ACCELERATION TOLERANCE: WHAT HELPS AND WHAT HURTS

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ACCELERATION TOLERANCE

- G-tolerance
- G-endurance
- Vision loss
- G-induced loss of consciousness
- G-induced almost loss of consciousness
A NEGLECTED PROBLEM

ACCELERATION-INDUCED ALMOST LOSS OF CONSCIOUSNESS (A-LOC)
• Loss of consciousness during high-G (G-LOC) is recognized as a major risk for fighter pilots

• Much less attention is paid to the possibility that acceleration may produce neurocognitive effects without reaching the threshold for frank loss of consciousness
A study was made to develop measures of A-LOC and to identify centrifuge profiles, which produce more prolonged A-LOC.

Of 58 centrifuge runs, 37 produced evidence A-LOC and three resulted in G-LOC.
The subjects often reported:
- difficulty in thinking
- loss of memory
- visual changes other than gray- and black-out
- hearing loss
# A-LOC Symptoms and signs

<table>
<thead>
<tr>
<th>Symptom</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Difficulty thinking, could not concentrate, did not remember</td>
<td>34</td>
</tr>
<tr>
<td>Visual changes – flashing colors, rotating visual field with vection</td>
<td>21</td>
</tr>
<tr>
<td>Hearing loss/impairment</td>
<td>16</td>
</tr>
<tr>
<td>Twitching of the face, hands, or feet</td>
<td>12</td>
</tr>
<tr>
<td>Impaired motor control; inability to act, maintain control</td>
<td>5</td>
</tr>
<tr>
<td>Felt ‘slow’; i.e., temporal distortion</td>
<td>4</td>
</tr>
<tr>
<td>Lightheaded</td>
<td>3</td>
</tr>
</tbody>
</table>
What helps:

1. A correct Muscle and Respiratory Straining Maneuver
2. Anti-G suit, especially with full coverage of the lower body and possibly with a continuous ready pressure
3. Pressure breathing during G, unassisted for short G exposures and assisted pressure breathing for endurance
4. Muscle strength training program and physical endurance training (however, evidence difficult to scientifically prove)
5. Avoid physical and mental fatigue before flying
6. Avoid heat stress and dehydration
7. Avoid low blood sugar concentration
8. Regular high G-exposures
9. Good health before flying
10. Tilted seat back angle and elevated legs
What hurts:

1. Not used to high G exposures
2. Poorly timed anti-G straining maneuver
3. Not properly fit anti-G suit
4. Mask leakage when pressure breathing during G
5. High body temperature and dehydration
6. Low blood sugar concentration
7. Fatigue and minor illness
8. Tall body length with long heart-brain distance
9. Upright seat position
10. Hang-over
EFFECT OF ANTI-G STRAINING MANEUVER ON HEAD-LEVEL BLOOD PRESSURE

HEAD-LEVEL BLOOD PRESSURE (mmHg)

TIME (s)

GOOD TECHNIQUE
POOR TECHNIQUE (INSUFFICIENT STRAINING TIME)
POOR TECHNIQUE (STRAINING TOO LONG)
NO STRAINING

(from K. Gillingham, MD, PhD)
(from K. Gillingham, MD, PhD)
G-Layoff effect (from K. Gillingham, MD, PhD)
Seat back angle and G-tolerance (from HJ van Beck)
Muscle strength training programs to enhance G-tolerance and endurance.

Evidences difficult to scientifically prove.
Muscle strength training programs to increase G-endurance


and


SACM time in 11-12 weeks of strength training in centrifuge subjects or 11 fighter pilots increased by 20-40%.


SACM time increased from the second controls in 17 fighter pilots by 24% after 6 months of physical training and by 38% after 12 months of training.
Abdominal muscle strength training only


No increase in G-tolerance of fighter pilots was found with muscle strength training of abdominal muscles only.
Assisted Positive Pressure Breathing for Augmentation of Acceleration Tolerance Time

John W. Burns, Ph.D., and Ulf I. Balldin, M.D., Ph.D.

Acceleration Effects Laboratory, School of Aerospace Medicine, Brooks Air Force Base, Texas
POSITIVE PRESSURE BREATHING—BURNS & BALLDIN

- PPB0, n = 7, 74 sec
- PPB10, n = 7, 139 sec
- PPB∞, n = 6, 154 sec

(p < .01)
PRESSURE BREATHING DURING G

- AUGMENTS ACCELERATION TOLERANCE and ENDURANCE
- USED IN USAF F-16 AND F-15 (COMBAT EDGE)
Positive Pressure Breathing and Atelectasis

30 mmHg Unassisted Positive Pressure Breathing REDUCES or ELIMINATES G-induced pulmonary atelectasis formation
PRESSURE BREATHING DURING G IN COMBINATION WITH EXTENDED COVERAGE ANTI-G SUIT

• AUGMENTS ACCELERATION TOLERANCE STILL FURTHER

• USED IN SWEDISH AIR FORCE GRIPEN AND IN FINNISH AIR FORCE F-18

• USAF F-22 AND EUROFIGHTER
Improved Anti-G Protection Boosts Sortie Generation Ability

Andrew Tong, M.D., M.P.H., Ulf I. Ballin, M.D., Ph.D.,
Ronald C. Hill, M.S., Ph.D., and James W. Dooley, M.S.,
Ph.D.
GOR to +9Gz max
rest
+4.5 to +7Gz SACM
4 peaks max
rest
“TACM”
4 x 2-peak cycles (max)
rest
+5 to +9Gz
4 peaks max
rest
repeat whole sequence 2 times
20 min rest
# Incidences of G-LOC and relaxed G-tolerance

<table>
<thead>
<tr>
<th>G-LOC</th>
<th>Mean max G during GOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>CE/ATAGS</td>
<td>0</td>
</tr>
<tr>
<td>Standard anti-G suit</td>
<td>4</td>
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</tbody>
</table>

(p<0.001)
Mean heart rate, peripheral light loss % and effort level at the end of sortie three with CE/ATAGS and standard anti-G suit (STD)

<table>
<thead>
<tr>
<th>Profile/ensemble</th>
<th>HR</th>
<th>PLL</th>
<th>Effort level</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.5-7 SACM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CE/ATAGS</td>
<td>140</td>
<td>24</td>
<td>4.5</td>
</tr>
<tr>
<td>STD</td>
<td>166*</td>
<td>53*</td>
<td>7.0*</td>
</tr>
<tr>
<td>TACM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CE/ATAGS</td>
<td>151</td>
<td>46</td>
<td>6.5</td>
</tr>
<tr>
<td>STD</td>
<td>173*</td>
<td>66*</td>
<td>8.7*</td>
</tr>
<tr>
<td>5-9 SACM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CE/ATAGS</td>
<td>156</td>
<td>33</td>
<td>6.0</td>
</tr>
<tr>
<td>STD</td>
<td>169 (ns)</td>
<td>63*</td>
<td>9.3*</td>
</tr>
</tbody>
</table>
Mean subjective fatigue and reported recovery time with CE/ATAGS and USAF standard anti-G suit (STD)

<table>
<thead>
<tr>
<th></th>
<th>Subjective fatigue (lower value more fatigue)</th>
<th>Recovery time</th>
</tr>
</thead>
<tbody>
<tr>
<td>CE/ATAGS</td>
<td>3.8 units</td>
<td>21 hr</td>
</tr>
<tr>
<td>STD</td>
<td>2.6 units</td>
<td>42 hr</td>
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(p=0.001) (p=0.003)
ENDURANCE DURING MULTIPLE INTENSE HIGH +Gz EXPOSURES WITH EFFICIENT ANTI-G PROTECTION EQUIPMENT

UI Balldin¹,², PM Werchan¹, J French¹, B Self¹, A Tong³.

¹Biodynamics and Protection Division, Air Force Research Laboratory, Brooks AFB, Texas; ²National Defence Research Establishment, Sweden; ³Currently USAF Senior Exchange Officer, Japan Air Self Defense Aeromedical Laboratory, Japan
In a war time scenario pilots may be required to fly multiple missions during the same day.
OBJECTIVE

ARE MULTIPLE STRENUOUS SORTIES
WITH SEVERAL DOG-FIGHT LIKE ENGAGEMENTS
INCLUDING PEAKS UP TO +9 Gz

ENDURABLE

WITHIN A 4-HR PERIOD

USING

COMBAT EDGE & ATAGS?
METHODS

AFRL centrifuge at Brooks AFB
(6 G/s onset rate)

9 subjects:
COMBAT EDGE & ATAGS
Brooks City-Base
one engagement

+ 9 G_z
+ 8 G_z
+ 6 G_z
+ 4 G_z
+ 3 G_z
+ 1.5 G_z

<5 s>

80 sec
5 sorties with 4 engagements each

<table>
<thead>
<tr>
<th></th>
<th>5 min</th>
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<tbody>
<tr>
<td>1</td>
<td></td>
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<td>5</td>
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30 min
RESULTS

• 7 of 9 subjects endured all 5 sorties

• 3 G-LOCs (2 in the same subject)

• 4 A-LOCs
MAXIMUM EFFORT LEVEL

The bar chart shows the maximum effort level for different subjects. Each red bar represents an individual subject's maximum effort level, ranging from 0 to 10. The green bar represents the mean effort level across all subjects.
HIGHEST RECORDED PERIPHERAL LIGHT LOSS

Subject

Peripheral Light Loss (%)

0 20 40 60 80 100

Subject

Mean
HIGHEST RECORDED CENTRAL LIGHT LOSS
MAXIMAL HEART RATE

Subject

Max Heart Rate (bpm)

Mean
MINIMAL OXYGEN SATURATION

Subject

Min Oxygen Saturation (%)
SUBJECTIVE RECOVERY TIME

Recovery Time (hours)

Subject

1 2 3 4 5 6 7 8 9 Mean
CONCLUSION

Subjects can withstand five consecutive high intensive air-to-air combat sorties with PBG and extended coverage anti-G suit
QUESTIONS HAVE BEEN RAISED IF PRESSURE BREATHING DURING G IN COMBINATION WITH EXTENDED COVERAGE ANTI-G SUIT COULD INCREASE THE RISK OF CARDIAC DYSRHYTHMIAS
GOR to +9Gz max 2 min rest +4.5 to +7Gz SACM 4 peaks max 2 min rest “TACM” 4 x 2-peak cycles (max) 2 min rest +5 to +9Gz 4 peaks max 20 min rest repeat whole sequence 2 times
RESULTS

No PVCs during GOR

In all SACMs and TACMs together:
- 157 PVCs with Standard Equipment
- 156 PVCs with COMBAT EDGE and ATAGS
CONCLUSIONS

• NO DIFFERENCE WAS SHOWN IN THE OCCURRENCE OF PVCs BETWEEN STANDARD ANTI-G SUIT AND COMBAT EDGE WITH ATAGS EQUIPMENT WITH THE SELECTED AIRWAY AND G-TROUSER PRESSURES

• ALL CARDIAC DYSRHYTHMIAS DISAPPEARED AFTER THE HIGH G-LOADS
Arm Pain Among Swedish Fighter Pilots During High +Gz Flight and Centrifuge Exposures

LENA LINDE, PH.D., AND ULF BALDIN, M.D., PH.D.
Conclusion

This survey indicated that $+G_z$-induced arm pain is less of a problem in-flight than it is in the centrifuge. However, as more than 50% of the fighter pilots in the Swedish Air Force sometimes have experienced arm pain in flight, it is still a problem to be taken into consideration.
PRESSURIZED ARM SLEEVES AND GLOVES FOR PROTECTION AGAINST G-INDUCED ARM PAIN

Ulf I. Balldin, M.D., Ph.D.¹, ²), Brian P. Self, Ph.D.¹), Robert M. Shaffstall, M.S.³), Thomas R. Morgan, Ph.D.¹)

¹) Biodynamics and Protection Division, Air Force Research Laboratory, Brooks AFB, Texas; ²) National Defence Research Establishment, Sweden and ³) Wyle Laboratories, Brooks AFB, Texas
COMPLAINTS OF ARM PAIN at high sustained $+G_z$ among Swedish fighter pilots

- During high $+G_z$ flight (in Swedish Air Force’s Viggen and Gripen fighter aircraft)
- In centrifuge exposures (AFRL Centrifuge tests at Brooks Air Force Base, Texas)
Presumed causes of G-induced arm pain

- Similar to causes of G-induced petechiae
- Raised venous hydrostatic pressure
- Increased transmural pressure
- Over-distention of blood vessels
PRESSURIZED ARM SLEEVES and GLOVES for PROTECTION against G-INDUCED ARM and HAND PAIN
Sleeve and glove pressure schedules

- 80 mmHg
- 60 mmHg
- 40 mmHg
Subject wearing COMBAT EDGE, ATAGS, pressurized sleeves and gloves seated in the AFRL centrifuge with his hands on the throttle and control stick as in a Gripen fighter cockpit.
PAIN LEVEL

- G-induced arm and hand pain usually started above $+6 \text{ G}_z$ and was often the reason for termination of the G-exposure without the pressurized sleeves and gloves.
- The pressurized sleeves and gloves significantly ($p<0.001$) decreased arm and hand pain.
- No significant difference was found among the different pressures used.
Figure 4. Average subjective left arm pain scores for the gradual onset rate (GOR) and exposures from 3 - 9 Gz.
Figure 5. Pain levels for the left and right arms during the SACM runs. Pain levels during the CONTROL were significantly higher than all other conditions.
CONCLUSION

• The pressurized sleeves and gloves appear to alleviate and sometimes eliminate G-induced arm and hand pain

• Pressurization level (40 - 80 mm Hg) did not seem to alter the results
Foot pain due to extended periods at high G and lack of counter-pressure to the feet

G-measles
G-measles on the uncovered back
Dehydration and G-endurance


A 3% dehydration may decrease G-endurance measured as the ability to withstand repeated 15-s periods at +3.5 and 5 G with normal body temperature by about 40%.
HEAT STRESS-INDUCED DEHYDRATION AND DETERIORATION IN ACCELERATION-TOLERANCE

BALLDIN UI, O’CONNOR RB, ISDAHL WM, WERCHAN PM, MORGAN TR, STORK RL
THIS STUDY WAS ACCOMPLISHED TO DETERMINE HEAT STRESS AND DEHYDRATION IN SIMULATED FLIGHT OPERATIONS OF HOT AND HUMID DAYS USING ANTI-G SUIT FLIGHT EQUIPMENT WITHOUT PRESSURE BREATHING
12 subjects (6 fighter aircrew and 6 Brooks AFB centrifuge subjects)

USAF standard anti-G suit CSU-13B/P (without pressure breathing during G) and other ordinary flight equipment
- Gradual onset (0.1 G/s), relaxed without straining maneuvers to loss of peripheral or central vision

- Rapid onset (6.0 G/s), relaxed without straining maneuvers to 3, 4, 5, 6, 7, 8 or 9 G in periods of 15 s with 2 min rest periods in between to loss of peripheral or central vision
HEAT LOAD and EXERCISE in the THERMAL CHAMBER

- Ambient temperature 35°C (95 °F)
- Relative humidity 85%
- Radiant heat black globe temperature 50 °C (122 °F)
- Walking on level treadmill at 4 km/hr (2.5 mph) for 20 min
- Gradual cooling to room air and relative humidity during a 20 min period, while sitting in an aircraft seat
Mean Core Temperature and Heat Score

- Treadmill Start
- Heat lamps off.
- Treadmill stopped.
- Start Cooling
Mean Chest/Back Skin Temperatures and Heat Score

Treadmill Start
Treadmill stopped. Heat lamps off.
Start Cooling
Mean sweat loss was 1.1 liter ±0.3 corresponding to 1.3% ±0.2 loss of body weight.
BLOOD SAMPLES
BLOOD SAMPLES

- **HEMOGLOBIN** increased from 15.2 G/DL ±0.9 to 15.6 G/DL ±0.9 (p<0.01)

- **HEMATOCRIT** increased from 45.6 % ±2.5 to 46.3 % ±2.4 (p<0.05)
G-tolerance

• Max attained relaxed gradual onset G
  – before heat stress 7.1 G±0.8
  – after heat stress 6.3 G±0.9
(p<0.001)

• Time at increased G with relaxed rapid onset G
  – before heat stress 55 s ±16
  – after heat stress 48 s ±20
(p<0.001)
Tracking Task
F-16 FLIGHT SIMULATION TRACKING TEST

No statistically significant differences were found in:

- **RMS** (Root Mean Square of the G-level error)
- **Time on Target** during tests before and after heat stress
CONCLUSIONS

• The heat load used caused significantly increased body and skin temperatures, and a significant dehydration (revealed by fluid loss and blood chemistry)

• The heat load caused significantly decreased relaxed G-tolerance and significantly increased heart rate during rapid onset G

• Flight simulation performance measures were not impaired after heat stress
RECOMMENDATIONS

– The pilot should be aware of the dangers of heat load. Be encouraged to maintain hydration.

– Avoid excessive heat exposure during pre-flight transportation to the aircraft and during pre-flight walk-around inspections of the aircraft.

– Use hangars or sun shades to protect the aircraft when parked before take-off in hot climate.
COMPARISONS OF HEATS STRESS WITH STANDARD ANTI-G SUIT, COMBAT EDGE AND ATAGS

• No difference was seen in heat stress effects (fluid loss, blood samples, maximal rectal and skin temperatures) between the different combinations of standard anti-G suit, COMBAT EDGE and ATAGS ensembles.

• However, G-tolerance were improved with COMBAT EDGE or COMBAT EDGE WITH ATAGS and flight simulation data were improved with COMBAT EDGE with ATAGS in comparison with standard anti-G ensemble even after heat stress.
What helps:

1. A correct Muscle and Respiratory Straining Maneuver
2. Anti-G suit, especially with full coverage of the lower body and possibly with a continuous ready pressure
3. Pressure breathing during G, unassisted for short G exposures and assisted pressure breathing for endurance
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