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High-G training has been reported to provoke dysrhythmias in many subjects. These reports have been based on small subject groups. Students attending aeromedical professional courses at the USAF School of Aerospace Medicine are offered the opportunity to participate in high-G centrifuge training on the Armstrong Laboratory Centrifuge, during which ECG monitoring is routinely performed. This study documents the incidence of dysrhythmias in this large group of subjects. The pertinent information from the records of 1180 training sessions from 1984 through 1991 were transcribed to a database on a personal computer. Dysrhythmias were recorded in 552 (47%) of the training sessions. Ventricular ectopy occurred in 480 (41%) of the sessions, and supraventricular dysrhythmias appeared in 127 (11%). In 53 (4.5%) of the sessions, training either was or would have been terminated because of the arrhythmia. Session-terminating dysrhythmias included: 26 ventricular tachycardias (2.2%), including 18 triplets (1.5%); 9 ventricular couplets (0.8%); 8 episodes of too-frequent ventricular premature beats (0.7%); 4 of supraventricular tachycardia (0.3%), including 2 with aberrant conduction (0.2%); 2 of aberrantly conducted beats (0.2%); and 4 of anomalous bradycardia (0.3%). Centrifuge training can provoke serious dysrhythmias in ostensibly healthy individuals, and ECG monitoring of aircrew undergoing such training is recommended for their safety. Because some of these dysrhythmias are disqualifying for aircrew duties, the need for a more lenient aeromedical disposition policy must be considered.

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Incidence of Cardiac Dysrhythmias Occurring During Centrifuge Training

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High-G training has been reported to provoke dysrhythmias in many subjects. These reports have been based on small subject groups. Students attending aeromedical professional courses at the USAF School of Aerospace Medicine are offered the opportunity to participate in high-G centrifuge training on the Armstrong Laboratory centrifuge, during which ECG monitoring is routinely performed. This study documents the incidence of dysrhythmias in this large group of subjects. The pertinent information from the records of 1,180 training sessions from 1984–91 were transcribed to a database on a personal computer. Dysrhythmias were recorded in 552 (47%) of the training sessions. Ventricular ectopy occurred in 480 (41%) of the sessions, and supraventricular dysrhythmias appeared in 127 (11%). In 53 (4.5%) of the sessions, training either was or would have been terminated because of the dysrhythmia. Session-terminating dysrhythmias included: 26 ventricular tachycardias (2.2%), including 18 triplets (1.5%); 9 ventricular couplets (0.8%); 8 episodes of too-frequent ventricular premature beats (0.7%); 4 of supraventricular tachycardia (0.3%), including 2 with aberrant conduction (0.2%); 2 of aberrantly conducted beats (0.2%); and 4 of anomalous bradycardia (0.3%). Centrifuge training can provoke serious dysrhythmias in ostensibly healthy individuals, and ECG monitoring of aircrew undergoing such training is recommended for their safety. Because some of these dysrhythmias are disqualifying for aircrew duties, the need for a more lenient aeromedical disposition policy must be considered.

HUMAN-USE CENTRIFUGES provide a practical means to produce increases in G loading for extended periods of time, for both research and training purposes. Aircrew flying high-performance fighters in the USAF now routinely undergo high-G training, with the objective of tolerating $+8$ or $+9$ G_z (depending on seat configuration) for 15 s while using an anti-G suit and performing an anti-G straining maneuver. It is USAF policy to conduct high-G training of pilots without electrocardiographic (ECG) monitoring. This policy resulted from pilots' concerns that dysrhythmias seen during centrifuge training could disqualify them from flying status.

Changes in the electrocardiogram have been reported by many investigators of physiologic responses to high acceleration (1). Several authors (6–9) have reported the occurrence of dysrhythmias during centrifuge training at this laboratory. There have been few comparable reports from other training facilities, an exception being that of Sekiguchi et al. (5), who found that over 50% of pilots from the Japanese Air Self Defense Force had dysrhythmias during high-G training. Whinnery (9) has reported that treadmill stress testing and exposure to $+G_z$ forces produce a comparable incidence of dysrhythmias, but that G forces have a tendency to produce more serious dysrhythmias, such as ventricular tachycardia. The occurrence of these dysrhythmias is remarkably consistent, with nearly all electrocardiographic studies on the centrifuge demonstrating the occurrence of ventricular tachycardia in a small percentage of subjects. These dysrhythmias generally are asymptomatic and resolve rapidly when the subjects return to 1 G.

Students attending professional aeromedical training courses at the USAF School of Aerospace Medicine (USAFSAM) are offered the opportunity to undergo high-G training, similar to that provided to pilots, on the Armstrong Laboratory centrifuge. Most of the students in these courses are physicians attending the Aerospace Medicine Primary, Residency in Aerospace Medicine, or Advanced Aerospace Medicine for International Medical Officers courses. The remainder are students in the Aerospace Physiologist course. High-G training is not compulsory, but is highly encouraged for these students. All of these volunteers are monitored with ECG. Past studies (8) that attempted to estimate the incidence of various dysrhythmias during centrifuge training have been based on small numbers of subjects. The records of the centrifuge training runs at USAFSAM afforded an opportunity for a retrospective study to determine the incidence of dysrhythmias occurring during high-G training in a larger group of subjects.

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METHODS

All subjects were currently certified to USAF Flying Class II or III medical standards, or foreign equivalent, as a requirement for their duties. Subjects were fitted with anti-G suits and seated in a simulated F-16 aircraft seat, with a seatback angle of 30° and elevated rudder pedals, mounted in the gondola of the centrifuge. Thus, they experienced primarily $+G_z$ forces. The subjects were visible and audible to staff in the centrifuge control room through a closed circuit video system. All runs were monitored by a physician. Two mutually perpendicular (sternal and biaxillary) leads were used to monitor the ECG, which was displayed on a cathode ray tube and a strip chart in the control room at the medical monitor's position. Heart rate, derived from the ECG, was displayed both on the strip chart and on the video monitor. A hand-held control ("dead-man switch") enabled the subject in the gondola to terminate a run at any time.

In an ideal training session the subject was exposed to four out of the five G profiles used for training USAF fighter pilots (4). The subject began with a gradual-onset run (0.1 G/s) in a relaxed condition with the anti-G suit pressurization turned off. The L-1 anti-G straining maneuver was started as soon as the subject experienced either 100% peripheral or 50% central light loss (100% PLL or 50% CLL). This run was continued until the light loss criterion was again met with the subject exerting a maximal straining effort. Several rapid-onset runs (6 G/s) then followed, with the anti-G suit pressurization turned on. These runs were normally a sequence of 30 s at 6 G, 15 s at 8 G, and 15 s at 9 G, with the training goal being completion of the 15-s 9-G run. The subjects were instructed to terminate a run early if they experienced light loss at or beyond the 100% PLL or 50% CLL criterion, or if they wanted to stop for some other reason (e.g., pain or apprehension). By no means did all the subjects complete the training goal (less than 20%, vs. greater than 90% for pilots); and in many cases the G levels were tailored to suit the individual subjects, especially when the subjects had difficulty performing an effective anti-G straining maneuver.

During the training, the medical monitor completed a record (AFSC Form 3040) for each subject. The following information was transferred from these forms to a database on a personal computer: subject identifier, age, type of run, maximum heart rate, and reason for termination of run. Although both male and female subjects undertook the training, gender was not recorded, so the responses of males and females could not be compared. The AFSC Form 3040 did not specifically require dysrhythmias to be coded, but sections labeled "electrocardiogram" and "heart rate" encouraged medical monitors to observe and document on the form the occurrence of dysrhythmias. This dysrhythmia information, as well as any other relevant comments entered on the forms by the various medical monitors, was also transcribed to the database. A total of 1,180 records, covering training from August 1984 through July 1991, were transcribed and reviewed. There were no repeat sessions within the records reviewed.

RESULTS

Dysrhythmias were recorded in 552 (47%) of the 1,180 sessions. A wide variety of dysrhythmias were seen. They could broadly be divided into ventricular ectopy (480, 41%) and supra-ventricular ectopy (127, 11%). These two groups were not mutually exclusive, as in some subjects both types of ectopy occurred during the same training session, and in some cases during the same run. Table 1 gives a more detailed breakdown of the dysrhythmias. The categories in the table are, again, not mutually exclusive, because often dysrhythmias in more than one category were recorded for a given session or run. The dysrhythmia classification is derived from the terminology used by the individual medical monitors when they recorded the dysrhythmias. It includes premature ventricular contractions (PVC's) in various numbers, occasional PVC's (occPVC), frequent PVC's (freqPVC), ventricular bigeminy (bgPVC), ventricular trigeminy (tgPVC), PVC couplets (PVC2), PVC triplets (PVC3), ventricular tachycardia (VT), multiform PVC's (mltPVC), aberrantly conducted beats (ACbt), premature atrial contractions (PAC's) in various numbers, occasional PAC's (occPAC), frequent

TABLE 1. FREQUENCY OF CARDIAC DYSRHYTHMIAS IN THE DIFFERENT CATEGORIES.

	n	%
Ventricular ectopy		
1 PVC	181	15.3%
2 PVC	121	10.3%
3 PVC	62	5.3%
4 PVC	26	2.2%
5 PVC	24	2.0%
6 PVC	12	1.0%
7 PVC	7	0.6%
8 PVC	8	0.9%
occPVC	138	11.7%
freqPVC	37	3.1%
bgPVC	23	1.9%
tgPVC	4	0.3%
PVC2	63	5.3%
PVC3	18	1.5%
VT	8	0.7%
mltPVC	8	0.7%
ACbt	12	1.0%
TOTAL	480	40.7%
Atrial ectopy		
1 PAC	32	2.7%
2 PAC	12	1.0%
3 PAC	9	0.8%
4 PAC	3	0.3%
5 PAC	5	0.4%
occPAC	74	6.3%
freqPAC	8	0.7%
EAR	2	0.2%
WAP	1	0.1%
TOTAL	127	10.8%
Others		
SVT	4	0.3%
ASB	15	1.3%
JB	1	0.1%

See text for dysrhythmia codes. More than one type of dysrhythmia was often recorded for a training session, so category percentages total to more than 47%, the percent of sessions in which any dysrhythmia was recorded.

PAC's (freqPAC), ectopic atrial rhythm (EAR), wandering atrial pacemaker (WAP), supraventricular tachycardia (SVT), anomalous sinus bradycardia (ASB), and junctional beats (JB). The precision with which dysrhythmias were recorded varied among the individual medical monitors, with some carefully counting the number of PVC's and PAC's, and others only describing either occasional or frequent occurrences of these dysrhythmias but not differentiating them in any more detail.

The majority of ventricular dysrhythmias were isolated single PVC's (recorded as 1, 2, or occasional PVC's). In a smaller number of subjects, PVC's were frequent or multiform. Atrial ectopy was less common than ventricular ectopy, and generally consisted of 1, 2, or occasional PAC's, with most other forms of atrial ectopy (freqPAC, EAR, WAP) being recorded infrequently. Anomalous sinus bradycardia was seen in 15 subjects. It was often associated with G-induced loss of consciousness (G-LOC) or with the recovery from a high-G exposure.

Training was (or would have been) stopped because of the occurrence of dysrhythmias in 53 (4.5%) of the sessions. This number includes not only those sessions in which the medical monitor terminated the session because of a dysrhythmia, but also those in which a dysrhythmia occurred during the last run of a session, and would have precluded continuation of training had it occurred in an earlier run. These dysrhythmias were of a type that would usually be considered clinically significant. Session-terminating dysrhythmias consisted of the following: 26 VT (2.2%), including 18 PVC3 (1.5%); 9 PVC2 (0.8%); 8 episodes of freqPVC (0.7%); 4 of SVT (0.3%), including 2 with aberrant conduction (0.2%); 4 of ASB (0.4%); and 2 ACbt (0.2%). In some of the subjects who had frequent PVC's leading to session termination, coupled PVC's also occurred; however, as the runs were terminated because of the high frequency of PVC's rather than the coupling, they were not included in the PVC2 category. In all 24 cases where VT was seen, the dysrhythmia either was limited to the run or resolved spontaneously soon after the run was stopped. There was one case in which the VT lasted a total of 50 s, continuing into the post-G recovery period. Fig. 1 illustrates this case. The other occurrences of VT in which the specific details were recorded include one 7-beat, two 5-beat, and three 4-beat runs, and one subject noted as having short, repeated runs of VT. Fig. 2 shows a session-terminating run of SVT with aberrant conduction, which strongly resembles VT on one of the leads.

Table II presents those cases in which training sessions were or would have been terminated because of the dysrhythmias, broken down into the individual dysrhythmias and the G level at which they occurred. The three largest categories of dysrhythmia (in descending order) were PVC3, freqPVC, and PVC2. Overall, these dysrhythmias tended to increase in frequency as G level increased, with the majority appearing at levels greater than 5 G. Further, the fact that there were fewer 9-G runs than 8-G runs and fewer 8-G runs than 6-G runs (because of attrition due to reaching physiological or motivational limits) means the correlation of run-terminating dysrhythmias with G level is even stronger than it would appear to be from Table II. Similar data could not be produced for the dysrhythmias that did not end training sessions, because the G level at which they occurred was often not recorded.

The mean age of all of the subjects reviewed was 33.6 ± 6.9 years ($\bar{X}$ ± S.D.). The subjects were divided into three mutually exclusive groups: those in whom no dysrhythmia was seen, those in whom dysrhythmias other than VT were seen, and those who had runs terminated on the appearance of VT. The mean age of the first group was 33.2 ± 6.0 years, that of the second was 34.0 ± 7.2 years, and that of the third was 37.4 ± 8.5. The differences between the groups were tested with two-tailed *t*-tests, which showed significant differences between all of the mean ages. The dysrhythmia group was significantly older than the non-dysrhythmia group ($p = 0.05$); however, the difference in the means of less than 1 year is of little practical significance. The VT group was significantly older than the other-dysrhythmia group ($p < 0.02$), and the non-dysrhythmia group ($p < 0.001$). The larger differences in the means (3.4 and 4.2 years) between this group and the other two groups may be important, possibly representing some degree of age-related cardiac dysfunction in the VT group.

DISCUSSION

A study of this type is open to many criticisms. Many different medical officers acted as medical monitors

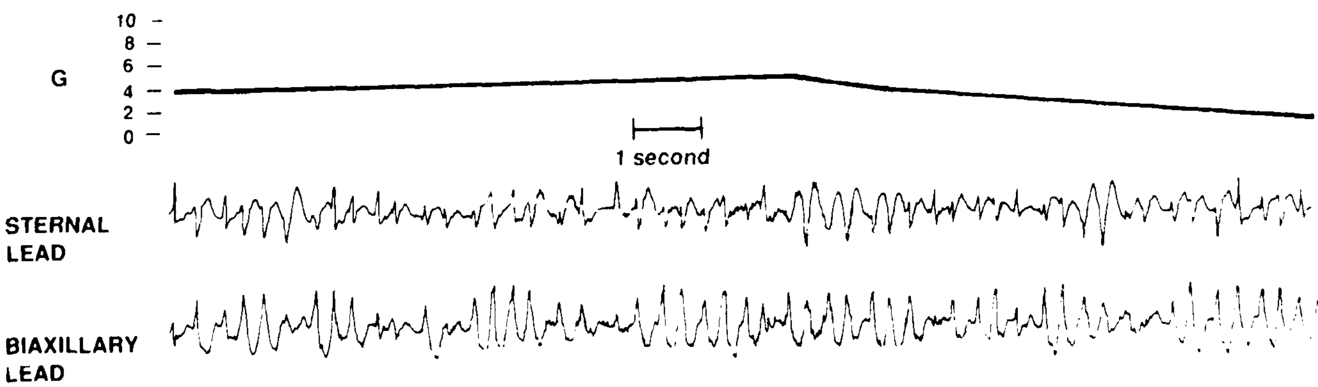

Fig. 1. An example of ventricular tachycardia occurring at 5 G during a gradual-onset run. The onset of ventricular tachycardia was preceded by increasing ventricular ectopy. This episode persisted for 50 s, extending 30 s into the post-G recovery period.

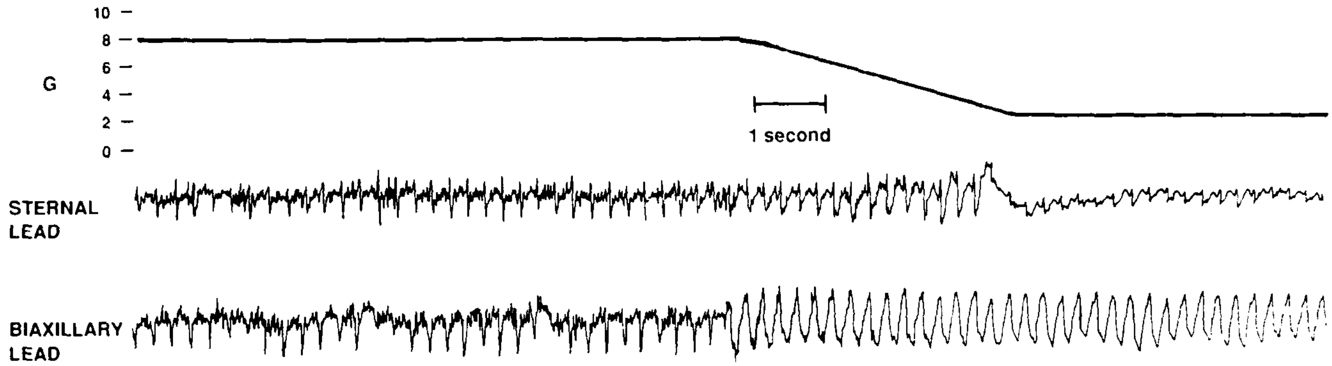

Fig. 2. An example of supraventricular tachycardia with aberrant conduction occurring during an 8-G rapid-onset (6 G/s) run, initially diagnosed as ventricular tachycardia by the medical monitor. Subsequent cardiology review led to the reinterpretation of the ECG. This episode lasted 20 s, extending into the post-G recovery period.

TABLE II. FREQUENCY OF RUN-TERMINATING DYSRHYTHMIAS BY TYPE AND G LEVEL.

	G Level of Occurrence								
Type of Ectopy	≤3 G	4 G	5 G	6 G	7 G	8 G	9 G	Post G	Totals
PVC2				1	1		5	2	9
PVC3				5		7	5	1	18
PVC4				1		1		1	3
PVC5						1	1		2
PVC7							1		1
extdVT				1			1		2
freqPVC	2	1		3		2			8
SVT				1	1				2
SVT + ACbt					1	1			2
SB				1	1			2	4
ACbt			1				1		2
Totals	2	1	1	13	4	12	14	6	53

See text for dysrhythmia codes. extdVT includes the cases where there were repeated short runs of VT, or more than 7 beats of VT. As only one type of dysrhythmia caused each session to be terminated, the numbers total to 53, the number of sessions that were or would have been terminated because of dysrhythmia.

during the time period covered by this study. Although competence in dysrhythmia recognition is essential for a centrifuge medical monitor, the quality of recording of the dysrhythmias observed was dependent on the individual monitors, with some counting the number of PVC's occurring in each run, while others distinguished only occasional PVC's or frequent PVC's. Also, the ECG was interpreted in real time, either from the CRT screen or from the strip chart. While gross abnormalities were reliably detected under these circumstances, identification of any particular abnormality was subject to error. This problem was made even more difficult by the decrease in quality of the ECG as the G level increased—especially when the trainee started straining, adding artifacts from muscle activity to the ECG. The ECG's were not reviewed by a cardiologist to confirm the interpretation, except when significant dysrhythmias were seen. This problem is highlighted by two cases in which runs were stopped because the medical monitor thought he observed VT, which upon review of the ECG was found to be supraventricular tachycardia with aberrant conduction (still a valid reason to terminate a run). Thus, the numbers recorded for the categories of the different dysrhythmias may be in error; in particular, it is possible that the reported incidence of VT is too high.

Despite the shortcomings of this study, it is clear that serious dysrhythmias do occur in ostensibly healthy individuals during centrifuge training. The high frequency with which dysrhythmias occurred in the USAFSAM trainees on the Armstrong Laboratory centrifuge—especially the high incidence of PVC's—is in keeping with observations made by other investigators. The subjects used in this study had a mean age 33.6 years, compared to USAF pilots undergoing centrifuge training, who had a mean age of 30.5 years (Slyter T M, personal communication). Although the pilots are 3.1 years younger than our study group and would probably have a slightly lower incidence of dysrhythmias, in our opinion it is unlikely that this difference would be large.

The 2.2% incidence of VT cannot be ignored. This dysrhythmia would be clinically significant if seen spontaneously in an electrocardiogram taken at rest or during exercise testing, especially in the presence of symptoms or other evidence of cardiovascular disease. The fact that the subjects were relatively young, asymptomatic, and already certified to USAF Flying Class II or III standards influenced the medical monitors' judgment regarding the need for medical work-up. In a few cases, consultation with a cardiologist led to a reinterpretation of the ECG (the data in Tables I and II used the reinterpreted ECG's). One subject referred for further investigation continued to show dysrhythmias on further monitoring, but had no other pathology.

Riding the centrifuge is generally a stressful experience, and it was especially so for this group of subjects, for whom it was their first such experience. The high incidence of dysrhythmias seen in naive centrifuge subjects is usually ascribed to excessive autonomic activity. There is some evidence for excessive sympathetic drive to the heart in these subjects. Prior to the first centrifuge run, the ECG and heart rate were monitored for approximately 1 min. The average peak heart rate recorded for all of the subjects during this prerun period was 106 ± 18 bpm, which is certainly higher than would be expected if these subjects were relaxed and not anticipating the commencement of the centrifuge runs.

The high incidence of dysrhythmias produced during application of high G forces in the centrifuge suggests that dysrhythmias also occur in flight. Although there is no direct evidence that fatal G-induced dysrhythmias have occurred in flight, we can speculate that some of the fatalities attributed to G-LOC might have resulted from G-induced dysrhythmias. The incidence in flight is probably lower than that seen during centrifuge training, however, because: 1) the frequent and regular exposure to the aerial maneuvering environment should make aircrew less apprehensive about G forces experienced in flight; and 2) the high-G loads developed in flight are usually not sustained as long as they are in the centrifuge.

As the dysrhythmias that occur during high-G centrifuge training almost always resolve spontaneously upon return to 1 G, such occurrences can in most circumstances be considered benign. The relatively large number of PVC's, both coupled and uncoupled, in subjects experiencing high G stress should be attributed, in our opinion, to physiologic effects of the high G stress and to sympathetic stimulation concomitant with the novel training environment, and not to underlying pathology. In a clinical setting, the appearance of dysrhythmias such as PVC triplets in a routine ECG would make the clinician suspicious of cardiovascular pathology; but in subjects exposed to high G stress during centrifuge training, these minor degrees of ectopy should be considered benign.

Although nearly all the dysrhythmias observed during centrifuge training are benign, we believe such training should be done with ECG monitoring, because of the occasional exception that is bound to occur. For example, VT can become sustained, and could potentially evolve into ventricular fibrillation, a fatal dysrhythmia. Further, excessive sympathetic stimulation of the heart, manifested by abnormally high heart rates, has the potential to produce cardiomyopathy (2,3). ECG monitoring allows the medical monitor to terminate G exposures when high heart rates suggest trainees are at risk for cardiomyopathy due to excessive sympathetic stimulation.

If ECG monitoring of centrifuge training is done, a fair policy must be devised for the disposition of those aircrew showing significant dysrhythmias during training. Such a policy should be similar to that used for the group of trainees reported in this study. Short runs of coupled PVC's (certainly PVC triplets, and possibly longer runs) should be considered benign; but long runs of VT, especially those that are slow to resolve on cessation of G exposure, could have serious implications for the individual involved and should be investigated in the interest of the individual's future well-being. Some help in assessing the health risk associated with these G related dysrhythmias could come from statistics for subjects undergoing maximal exercise testing; but qualitative differences between G stress and exercise stress may prevent valid inferences from being made from such statistics. A prospective study, with expert review of the ECG's obtained during exposure to G, is probably necessary to accurately determine the incidence and significance of the various dysrhythmias that occur during centrifuge training.

The following tenets are offered as a guide for future policy regarding high-G training:

1. ECG monitoring should be accomplished during all high-G centrifuge training.
2. There should be no aeromedical consequences for dysrhythmias seen during centrifuge training, with rare exceptions.
3. Only those trainees showing strong indications of pathology (e.g., sustained VT or SVT, Wolff-Parkinson-White pattern, atrial flutter, or fibrillation) should be referred for further medical workup.

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