Artificial Gravity for Exploration Class Missions: Recent Results and Current Thinking

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Human Adaptation & Countermeasures Division
NASA Johnson Space Center
March 27, 2007
The following is brought to you by the men and women who are building and operating the International Space Station.
Factors Affecting Human Health and Performance During Space Flight

decreased gravity
  bone, muscle, cardiovascular, sensory-motor, nutrition, behavior/performance, immunology, human factors, clinical medicine

isolation/confinedement
  behavior/performance, nutrition, immunology, toxicology, microbiology

altered light-dark cycles
  behavior/performance

increased radiation
  immunology, carcinogenesis
Current Approach to Dealing with Decreased Gravity

1g

Earth Day

Space Day

0000 0600 2200 2400

Cavanagh et al. 2005
How well does our current approach work?

Results from Expeditions 1-9:
(n=12; 4 for 4 months & 8 for 6 months)

<table>
<thead>
<tr>
<th>Measure</th>
<th>Timing</th>
<th>Low</th>
<th>Avg.</th>
<th>High</th>
<th>Draft Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bone</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BMD lumbar spine</td>
<td>R+14-21</td>
<td>-7.5%</td>
<td>-3.0%</td>
<td>+0.5%</td>
<td>Red if &gt;2SD (~21%), Yellow if 1-2SD (~10-21%)</td>
</tr>
<tr>
<td>BMD trochanter</td>
<td>R+14-21</td>
<td>-11.5%</td>
<td>-5.5%</td>
<td>-0.5%</td>
<td>Red if &gt;2SD (~34%), Yellow if 1-2SD (~17-34%)</td>
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<tr>
<td>BMD femoral neck</td>
<td>R+14-21</td>
<td>-10.0%</td>
<td>-5.5%</td>
<td>-1.0%</td>
<td>Red if &gt;2SD (~32%), Yellow if 1-2SD (~16-32%)</td>
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<tr>
<td><strong>Muscle</strong></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>Quad Strength</td>
<td>R+6</td>
<td>-32%</td>
<td>-11%</td>
<td>+18%</td>
<td>Red if &lt; 80%, Yellow if 80-90%</td>
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<td>Hams Strength</td>
<td>R+6</td>
<td>-48%</td>
<td>-20%</td>
<td>-4%</td>
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<td>Quad Endurance</td>
<td>R+6</td>
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<td>-12%</td>
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<tr>
<td>Hams Endurance</td>
<td>R+6</td>
<td>-65%</td>
<td>-12%</td>
<td>+12%</td>
<td>Red if &lt; 80%, Yellow if 80-90%</td>
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<tr>
<td><strong>Cardio</strong></td>
<td></td>
<td></td>
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<tr>
<td>Tilt Test</td>
<td>R+0</td>
<td>6 min</td>
<td>8.4 min</td>
<td>10 min</td>
<td>N/A: clinical pass if survive 10 min</td>
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<tr>
<td>(Med Req’t)</td>
<td>R+1</td>
<td>9 min</td>
<td>9.8 min</td>
<td>10 min</td>
<td>R+1 includes 2 wearing kentavr</td>
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<tr>
<td>Aerobic Capacity FD 0-29</td>
<td></td>
<td>-30%</td>
<td>-18%</td>
<td>+4%</td>
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<tr>
<td>Aerobic Capacity R+4-7</td>
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<td>-17%</td>
<td>-3%</td>
<td>Red if &lt; 75%, Yellow if 75-90%</td>
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<tr>
<td><strong>Neuro</strong></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Balance Test-SOT6 FD 0-5.5</td>
<td>R+0</td>
<td>&gt;36%</td>
<td>&gt;18%</td>
<td>N/A: clinical criteria available for test</td>
<td></td>
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<tr>
<td>(Med Req’t)</td>
<td>R+5.5</td>
<td>&gt;36%</td>
<td>&gt;18%</td>
<td>Based on recovery model using ISS + Mir +STS</td>
<td></td>
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</table>

**Ops Caveats:** equipment reliability; prescription optimization; compliance issues
## Extrapolating Bone Results

<table>
<thead>
<tr>
<th>Measure</th>
<th>Timing</th>
<th>Low</th>
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<td>-1.0%</td>
<td>Red if &gt;2SD (~32%), Yellow if 1-2SD (~16-32%)</td>
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<td><strong>12 month</strong></td>
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<tr>
<td>BMD lumbar spine</td>
<td>R+14-21</td>
<td>-15%</td>
<td>-6%</td>
<td>+1%</td>
<td>Red if &gt;2SD (~21%), Yellow if 1-2SD (~10-21%)</td>
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<tr>
<td>BMD trochanter</td>
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<tr>
<td><strong>30 month</strong></td>
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<tr>
<td>BMD lumbar spine</td>
<td>R+14-21</td>
<td>-38%</td>
<td>-18%</td>
<td>+2.5%</td>
<td>Red if &gt;2SD (~21%), Yellow if 1-2SD (~10-21%)</td>
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<tr>
<td>BMD trochanter</td>
<td>R+14-21</td>
<td>-58%</td>
<td>-33%</td>
<td>-2.5%</td>
<td>Red if &gt;2SD (~34%), Yellow if 1-2SD (~17-34%)</td>
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<td>BMD femoral neck</td>
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<td>-50%</td>
<td>-28%</td>
<td>-5%</td>
<td>Red if &gt;2SD (~32%), Yellow if 1-2SD (~16-32%)</td>
</tr>
</tbody>
</table>
Don’t forget to pack the gravity

Exercise alone won’t be enough to keep astronauts healthy on a round trip to Mars.

LEWIS BARTLETT

FLOATING around in microgravity inside a spacecraft might look like fun, but it can do nasty things to your body. With the current enthusiasm for crewed space flight and particularly NASA’s plan to send astronauts to Mars, there is a need to find ways to counteract the damaging effects of a lack of gravity.

Without Earth’s gravity, astronauts lose their body-eye coordination and as the days go by, they suffer a steady loss of red blood cells and deterioration of bones and muscle, including the heart.

Back on Earth it can take weeks for an astronaut to re-adapt to terrestrial gravity, and they risk broken bones and torn muscles for much longer. “The body tries to adapt itself to a free-fall environment, and this creates enormous problems on return to gravity,” says Kevin Fong of the Centre for Aviation, Space and Extreme Environment Medicine at University College London.

This could be a huge problem if NASA decides to go ahead with its planned trip to Mars. Existing proposals for a “bank robbery” mission, in which a spacecraft would fly there and back as quickly as possible, would take six months each way. After such a spell in microgravity, astronauts could find themselves landing on the Martian surface in a deformed physical shape. The techniques so far developed to try to limit this deterioration, including subjecting astronauts to rigorous exercise in orbit strapped to a treadmill or cycling machine with a harness, may not be enough, says Fong.

The answer, space scientists increasingly believe, is to create artificial gravity in orbit. “We’ll be taking our own air, food, heat, and light to Mars. Why not just take gravity along with us as well?” says Fong.

Gravity can be simulated using a rotating body, which means a centrifuge. The idea was first proposed in 1981, when space-travel pioneer indicated the need for a large spinning doughnut-shaped section of a spacecraft that would provide a gravity-equipped habitat for astronauts. Among alternative designs was a large centrifuge created by two rotating crew habitats at each end of a long boom — rather like a spinning baton — putting out horizontally from the centre of the spacecraft. Work, exercise or recreational time spent in such centrifuges would greatly reduce the physical deterioration of astronauts on a trip to Mars.

The problem is that spinning spacecraft modules are not practical at present. Since the force generated by such a module depends on its radius and how fast it rotates, it would have to be well over 100 metres across, or roughly the size of the London Eye, to create the same gravity as Earth while spinning at a reasonably gentle few rotations per minute. Artificial gravity systems would also generate a number of other disorientating sensations and illusions (see “Light head, heavy feet”).

Far more feasible in engineering terms would be to create a small centrifuge that spins at high speed within the main body of the spacecraft. That’s what Bill Paloski, a neuroscientist at NASA’s Johnson Space Center in Houston, Texas, is investigating. He is carrying out a study in which volunteers spend three weeks lying in a bed with their head lower than their feet, to recreate some of the damaging effects of weightlessness. Half of the people are taken into a centrifuge and spun for a day to create an artificial gravity of 5.5 g at their feet, decreasing to zero at their head. They are finding what benefits artificial gravity brings to the body as a whole, looking at everything from muscle and bone strength to heart function, levels of stress hormones and aerobic fitness,” says Paloski.

The early results are encouraging, he says, and he hopes to be able to publish them next year.

Small centrifuges have a major drawback, however. A centrifuge around 6 metres across — small enough to be reasonably accommodated inside a space station or spacecraft — would have to spin at up to 30 rotations per minute to generate Earth gravity at an astronaut’s feet. This is enough to cause severe motion sickness. To prevent astronauts being crippled by these effects, teams are concentrating on developing spinning gyms rather than living or working quarters where astronauts would be free to walk around.

Vincent Caiazzo, an orthopaedics specialist at the University of California, San Diego, and his team have built a short-arm centrifuge in the Space Cycle. One astronaut sits on a suspended chair-like device, opposite which hangs a cage containing another astronaut, and both are attached to a central pole to form a centrifuge. By pedaling the cycle, the astronaut makes the centrifuge spin, swinging the bike and platform outwards. The device not only provides a strenuous cardiovascular workout for the pedal pusher, but also generates artificial gravity for both. The astronaut in the cage

“...We’ll be taking our own air, food, heat, and light to Mars. Why not just take gravity along with us as well?”

Kevin Fong, MD
New Scientist
4 November 2006
Physics of Rotating Environments

Artificial Gravity Level (Centripetal Acceleration)

\[ G = r\omega^2 \]

\[ \omega = \text{constant} \]

\[ G = \text{constant} \]

Coriolis Force: \(-2m(\omega \times v)\)

Cross-Coupling: \(\omega_{\text{cent}} \times \omega_{\text{head}}\)
Continuous AG-Artistic Concepts

Von Braun, W. (1952) Crossing the Last Frontier

Kubrick (1968) 2001: A Space Odyssey
Continuous AG-Engineering Concept

- Nominal design = 1.0 g
  - Essentially no data on efficacy of hypo-g as countermeasure
- Rotation levels ≤ 4 rpm
  - Acceptable crew adaptation times based on rotating room studies
- Implies radius of ≥ 56 meters

Courtesy of K. Joosten
Rotating Transit Vehicle Concept

Courtesy of NASA
Microgravity-induced osteoporosis and decreased bone structural properties and strength were mitigated by in-flight centrifugation.

**Cosmos-936 (1977)**
on-board centrifuge
18.5 days duration

Wistar Rats
(63 do, 202 gr)
0 g controls (n=20)
1 g treatment (n=10)
- radius = 32 cm
- velocity = 53.5 rpm

Adamovich et al.

**Continuous AG-Supporting Data**


Continuous AG-Future Research: Human Live-Aboard Studies
Do we need continuous AG?

Depends on how much risk/uncertainty we want to accept...

Continuous AG (spinning the vehicle) offers many benefits:
- passive
- reliable
- affects all $G$-sensitive physiological systems
- reduces complexity of other med/cm systems
- improves human factors for many ADLs
Decision for Spinning Vehicle

**Benefits:**
- physiological adaptation in-transit (bone, muscle, cardio, neuro, ...)
- human factors in-transit (spatial orientation, WCS, galley, ...)
- medical equipment/operations (countermeasures, surgery, CPR, ...)
- environmental (particulates, liquids, ...)

**Risks/Uncertainties:**
- engineering (requirements, design: truss, fluid loops, propulsion...)
- human factors during spin-up/down
- physiological adaptation during spin-up/down (neuro, cardio, ...)

Must be Evidenced-Based
Current Approach to Dealing with Decreased Gravity

Long Body Axis Loading

Earth Day

1g

Space Day

1g

Cavanagh et al. 2005
During 4 days of 6° head-down bed rest, intermittent exposure to 1g plus exercise (treadmill walking at 3.0 mph) prevented the increase in urinary calcium excretion typically seen during simulated microgravity.

n=9 males, 38 ± 5 yo, 182 ± 5 cm, 84 ± 8 Kg
4 days 6°HDT BR X 5 CM conditions (1 m recovery)
CM: None, stand 15/60min for 8 or 16 hrs, walk 15/60min for 8 or 16 hrs

Redrawn from Vernikos et al. Aviat Space Environ Med 1996
Intermittent AG-Practice
Intermittent AG-Practice

**Rotational AG**
- Bone
- Muscle
- Cardiovascular (VO₂ & OI)
- Neuro (prop & vest)

*Enhanced by coupling w/ exercise

STS-90 (Neurolab)  
STS-42 (IML-1)

**Intermittent Rotational AG Trade Space**
- g, r, ω, duty cycle
- exercise req’ts
- optimal prescription
IMAG Project Plan

I Pilot Study
12-18 months
US only (UTMB)

II Science Phase
~5 years
UTMB, IMBP, DLR

III Flight Demo
~5 years
ISS

- Prescription to protect bone, muscle, cardio, neuro using intermittent AG
- Optimal duty cycle (g, \( \omega \), frequency, duration, exercise)
- Axial (z-axis) loading thresholds
- Capacity for adaptation: neuro, cardio (fluid shifts)
- Lead to flight testing (prescription validation, vestibular responses, ?)

IMAG = International Multi-Disciplinary Artificial Gravity
Pilot Study of Artificial Gravity as a Multi-System Countermeasure to Bed Rest Deconditioning

Preliminary Findings
Pilot Study Investigator Team

PI: W. Paloski    Co-PI: L. Young
Clinical PI: M. Camacho, A. Barzi, K. Anderson & S. Aunon
Bone: A. LeBlanc, H. Evans, L. Shackelford & S. Smith
Neuro: L. Young, T. Jarchow, H. Hecht, S. Moore, W. Paloski & M. Reschke
Nutrition: S. Smith, A. Ferrando, M. Heer & S. Zwart
Psych: W. Sipes, F. Carpenter, A. Holland & K. Seaton
Biostats: A. Feiveson & A. Natapoff

Clinical/Operational Consultants: J. Jones & J. Hoffman
Pilot Study Specific Aims

1. Validate the suitability of the proposed:
   a. subject selection criteria,
   b. medical monitoring requirements,
   c. medical care procedures,
   d. experiment control procedures, and
   e. standardized dependent measures.

2. Obtain data that demonstrate the potential effectiveness of short-radius, intermittent AG as a countermeasure to the bone, muscle, and cardiovascular, and possibly neurovestibular deconditioning that occur during three weeks of 6° head down tilt bed rest.

3. Exercise IMAG programmatic elements: international NAR panel, data sharing processes, standardization processes, etc.
Subjects: 32 16 human subjects
  • Screened to match astronaut population
  • 50% female, 50% 100% male (representative race/ethnicity)
  • 16 8 control (no countermeasure)
  • 16 8 treatment (AG countermeasure)

Deconditioning Stimulus: 21 days of 6° head-down bed rest

Countermeasure: daily 1 hr doses of AG
  • 2.5 g at feet (base-of-support) decreasing to 1.0 g at heart

Dependent Measures:
  • Multiple per system (operational & mechanistic)
  • Downward compatible with space flight standard measures
Pilot Study Protocol

41 day Study Duration:

**Pre-Bed Rest Phase (11 days)**
- Acclimatization to facility/diet
- Baseline (control) measurements
- Ambulatory, but restricted to facility
- Strict dietary and sleep/wake cycle controls

**Bed Rest Phase (21 days)**
- 6° HDBR
- daily 1 hour dose of AG (2.5g at feet, 1g at heart)
- Strict dietary and sleep/wake cycle controls

**Post-Bed Rest Recovery Phase (9 days)**
- Recovery measurements
- Ambulatory, but restricted to facility
- Strict dietary and sleep/wake cycle controls
Short Radius Centrifuge
Treatment Protocol SRC Ramp-Up
Detailed View of Force and EMG Data

$\Sigma F_z$ at feet (lbs)

Gastrocnemius EMG
Centrifuge Tolerance Test Subjective Reports

- **Motion Sickness**: Mostly stable, with slight increases at certain intervals.
- **Perceived Tilt (deg)**: Shows a slight decrease over time, then stabilizes.
- **Overall Health**: Remains fairly constant with a slight dip at one point.

**Rotation Rate (rpm)**: Peaks sharply at the beginning, then fluctuates slightly before stabilizing.
Preliminary Results

Konstantin Edouardavich Tsiolkovsky
(1857 - 1935)
## Subject Characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Acceptable Range</th>
<th>Control (n=7)</th>
<th>Treatment (n=8)</th>
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</thead>
<tbody>
<tr>
<td><strong>Age</strong> (yrs)</td>
<td>25-55</td>
<td>27.3 ± 1.8</td>
<td>30.5 ± 3.4</td>
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<tr>
<td><strong>Height</strong> (cm)</td>
<td>169-190</td>
<td>176 ± 7.4</td>
<td>175 ± 6.1</td>
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<tr>
<td><strong>Mass</strong> (Kg)</td>
<td>65.8-98.5</td>
<td>82 ± 8.2</td>
<td>81 ± 9.4</td>
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<tr>
<td><strong>BMI</strong></td>
<td>21-30</td>
<td>26 ± 2.0</td>
<td>26 ± 2.4</td>
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<td><strong>Ethnicity</strong></td>
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<tr>
<td>• Caucasian</td>
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<td>• African American</td>
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<tr>
<td>• Hispanic</td>
<td>1</td>
<td>2</td>
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<tr>
<td><strong>BMD</strong> (g/cm²)</td>
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<tr>
<td>• Femoral Neck</td>
<td>0.726-1.134</td>
<td>0.90 ± 0.026</td>
<td>0.95 ± 0.058</td>
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<tr>
<td>• Trochanter</td>
<td>0.588-0.966</td>
<td>0.78 ± 0.038</td>
<td>0.84 ± 0.050</td>
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<tr>
<td>• Lumbar Spine</td>
<td>0.926-1.256</td>
<td>1.03 ± 0.028</td>
<td>1.08 ± 0.036</td>
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<tr>
<td><strong>VO₂max</strong> (ml/kg/min)</td>
<td>30-58</td>
<td>36.4 ± 2.23</td>
<td>37.4 ± 2.04</td>
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<tr>
<td><strong>CDPSOT5</strong> (EQ score)</td>
<td>&gt;55.8</td>
<td>71 ± 2.8</td>
<td>72 ± 2.0</td>
</tr>
</tbody>
</table>
Daily Spin Summaries

Δ Blood Pressure (mm Hg)

Δ Heart Rate (min⁻¹)

EMG Activity (% time)
Gastrocnemius

ΣF_z at feet (%BW)

Bed Rest Day
BW, Energy & Fluid Intake

Body weight (kg)

Energy Intake (kcal/d)

Fluid Intake (mL/d)

AG

CON
There are trends toward reduced bone resorption for AG subjects.
Ca++ kinetic data and remaining markers may help clarify/reinforce these trends.
Detailed evaluation of the complete data set (e.g., relationship to race, genetics, meds, diet, body weight, etc.) may help tease out individual responses.
Muscle System Response—Cellular/Molecular

Muscle Fiber Cross-sectional Area

Muscle Protein Balance

Significant but incomplete amelioration of bed rest-associated muscle protein synthesis reduction in AG treatment group.
An AG prescription (combined with loading exercises) has excellent potential to play a major role in maintaining skeletal muscle structure & function, which are essential to total body health, fitness, and the performance of EVA activities on platforms in the solar system.
Cardiovascular System Responses

Peak Oxygen Consumption

Peak VO$_2$ decreased in controls ($p=0.01$) but not in the AG treatment subjects.

\[
\begin{array}{c|c|c}
& \text{Pre} & \text{Post} \\
\hline
\text{Control} & 45 & 35 \pm 12\% \\
\text{AG} & 40 & 35 \pm 5\% \\
\end{array}
\]

BR+0 Orthostatic Tolerance

AG treatment subjects > Controls ($p=0.012$; Kaplan-Meier)

Daily AG training appears to have the potential to maintain cardiovascular fitness.
Daily 1 hr rotational AG (2.5 g @ ft, 1.0 g @heart, \(\omega\sim 30\) rpm) + mild exercise (z-axis translations w/ Coriolis acceleration stimuli) cause no untoward, functionally-significant sensory-motor adaptive responses after 21 days.
Effectiveness of AG Prescription

<table>
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<tr>
<th></th>
<th>main hypotheses*</th>
<th>prelim. finding</th>
<th>comment</th>
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<td><strong>Bone</strong></td>
<td>⇔ bone mineral density</td>
<td>as expected</td>
<td>short duration</td>
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<tr>
<td></td>
<td>↑ bone homeostasis</td>
<td>equivocal</td>
<td>further analysis</td>
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<tr>
<td><strong>Muscle</strong></td>
<td>↑ strength</td>
<td>supported</td>
<td></td>
</tr>
<tr>
<td></td>
<td>↑ fiber-type homeostasis</td>
<td>supported</td>
<td></td>
</tr>
<tr>
<td></td>
<td>↓ muscle atrophy</td>
<td>supported</td>
<td></td>
</tr>
<tr>
<td><strong>Cardio</strong></td>
<td>↑ orthostatic tolerance</td>
<td>supported</td>
<td>further analysis</td>
</tr>
<tr>
<td></td>
<td>↑ sympathetic response</td>
<td>none yet supported</td>
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</tr>
<tr>
<td></td>
<td>↑ aerobic capacity</td>
<td>supported</td>
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<td><strong>Neuro</strong></td>
<td>⇔ CDP, OCR</td>
<td>as expected</td>
<td>no adverse response</td>
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<td>⇔ SVV</td>
<td>not supported</td>
<td>spatial disorientation</td>
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<tr>
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<td>↑ proprioceptive reflexes</td>
<td>supported</td>
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<td><strong>Immuno</strong></td>
<td>↑ stress marker response</td>
<td>not supported</td>
<td>no ↑ either group</td>
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<tr>
<td><strong>Psych</strong></td>
<td>⇔ cognitive performance</td>
<td>not supported</td>
<td>↓ trend, but low n</td>
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</table>

*expected outcome of Treatment Subjects when compared to Control Subjects
Preliminary Conclusions

1. The AG prescription was well-tolerated by all subjects over the 21 day deconditioning period; however, women were excluded, and much longer deconditioning periods must be tested.

2. The AG prescription tested was effective in ameliorating many of the adverse changes associated with 6° head-down bed rest; however the small n was underpowered for some analyses.

3. The project should continue into Phase II, focusing on:
   a. Increasing n, testing women, increasing the study duration
   b. Adjusting the prescription parameters (g-level, ω, r, duration/duty cycle) for optimal effectiveness and/or efficiency
   c. Adding exercise capability
Implications

*Earth is the cradle of humanity,*
*but one cannot remain in the cradle forever.*

*Konstantin Edouardavich Tsiolkovsky*
AG Project Deliverables

Evidence Base to Guide Program Decisions

Transit Vehicle

Continuous AG Trade Space
• g, r, ω
• spin up/down req'ts
• human factors

Intermittent AG Trade Space
• g, r, ω, duty cycle
• exercise req'ts
• optimal prescription

Surface Ops

3/8 g enough?
• yes
• no

Intermittent AG Trade Space
• g, r, ω, duty cycle
• exercise req'ts
• optimal prescription

Continuous AG Trade Space
• g, r, ω
• spin up/down req'ts
• human factors
Other Recent Advances in Rotational AG

1. Young et al.—head movements
2. Lackner, DiZio et al.—human factors
3. Iwase et al.—cardiovascular training
4. Evans, Knapp et al.—cardiovascular training
5. Fuller et al.—circadian rhythms
6. Wuyts et al.—shakedown new ESA centrifuge
7. Young, Duda, Edmonds et al.—exercise at high $\omega$
8. Caiozzo, Baldwin et al.—exercise at high $\omega$

Von Braun, W. (1952) Crossing the Last Frontier
Toward a practical AG/Exercise Device

Courtesy of Dr. Vince Caiozzo, UC Irvine
Why Consider Artificial Gravity?

1. There is currently no demonstrated, effective multi-system countermeasure (or suite of countermeasures) to offset the microgravity-induced deconditioning of prolonged space flight.

2. A spinning transit vehicle would likely offer the most effective and efficient multi-system (preventive) countermeasure to microgravity deconditioning.

3. The preliminary results of the IMAG pilot study suggest that even intermittent AG could effectively meet that need, particularly if coupled with loading exercises.

4. We’ll be taking our own air, food, heat, and light... why not just take gravity along with us as well?
Questions/Discussion

“Artificial gravity is an idea whose time has come around... and around...and around...”

Larry Young (1999)
backup
## Pilot Study Dependent Measures

<table>
<thead>
<tr>
<th>Bone</th>
<th>density and morphology: DEXA, pQCT, MRI biochemical markers, Ca++ kinetics/balance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muscle</td>
<td>strength (TVD), volumes (MRI), morphology/biochemistry: soleus and vastus lateralis biopsies</td>
</tr>
<tr>
<td>Cardio</td>
<td>tilt test, VO$_2$ max, neuro-endocrine responses, plasma &amp; segment volumes, ECG spectral analysis</td>
</tr>
<tr>
<td>Neuro</td>
<td>Spatial orientation (SPP, SVV, OCR), balance control (CDP), proprioceptive reflexes (FSR)</td>
</tr>
<tr>
<td>Immuno</td>
<td>stress markers, viral reactivation, virus-specific T-lymphocyte</td>
</tr>
<tr>
<td>Psyche</td>
<td>cognitive assessment: Winscat</td>
</tr>
<tr>
<td>Nutrition</td>
<td>clinical assessment</td>
</tr>
</tbody>
</table>
Coriolis Force Effects

\[ F_c = -2m(\omega \times v) \]

\( \omega \) = angular velocity
\( F_g \) = centrifugal force
\( F_c \) = Coriolis force
\( V \) = subject’s velocity
\( m \) = subject’s mass

*after Stone, 1970*
Cross-Coupling Effects

\[ \omega_{c-c} = \omega_{cent} \times \omega_{head} \]

\( \omega = \text{angular velocity} \)
Centrifuge Tolerability - Typical Subject

- **Δ Blood Pressure (mm Hg)**
- **Δ Heart Rate (min⁻¹)**
- **EMG Activity (% time) [Gastrocnemius]**
- **ΣFz at feet (%BW)**

* Spin terminated early (intolerance)