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G-transition effects and their implications

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# G-Transition Effects and Their Implications

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G-transition effects are defined as the spectrum of physiological and psychophysical effects induced by rapid changes in gravitoinertial forces, alternating between hypogravity ($<1\ G_z$) and hypergravity ($>1\ G_z$) and vice versa. They appear to involve the cardiovascular and spatial orientation systems This note attempts to briefly review past and current research efforts on the consequences of G-transitions and to examine potential confounding Coriolis-induced bias in both ground-based and inflight research. A brief review of current evidence of vestibular influence on orthostatic compensation and their implications for G tolerance is presented. The effects of roll-induced hypogravity on subsequent G tolerance and possible misperception of attitude during roll rotation are discussed An integrated approach is recommended for future research on acceleration and disorientation

**Keywords:** G-transitions, hypogravity, hypergravity, and disorientation.

THERE HAS BEEN A RENEWED interest in how $+G_z$ tolerance is reduced by a period of hypogravity (less than $+1\ G_z$) followed by hypergravity (greater than $+1\ G_z$). This reduction was termed the "push-pull" effect (1). The transition from hypogravity to hypergravity was commonly interpreted as occurring in the classical "bunt-then-pull" (i.e., stick pushed forward, then pulled back) maneuver. However, some evidence suggests that such a narrow interpretation of this phenomenon may inadequately account for the broad spectrum of potentially hazardous scenarios and the wide range of adverse effects that may ensue. On review of earlier literature and current findings, we propose that the reduced $+G_z$ tolerance is one of the potential consequences of any G-transition. We define G-transition effects (GTEs) as a spectrum of physiological and psychophysical effects induced by rapid changes in gravitoinertial forces alternating between hypogravity and hypergravity and vice versa. They appear to influence both the cardiovascular and spatial orientation systems. More importantly, recent evidence suggests that an interaction between the vestibular and cardiovascular systems mediated by the vestibulo-sympathetic reflex (26) may play a role in cardiovascular compensation for orthostatic stress experienced during G-transitions. The objectives of this science note are to review pertinent past and current research efforts, to examine the potential confounding physiological effects in centrifuge-based G-transitions research, to examine disorientation possibly associated with G-transitions, and to examine the operational impact of these effects.

## *Background*

von Beckh conducted inflight research and reported that exposure to G-transitions induced stress on the cardiovascular system (21,22). He reported that the effects of exposure from hypogravity to hypergravity included reduced G-tolerance, G-induced loss of consciousness (G-LOC) at lower G-values and at shorter G-duration, reduced efficiency in physiologic recovery mechanisms and subjects experiencing higher strain (22). The effects of the reverse, i.e., hypergravity to hypogravity transitions, included pronounced disorientation and extended duration of G-LOC. von Beckh referred to the reduced G-tolerance and greater strain as "a logical consequence of the transition from hypogravity to hypergravity." Regarding disorientation related to G-transitions, he speculated that it was due to incorrect vestibular cues (21).

More recent ground-based research (1,11) has indicated that exposure to hypogravity immediately before hypergravity resulted in a more profound fall in arterial BP and by inference, a reduced $G_z$ tolerance. Flight tests concentrating on the effects of hypogravity to hypergravity transition have also been performed (12,25). It was concluded that there was a significant decrease in $+G_z$ tolerance. This observation is similar to the reduction previously reported in the centrifuge studies. It should be noted that some of the flight profiles that were used in these studies were dissected single maneuvers that typically occur in rapid sequence in flight.

G-transitions effects raise a number of concerns: possible Coriolis induced bias in centrifuge-based research; differences in cardiovascular responses to roll as opposed to pitch rotation; airborne maneuvers producing GTEs; and disorientation during prolonged rotation.

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### *Possible Coriolis-Induced Bias*

Ground-based simulations of G-transitions that employ centrifuges (and similar devices) produce possible confounding factors: G vectors other than pure $G_z$ (i.e., $G_x$ and $G_y$ biases), and Coriolis cross-coupling prior to the onset of increased acceleration. For example, to provide $-G_z$ exposure, most centrifuges require an orientation of the subject in the gondola so that the subject's head swings away from the axis of rotation. While the centrifuge begins planetary rotation, the subject's head is reoriented toward the axis of rotation to create the $+G_z$ acceleration. In this case, significant Coriolis cross-coupling effects are produced simultaneously. Other techniques can also be employed to provide the initial $-G_z$ exposure: for example, the subject's head could be placed in an initial pitch down position. However, Coriolis cross-coupling effects cannot be avoided since they are due to simultaneous rotation about more than one axis, which is inevitable in centrifuges. Both the perception of spatial rotation and the discomfort associated with such head/body movements may be explained on the basis of the signals processed by a combination of different sets of semicircular canals and the otoliths of the vestibular apparatus.

The cardiovascular effects of Coriolis cross-coupling were highlighted by Sunahara et al. (19). They demonstrated that Coriolis cross-coupling effects caused significant increases in forearm blood flow as measured by venous occlusion strain gauge plethysmography. In subjects with low tolerance, there was an immediate two- to three-fold increase in forearm blood flow within 2 min of head movements, and concomitant reports of nausea. The increase in forearm blood flow suggests a decrease in sympathetic activity to this vascular bed. However, in subjects with high tolerance, there were no important changes in forearm blood flow. The effect of the vestibular Coriolis reaction on forearm blood flow changes in humans was later confirmed by Sinha (18). He reported that the latencies to blood flow increase were from 50 s to 1.6 min in subjects with low tolerance. In general, the magnitude of the change in forearm blood flow correlated with the severity of motion sickness symptoms, definite nausea being the end-point for all these studies (18,19). Vasodilatation in the limbs impairs orthostatic tolerance, particularly if blood flow is shown to increase simultaneously in the lower limbs, which raises the possibility that G tolerance may also be impaired.

Since the venous occlusion technique does not allow continuous data sampling, the time course of blood flow changes may be underestimated. Recently, Cheung et al. (3,4) extended Sunahara's findings, using laser Doppler flowmetry (providing real-time monitoring of cutaneous blood flow) to investigate how the time course of the blood flow changes correlate with the subjective reports of symptoms of motion sickness. During Coriolis cross-coupling stimulation, significant forearm and calf cutaneous blood flow was found to increase simultaneously. The temporal sequence of the peak increase in forearm and calf blood flow was consistent within the subjects from trial to trial but varied across the subjects. Latency to blood flow increases ranged from 14–90 s from stimulus onset without overt symptoms of motion sickness. However, peak increase of blood flow in both forearm and calf occurred when the subject reached definite nausea. In other words, humans may have different sensitivity to these Coriolis-induced vascular changes. As mentioned above, limb blood flow increase may compromise the ability to withstand orthostatic stress. Therefore, these findings may confound previous reports on reduced G tolerance using ground-based simulators/centrifuges to produce hypogravity to hypergravity transitions where simultaneous Coriolis stimulation was unavoidable. In subjects with low tolerance to Coriolis cross-coupling, is the observed G-tolerance impairment a partial response to Coriolis stimulation, or hypogravity to hypergravity G-transition, or both?

The pertinence of these findings to the inflight setting is unclear. In high performance aircraft, the magnitude of physical cross-coupling would be low because of the low angular velocities during most coordinated turns. However, under high G and rapid G-transition, the physical magnitude of the cross-coupling effect is more intense and disorienting. Also, it is rare for the aircraft to execute maneuvers involving angular motion without associated changes of gravitoinertial force. It has been suggested by Benson (2) that in flight, the disorientation produced by head movements during turning and spinning is probably a combination of cross-coupled (canal-mediated) and G-excess illusions (otolith-mediated). This combination of stimuli might also be expected to have cardiovascular effects, in particular, impaired orthostatic tolerance. The relative importance of canal and otolithic influences in the disorientation caused by head movement and in cardiovascular compensation has yet to be resolved, but head movements are undoubtedly a potent cause of perceptual error in flight. It has also been suggested that cross-coupled and G-excess illusions can be induced in high agility aircraft without head movements from the pilot (17). Whether Coriolis-induced peripheral pooling occurs inflight remains to be investigated.

### *Cardiovascular Responses to Roll vs. Pitch Rotation*

Considerable evidence from animal and human studies (5,8,26) suggests that we are less capable of compensating for roll-induced orthostatic stress, and that the vestibular system plays an important role through the vestibulo-sympathetic reflex in compensating for such stresses. The vestibular system responds to gravitoinertial forces and postural changes; therefore, it is reasonable to postulate that the vestibular system might exert a direct influence on cardiovascular compensation.

Recent studies in decerebrate cats (24,26) demonstrated that increases in sympathetic outflow are elicited by pitch rotation but not by roll rotation. As a control for other reflexive responses, these cats also underwent other surgical intervention such as upper cervical root transection, cerebellectomy, baroreceptor denervation and vagotomy. Bilateral transection of the vestibular nerves in paralyzed, choralose-anesthetized cats impaired hypotension compensation (8). The response characteristics of the sympathetic outflow are similar to those of the otolith afferents. The gain of the vestibulo-sympathetic reflexes during pitch rotation is constant across stimulus frequencies and is in phase with the stimulus (head) position, implying that the vestibular influence is primarily of otolith origin. Based on the evidence cited, the vestibular signals have been hypothesized to provide feed-forward adjustments of BP during unexpected postural change (24), such that the compensation for orthostatic hypotension can begin before BP drops significantly.

In humans, using an electronic tilt-table, Cheung et al. (5) indicated that the rate and magnitude of BP decrease as induced by a 135° head down (HD $-0.7$ $G_z$) to 15° head up (HU $+0.98$ $G_z$) maneuver is significantly higher in roll than in pitch rotation. Simultaneously, the increase in heart rate was significantly greater during pitch than during roll rotation. These results suggest relatively poorer cardiovascular compensation for orthostatic stress (HD to HU tilt) during roll rotation, and that pitch rotation is better compensated for. This is not surprising from an evolutionary standpoint since we develop adaptations according to the needs of daily living: we often pitch forward but we seldom have to roll more than 5–10°. Furthermore, roll movements that we often make usually are restricted to the head level only. In other words, teleologically we are not "hardwired" to roll. Whether a direct vestibular influence is involved in this observation is unclear.

The foregoing tilt-table study had some important limitations: the maximum angular speed is $45° \cdot s^{-1}$; maximum acceleration can never exceed $+1$ $G_z$; and that there is a changing G-vector during roll rotation. Nevertheless, the data suggests that in flight, a roll maneuver executed during hypogravity to hypergravity G-transitions could impair subsequent G-tolerance as suggested by von Beckh (22). It was also shown that high angular acceleration of the head about the yaw axis reduces the baseline baroreflex responsiveness by 30% (20), when RR interval in milliseconds was plotted against estimated carotid pressure. This finding suggested that high angular acceleration inhibits vagally mediated baroreflex control of heart rate, and impairs orthostatically induced tachycardia (6) almost immediately. High-speed yaw rotation also caused progressive tachycardia, narrowing of pulse pressure, a drop in mean arterial pressure, and inferentially a drop in cardiac output. The major increments on the heart rate were achieved in the first 2 min (20). This data provides support for the influence of the vestibular system on sympathetic outflow in humans, and is a concern for G-tolerance.

### *Flight Maneuvers that Produce G-Transitions*

Aircrews often regard $-G_z$ (hypogravity) exposure as unpleasant, but it is not avoided in aerial combat. Analysis of the $G_z$ environment during one-on-one air combat maneuvring in the F-15, F-16 (10) and F-18 (16) indicated that pilots experienced high peak levels of $+G_z$, but very little $-G_z$. However, there are situations in which negative to positive $G_z$ (hypogravity to hypergravity) transitions occur in flight. In aerial combat, one of the common methods to gain kinetic energy (airspeed) in order to acquire tactical advantage over the opponent involves "unloading" the aircraft from positive to negative $G_z$. In some cases, this maneuver involves rolling and then by pulling the maximum G-forces available. G-meter recording from operational head-up display (HUD) tapes suggests that hypogravity to hypergravity maneuvers were present during air combat training missions performed by the USAF (14). However, the analysis focused only on the hypogravity to hypergravity G-transition phase; the maneuvers that preceded the transitions were not examined. Extreme pitch used in aerial combat and the repeated and very intense roll exposures accompanying them may have significant vestibular and cardiovascular effects similar to those described in the preceding sections.

Current research has focused mostly on the effects of the transition from hypogravity to hypergravity. However, during most military flight maneuvers, hypergravity to hypogravity transition often precedes the transition from hypogravity to hypergravity. The $G_z$-time history prior to a G-transition may have an effect on subsequent $G_z$ tolerance as suggested by von Beckh (21,22). Frazier et al. advocated that the recent $G_z$-time history be addressed in the design of future electronic microprocessor-controlled G valves (9).

A point roll (where level flight is maintained throughout by reference to a point in the horizon), followed by high $+G_z$ loading is another instance where hypogravity to hypergravity transition can be encountered. When a seated subject is rotated at a constant speed about the Earth's horizontal axis, blood flow along the longitudinal body axis will be subjected to two force components. One will be the centrifugal force component, $\omega^2 r$ where $\omega$ = angular velocity and r = radius of rotation. The other will be gravity, which will vary sinusoidally between $+1$ $G_z$ when upright and $-1$ $G_z$ when inverted. The center of gravity of high performance fighters is located somewhere below the seat of the pilot. Physical principles dictate that hypogravity could be induced by a point-roll maneuver during level flight (rolling about the longitudinal axis of the aircraft).

The centripetal acceleration experienced at the pilot's head during unloaded roll depends on the rate and the radius of rotation (i.e., distance from the eye level of the pilot to the center of gravity of the aircraft). For example, in the CF18 it varies from 0.8 m to over 1 m, depending on the height of the pilot's upper torso. If the aircraft executes a point roll at $90° \cdot s^{-1}$ and at an eye level rotation radius of 0.8 m, the centripetal acceleration experienced is $-0.2$ $G_z$ and at a rate of $180° \cdot s^{-1}$, the centripetal acceleration is $-0.8$ $G_z$. Similarly, hypogravity may be induced by unloaded barrel rolls in which rotation is rapid enough and that the pilot is situated off-center.

Therefore, similar to the "bunt-then-pull" maneuver, pulling $+G_z$ following a point roll or unloaded barrel roll can result in a hypogravity to hypergravity G-transition. Such G-transitions during operational flight may be associated with more complex cardiovascular effects than previously suggested. Indeed, several aircraft occurrences exist in which G-transitions ensuing rolls may have led to reduced G tolerance (15). Accordingly, fight safety concerns may be warranted.

### *Disorientation During Prolonged Rotation*

Reduced G-tolerance is not the only deleterious consequence of G-transitions. In von Beckh's study, disorientation was reported during the transition from hypergravity to hypogravity. However, the type of disorientation that was induced and how it might affect subsequent G-transition and G-tolerance remains to be investigated. Surveys of civilian aerobatics pilots revealed that 12.7% reported persistent vertigo after aerobatics flights with maneuvers involving $-G_z$ (23).

During constant roll rotation, the lack of sensory information about rolling as well as the erroneous signal of rolling in the opposite direction on recovery, are well known. Typically, in a constant roll of 2 $rad \cdot s^{-1}$ (about $100° \cdot s^{-1}$), the sensation of roll lingers for another 10 to 15 s (2). The hydrodynamics and frequency response of the mechanical component of the semicircular canals are well known. The effective time constant of post-rotational decay (the equivalent time constant of cupula return), as measured by the post-rotational sensation and the time course of compensatory slow phase nystagmus, are considerably shorter in roll (4 s) than in pitch (7 s) and yaw (16 s) (13). The sooner the cupula returns to neutral position, the sooner the sensation of rotation will stop, while actual rotation is physically occurring. Therefore, in the context of aviation, this implies a considerably greater rate of development of error in response to rotational stimuli in roll than in pitch and yaw. The short time constant in roll might not exert any significant effects when the roll rates could be as high as $300° \cdot s^{-1}$. However, it may be of concern for moderate rotation. For example, if visual reference is unavailable, for a 360° roll having an angular velocity of $60° \cdot s^{-1}$ throughout, the apparent rate of roll would have fallen to $18° \cdot s^{-1}$ at the end of the maneuver (using 4 s as the time constant). The apparent total angle of roll would only amount to approximately 230°; if the pilot had started from the erect position he would feel himself still upside down after one complete turn. Since G-transitions often involve roll rotation, it is reasonable to view disorientation under prolonged roll as a G-transition effect.

## CONCLUSIONS

G-transition effects involve both the cardiovascular and vestibular systems. An integrated approach to disorientation and acceleration research and accident investigation is warranted in order to recommend the most appropriate countermeasures. Possible disorientation and misperception of roll angle and roll rate during "roll then pull" maneuvers must be investigated because it could affect the intended attitude for the subsequent G-transition if a visual horizon is not available. The interaction between disorientation and acceleration is an important issue since next generation thrust-vectored, high performance; superagile aircraft provide greater multi-axis maneuver capability. The hypogravity (less than $+1\ G_z$) of "bunt-then-pull" maneuvers are not the only manner in which G-tolerance is reduced. For example, the effects of roll-induced hypogravity have not been heretofore considered. Recent $G_z$-time history and vestibular influences may contribute to the reduced G-tolerance induced by hypogravity to hypergravity transition. How much vestibular influences can impair G-tolerance has yet to be determined. Definitive future studies are needed to investigate the vestibular contribution to sudden postural change. Investigation using ground-based facilities to simulate G-transitions should account for the potentially confounding effects of Coriolis cross-coupling. Inflight studies should use maneuvers representative of aerial combat.

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