $P = 0.979$), and both SI and hypertension (OR = 1.96, $P = 0.196$). Only one to three case counts were available for these calculations and they were not adjusted for age or other confounding factors. Six accidents mentioned by the NTSB were also reviewed. They found little evidence to support restriction of aerobatic flight in pilots with cardiac disease or medications. The Aircraft Owners and Pilots Association came to a similar conclusion.[21] Based on three additional aerobatic accidents, the NTSB issued a further similar safety recommendation in 2015. The FAA addressed this recommendation by adding a warning to special issuance waivers issued to pilots with cardiac disease advising that their cardiac function may be impaired by aerobatic maneuvers. The NTSB classified this latest safety recommendation as "Open – Acceptable Response."[10]

Numerous organ systems and medication classes need consideration when identifying medical factors that could decrease G force tolerance and lead to pilot incapacitation. The susceptibility of the cardiovascular system to the adverse effects of high G load is of particular interest. D'Arcy et al. discusses the unique demands aerobatic flight puts on the cardiovascular system that may lead to compromise in maintaining cerebral and coronary perfusion.[7] The NTSB's safety recommendation specifically mentions coronary artery disease and valvular disease found during autopsy of airshow pilots. Of the valvular diseases, aortic stenosis is likely the greatest threat. G forces are also known to precipitate significant arrhythmias, even in healthy individuals without such history. Centrifuge studies, civilian and military, have produced temporary arrhythmia in even the healthiest of subjects.[26] There are theoretical reasons why central and autonomic nervous system disease could decrease G tolerance, but fortunately these are very rare in aerobatic pilots. The majority of these conditions are disqualifying for civilian pilots as well as military pilots.

There are many medications that theoretically could impair G tolerance. These include, particularly, cardiac medications such as antihypertensives and antiarrhythmics. They have the potential to decrease blood pressure, modify conduction pathways, alter cardiac output, and some have potential for central nervous system/autonomic nervous system dampening (i.e., beta-blockers).[19,20] Medications directly acting on the central nervous system, i.e., muscle relaxants, agents for Parkinson's, MS, and psychiatric medications also seem likely to reduce tolerance to high G. Substances of abuse, such as alcohol, marijuana, and other illicit substances also fall into this category. Also of note is the need to consider the risk of supplements, which are largely sold over-the-counter and not regulated.[6]

METHODS

Subjects

This study was approved in advance by the FAA Institutional Review Board. The NTSB maintains a public database of U.S. aviation accidents that contains detailed investigative information on almost 80,000 accidents.[18] This database was searched for accidents since 1995 in which "aerobatic" was cited in the probable cause findings fields. These accidents were limited to fatal U.S. general aviation accidents with only one pilot on board. We captured the remaining 4017 accidents meeting these criteria as controls for comparison purposes.

The autopsy team of the FAA's Aerospace Medical Research Division maintains the Medical Analysis and Tracking Registry (MANTRA). This database includes a detailed medical review of all (2516) fatal U.S. aviation accidents between October 2008 and November 2018. A query of MANTRA identified 138 accidents that involved aerobatic flight – including 15 accidents not identified elsewhere.

The NTSB database plus the MANTRA registry identified 199 accidents involving aerobatic flight. The authors manually reviewed each of these aerobatic accidents to confirm that high G force was likely involved in the accident sequence and that the aerobatic maneuver was initiated at an altitude sufficient to give a reasonable chance of successful completion. This resulted in a set of 76 aerobatic accidents meeting these criteria. The narratives from these high G force accidents were used as training data for a machine-learning algorithm based on a standard random forest classifier approach that was used to screen all of the other 4000+ accidents.[13] Manual review of the accidents flagged by the machine learning identified another 13 accidents meeting the criteria for cases. This group of 89 high G force accidents constituted the cases used in this study.

Procedure

The FAA's Aerospace Medical Research Division carries out the legally required toxicological analysis on pilots who are fatally injured in U.S. aviation accidents. This includes 6668 pilots. All toxicology case results from civil aircraft accident fatalities that occurred between 1990 and the present are stored electronically in the Toxicology Data Base (ToxDB). All of our aerobatic accidents and the comparison accidents were matched to the ToxDB database to identify the drugs detected in these pilots. We added findings for 290 different toxicology findings to our research database. We constructed additional fields for several drug classes, including diuretics, beta blockers, alpha blockers, calcium channel blockers, ACE inhibitors, and drugs for Parkinson's disease. Toxicology findings of ethanol are problematic due to the potential of postmortem production. To address this risk we restricted findings of ethanol only to cases with a level of at least the FAA limit of 40 $mg \cdot dl^{-1}$ in which no other postmortem volatiles were detected.

Aeromedical certification information for U.S. pilots is contained in the FAA's Document Imaging Workflow System (DIWS), which includes over 21,000,000 examinations for over 3,583,000 applicants. For each examination, this database includes demographic data, medical history and physical exam data, medical conditions assigned by the FAA, and detailed certification actions. Using matching information provided by the FAA Aviation Safety Information Analysis and Sharing System (ASIAS), the pilots of our case and comparison accidents were matched to DIWS and their known medical conditions, height, reported flight hours, and status of special issuance waivers were obtained. We limited medical conditions to those found in at least two pilots in the combined case/control accidents. This provided information on 99 different medical conditions for us to explore. We also used DIWS to confirm whether drugs found by toxicology had been reported to the FAA.

Statistical Analysis

We employed logistic regression models to explore the association of the presence of the drugs, medical conditions, special issuance waivers, and height with aerobatic accidents. This technique has been successfully used previously to explore the association of other conditions with risk of aircraft accidents using similar data sources.[4,14,16] The outcome variable was occurrence of an aircraft accident involving aerobatic flight with likely high G exposure compared to nonaerobatic accidents. The predictor variables included age and gender in addition to the drugs and medical conditions of interest. A great advantage of logistic regression modeling is the ability to remove the confounding effects of the covariates. We calculated odds ratios with 95% confidence intervals. Since a unit size of one for the quantitative predictor variables would result in ORs very close to one, a unit size of 10 yr was used for age and 6″ for height in order to scale the ORs to be more understandable.

A challenge for this analysis was the very sparse occurrence of many drugs and medical conditions of interest. The vast majority of the drugs and medical conditions did not reach statistical significance in our analysis. To improve the value of these findings we also report an estimated power for our models. We used a simulation power analysis to calculate estimates for the power of each logistic regression model.[1] Each simulation involved at least 1000 stochastic iterations of a Wald hypothesis test calculation based on the OR determined, the case count, and the control count.

Descriptive statistics, logistic regression, and Chi-squared testing were performed using SPSS version 21 (IBM, Armonk, NY). We used a statistical significance level of $\alpha = 0.05$. Power calculations were performed using Mathematica version 11.0 (Wolfram Research, Champaign, IL).

RESULTS

We identified 89 accidents found by our review over the period from 1 January 1995 to 17 November 2018 that involved at least possible exposure to high G force with initiation of the fatal maneuver at a reasonable altitude. The comparison group included 4017 accidents not involving aerobatic flight. All accidents were limited to fatal single-pilot general aviation accidents. There is no statistical difference in age, proportion of female pilots, weight, height, or BMI between these groups as displayed in **Table I**. The larger total and past 6-mo flight times found for the aerobatic accidents were statistically significant.

The crude OR for the association of a Special Issuance Waiver with accidents with at least the possibility of high G exposure was 1.105 (95% CI 0.477 to 2.580; $P = 0.816$). Adjustment of this association for age and gender with a logistic regression model gave an adjusted OR of 1.280 (95% CI 0.540 to 3.035; $P = 0.575$). Neither age nor gender was statistically significant in this model. The associations of special issuance waiver and hypertension were explored in a 1999 FAA study in which neither factor was statistically significant. An analysis of the hypothesis tests of the previous study and the current one indicate that the current study provides higher power. Using the OR value from the previous study, we estimate the power of the hypothesis test for special issuance in the previous study to be 55% compared to 79% in the current study. The power of a test measures the likelihood that it will detect an actual effect (that it will, in fact, reject a false null hypothesis). We can, therefore, place more confidence in the results of the current study when they fail to detect a significant association than in those of the previous study.

Table I. Descriptive Statistics for Aerobatic Accidents and Control Accidents.

METRIC	CONTROLS	CASES	*P*-VALUE
Age (years, mean)	53.79	51.42	0.131
Gender (% female)	1.9	4.8	0.081
Height (inches, mean)	70.3	70.8	0.119
Weight (lb, mean)	194.6	192.9	0.658
Total Flt Time (hours, median)	1126	2250	< 0.001
Past 6 mo (hours, median)	40.0	70.0	0.002
BMI (mean)	27.6	27.0	0.168
Special Issuance (%)	6.1	6.7	0.821

The OR for the association of height (per 6 inches) with accidents with probable high G exposure adjusted for age and gender was 1.543 (95% CI 0.982 to 2.426; $P = 0.102$). Logistic regression modeling was carried out on the toxicology data. The models were adjusted for age and gender, but neither of these were ever statistically significant. Detected drugs with *P*-values of 0.100 or less are displayed in **Table II**.

These drugs all have theoretical reasons for decreasing G tolerance, but only seven of them reached statistical significance and all but ethanol had such small case counts that we could not have much confidence in the results. In fact, if the case count is reduced by one, none of these drugs would still have statistically significant *P*-values except ethanol.

The logistic regression results for medical conditions with statistically significant results along with some of special aeromedical interest are displayed in **Table III**. Liver disease and alcohol abuse were both statistically significant and alcohol abuse continues to be statistically significant when its case count is reduced by one. This is not true for liver disease. There were no case pilots who had more than one of positive alcohol toxicology, alcohol related path code, or liver related path code, but our sample is too small to suggest that a relationship does not exist.

DISCUSSION

There are certainly theoretical reasons why increased pilot height, some medical conditions (e.g., cardiac disease), and some medications (e.g., antihypertensives and drugs with negative inotropic effect) would be likely to impair tolerance to high G exposure. There have been a few instances of aerobatic accidents in which the NTSB investigation identified such factors as contributing to the accident. These findings have led to several NTSB safety recommendations to place a restriction prohibiting aerobatic flight on the medical certificates of pilots having these factors. We are unable to identify any previous studies that quantitated the association of cardiac diseases and medications with civilian high-G_z accidents.

We were able to identify 89 aerobatic accidents in which exposure to high G appeared to be present during the accident sequence and in which the aerobatic maneuver was initiated at an altitude giving a reasonable chance for successful completion. We also had over 4000 nonaerobatic accidents available for a comparison group.

Textbook theory predicts that height increases the risk of G-LOC. Our point estimate for the association of height with high G accidents was mildly elevated, but did not reach statistical significance (OR = 1.543, 95% CI 0.982 to 2.426; $P = 0.102$). Several previous studies were also unable to find that the effect of a pilot's height had any practical significance in G tolerance.

For comparison with the previous 1999 FAA study, we evaluated the association of an FAA special issuance medical waiver and treated hypertension with high G accidents. A logistic regression model adjusted for age and gender failed to find a statistically significant association of these waivers with odds of

Table II. Drugs Detected by Toxicology with *P*-Value of 0.100 or Less.

DRUG NAME	*P*-VALUE	OR	95% CI	CASE COUNT	KNOWN TO FAA
Alprazolam	0.010	8.787	1.666–46.360	2	0
Bisoprolol	0.080	7.573	0.787–72.856	1	0
Brompheniramine	0.057	8.156	0.943–70.511	1	0
Clonidine	0.031	17.161	1.288–228.736	1	0
Ethanol (40 $mg \cdot dl^{-1}$)	0.014	2.697	1.221–5.957	7	NA
Meclizine	0.013	18.337	1.864–180.415	1	0
Phentermine	0.028	5.362	1.195–24.060	2	0
Triamterene	0.046	4.826	1.030–22.617	2	1
Zolpidem	0.049	3.576	1.007–12.703	3	0

OR = Odds Ratio, 95% CI = 95% confidence interval.

a high G accident ($P = 0.575$). The point estimate for the adjusted OR was 1.280 (95% CI 0.540 to 3.035), which was smaller than the previous FAA study. An analysis of the power of the current study to detect the OR of the previous study shows a power of 79% for our study compared to 55% for the previous study. We can, therefore, place more confidence in the results of the current study when it fails to detect a significant association than in those of the previous study. As in the previous study, hypertension treated with medication adjusted for age and gender did not have a significant association ($P = 0.434$), but our point estimate of the OR was protective at 0.740 (0.347 to 1.575.) rather than mildly elevated as in the previous FAA study. Hypertension was found to have a statistically significant protective effect in a large study of all accidents using a similar data source.[15] This protective effect may be due to other behaviors beneficial to safety that are associated with obtaining and reporting treatment for hypertension.

Analysis of the 290 different drugs detected by toxicology using logistic regression models identified six drugs other than alcohol with statistically significant associations with odds of high G accidents. Four of these (alprazolam, clonidine, phentermine, and zolpidem) were prescription drugs for which regular use is disqualifying for aeromedical certification—and none of these were reported to the FAA. Brompheniramine (almost statistically significant at $P = 0.057$) and meclizine ($P = 0.013$) are over-the-counter drugs that are not acceptable for use while flying. Use of these drugs was also not known to the FAA. Bisoprolol (almost statistically significant at $P = 0.080$) and triamterene ($P = 0.046$) may be acceptable for FAA medical certification if evaluation of the associated condition is favorable, but of these, only one of the pilots prescribed triamterene reported this to the FAA. All of these drugs have case counts of one or two except for zolpidem, which has three. A sensitivity analysis showed that a decrease of even one case for any of these drugs results in loss of statistical significance. Therefore we consider these results to be hypothesis generating rather than actionable. It is interesting that all of these drugs have the theoretical possibility of lowering tolerance to high G. The possibility of impairment by medications was mentioned by the NTSB in 5 of these 13 accidents, but none of these drugs were reported to the FAA. A few drug groups of interest were created to increase count sizes. Groups included first-generation antihistamines, beta blockers, calcium channel blockers, ACE inhibitors, alpha blockers, anti-Parkinson drugs, and diuretics. None of these drug classes had statistically significant or interesting results.

Table III. Pilot Pathologies of Interest.

PATHOLOGY	*P*-VALUE	OR	95% CI	CASE COUNT
Carotid artery disease	0.135	6.640	0.553–79.678	1
Hypertension with medication	0.434	0.740	0.347–1.575	8
Coronary artery disease (50% or greater)	0.640	1.984	0.112–35.047	2
Myocardial Infarction	0.668	0.590	0.053–6.580	1
Atrial fibrillation	0.951	1.081	0.091–12.894	1
Aortic valve disease	0.144	5.768	0.548–60.667	1
Liver disease	0.003	11.668	2.277–59.794	2
Alcohol Abuse	0.024	5.161	1.235–21.560	4
Alcoholism	0.282	4.454	0.293–67.659	1

OR = Odds Ratio, 95% CI = 95% confidence interval.

The proportion of these drugs detected by toxicology but not reported to the FAA is remarkable. A recent FAA study in publication compared drugs detected by toxicology to those reported to the FAA for all fatal accidents from 2009 to 2014 [DeJohn CA, Greenhaw R, Lewis R, Cliburn KD. Truth in reporting. Manuscript submitted for publication; 2019]. They found that pilots had reported only 3% of detected psychoactive drugs and 54% of cardiovascular drugs, so the poor reporting rate for these aerobatic accidents is not significantly different than that of all U.S. pilots.

Analysis using logistic regression models of 99 different medical conditions known to the FAA identified only two conditions that had statistically significant associations with high G accidents. These were alcohol abuse and liver disease. Liver disease had only two cases and sensitivity analysis showed that even one less case would not have been statistically significant ($P = 0.204$). Neither accident included anything to suggest pilot impairment. We report the results for a number of other cardiac conditions of aeromedical interest that did not reach statistical significance. These included coronary artery disease (50% or greater), myocardial infarction, atrial fibrillation, aortic valve disease, and carotid artery disease. These conditions involved nine unique accidents of which the NTSB cited two as having impairment from cardiac conditions. However, the odds of any of these conditions in high-G accidents was not significantly greater than for the comparison accidents.

The most convincing association we found was that with ethanol. To select cases of ingestion, we created a variable that required an ethanol level of at least 40 $mg \cdot dl^{-1}$ and no evidence of any other postmortem volatiles. This shows a statistically significant association with high-G accidents with OR = 2.70 (95% CI 1.22 to 5.96, $P = 0.014$) and had a case count of seven. A history of alcohol abuse was also statistically significant with OR of 5.16 (95% CI 1.24 to 21.56, $P = 0.024$, four accidents). These both continued to be statistically significant if the case counts were reduced by one. History of alcoholism also had an elevated OR of 4.45 (95% CI 0.29 to 67.66, $P = 0.282$, one accident). The NTSB cited possible impairment from alcohol in five of these nine accidents. Based on a recent study that looked at NTSB findings in all fatal U.S. accidents, an NTSB finding of impairment from alcohol was significantly more frequent in these high-G accidents ($P < 0.001$) [Greenhaw R, Hileman C. Pilot medical factors associated with medically related fatal aviation events. Manuscript submitted for publication; 2018]. This is plausible since judgment is so critical in aerobatic flight and may benefit from additional education directed at the community of aerobatic pilots.

The 1999 FAA study explored the presence of special issuance waivers and hypertension in pilots involved in aerobatic accidents compared to other accidents and failed to find any statistically significant association. Our study explored a much larger variety of medical conditions and medications using a more sophisticated analysis and a larger number of aerobatic accidents. We found a number of drugs and medical conditions had elevated OR point estimates but have such small counts that they must be considered as hypothesis generating rather than actionable. Very few of the drugs found on the toxicology reports during our accident reviews had been reported by the pilot to the FAA. Even if some of these associations should turn out to be validated in future studies, the number of aerobatic pilots affected would be minuscule due to their low prevalence of cardiac (and other) disease and use of medications. Therefore, this study supports the conclusion of the much less thorough 1999 CAMI study that placing a restriction prohibiting aerobatic flying on the medical certificates of pilots with cardiac disease or medications is not warranted. The current warning attached to special issuance waivers for cardiac disease seems sufficient.

Our conclusion receives additional support from a negative centrifuge study of civilians with a number of cardiac conditions and medications of interest exposed to 3.5 G.[5] Further evaluation of the factors flagged by this study and other factors of special aeromedical interest as risk factors for impaired G tolerance during aerobatic flight would likely require additional experimental studies since the natural exposures found in the high-G accidents are too rare to provide sufficient power for actionable results from observational studies such as this one.

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