The Heart in Space

Effects of Space Flight on the Cardio-Vascular System

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Lecture Outline

• How the cardio-vascular system works in Earth gravity to ensure constant blood pressure and to regulate blood flow to the body tissues

• The effects of space flight on the cardio-vascular system:
  – Before and during launch
  – On-orbit – fluid shift, heart rhythm disturbances, decrease in maximal exercise capacity
  – Post-flight – orthostatic intolerance, i.e., syncope during stand test

• Implications of such changes for long-term missions, and potential countermeasures
The Problem

- **U.S. space program**
  - Mercury-8 (9 hrs): modest increase in heart rate postflight
  - Mercury-9 (34 hrs): increase in heart rate (132 supine; 188 standing) postflight
  - Gemini: fainting episode
  - Apollo: heart rhythm disturbances
  - Shuttle: 8 episodes of dizziness or fainting in the first 26 missions

- **Soviet/Russian space program**
  - Soyuz-9 crew was so severely incapacitated they could not egress the capsule without assistance
  - Long-duration spaceflights: many returning crews are incapacitated and are unable to egress the capsule without help
So why is this a big deal?

- Pilots fly upside down at minus 1G instead of 0G with no problem
- How can these space travelers perform nominally on orbit and then be so incapacitated when they land?
- We see this on Earth with patients who have certain types of cardio-vascular disease
- Did we select individuals who were susceptible to these problems?
- Can a incapacitated crew respond to an emergency upon launch or landing?
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Cardio-Vascular Risk

• Based on experience with analog Earth data (submarines, Antarctic bases, remote outposts, etc.) the risk of a serious cardio-vascular event (heart attack, rhythm disturbance, etc.) happening on the ISS is at least once in 20 years.

• The risk of cardio-vascular medical events happening during or after a mission can be divided into two categories:
  – Medical events which occur as a consequence of the expected cardio-vascular physiological changes induced by spaceflight.
  – Medical events which occur as a consequence of pre-existing cardio-vascular disease which are aggravated by spaceflight.
The initial cardio-vascular exam for astronaut selection is similar to the non-pilot U.S. Air Force physical exam.

This initial medical exam is then followed by the NASA astronaut selection physical, which is similar to U.S. Air Force fighter pilot physical exam.

As a rule, astronaut candidates are in excellent physical shape and many have increased heart muscle mass compared to terrestrial “norms”.

“204 pounds on the left and 189 pounds on the right.”
As organisms increased in size (number of cells), isolated individual cells required to ingest nutrients (food and oxygen—O₂) and excrete waste (byproducts and carbon dioxide—CO₂)
The heart pumps blood through blood vessels to deliver oxygen and pick up CO₂ from various organs.

Contraction of leg muscles helps to pump blood toward the heart (venous return).

Lujan and White (1995)
• **Heart rate** is how fast the heart is beating (pulse)

• On Earth, there is a large pressure gradient from the head to the feet, with the mean arterial **blood pressure** being about 70 mmHg at the head level, 100 mmHg at the heart level, and 200 mmHg at the feet level

• **Flow** through a blood vessel is determined by 2 factors:
  – The force that pushes the blood through the vessel
  – The resistance of the vessel to the blood flow

• Blood flow in the entire human circulation is about 5000 ml/min at rest, but may be 5-6 times greater during exercise. The amount of blood pumped by the heart in one minute is called the **cardiac output**
Cardiac Output

- **Stroke volume** is the volume of blood discharged from the heart left ventricle with each contraction (about 70 ml at rest)

- **Cardiac Output** = Stroke Volume $\times$ Heart Rate  
  $(\text{ml of blood/min}) \quad (\text{ml of blood/beat}) \quad (\text{beats/min})$

- Some factors that influence arterial blood pressure:

![Diagram showing factors affecting blood pressure](Image)
Regulation of Blood Pressure

- The rapid transition between lying own, sitting, and upright postures requires that the heart and blood vessels adjust very quickly.

- The baroreceptor reflex is the body's rapid response system for dealing with changes in blood pressure.

- Baroreceptors are located in the neck (carotid) and in the aorta.

- A decrease in pressure (distention) will cause the cardio-vascular system to compensate by increasing cardiac output (stroke volume and/or heart rate).

- Spaceflight deconditions baroreceptor response, resulting in larger changes in baroreceptor distention needed to induce the same changes in heart rate compared to 1-g.
The baroreflex sensors can be “fooled” by manipulating the pressure outside the neck using an inflatable **cuff**

**Increasing** the cuff pressure will reduce the distension of the baroreceptors, the equivalent of a decrease in arterial pressure

This will cause the cardiovascular system to compensate by increasing **cardiac output** (stroke volume and/or heart rate)

Applying **vacuum** to the neck cuff will increase baroreceptors distension, simulating an increase in arterial pressure, resulting in a decrease in cardiac output
The Heart in Space

Pre-Launch Position

• The crew is placed in the Shuttle approximately 1-2 hours prior to expected launch.

• Crew can be in the Shuttle for as long as 4 hours before Mission Control considers a launch scrub.

• Supine position with 90° hip and knee flexion in order to limit launch acceleration to the $+G_x$ direction.

• The effect is that significant blood volume is placed above the heart, increasing load to the heart, central venous pressure, cardiac volumes, and cardiac output.

• The body compensates for this by reducing blood volume through urination and reduced thirst.

• The astronauts sometimes prefer to restrict their fluid intake prior to launch and “fly dry.”

• Reduction in blood volume on the launch pad may impair the ability to emergency egress (syncope upon standing)

Lujan and White (1995)
Three Phases of Space Flight

- The transition between upright, sitting, and lying down postures requires that the heart and blood vessels adjust very quickly.
- However, the control centers are not stimulated in microgravity.
- These deconditioned control centers do not respond appropriately to orthostatic challenge after space flight.
Pre-Launch Issues

• Could every crewmember use the escape system, and egress rapidly the launch site without any assistance wearing a 50 kg spacesuit?

Photos NASA
a. On Earth, gravity exerts a **downward force** to keep fluids flowing to the lower body (A)

b. In space, the fluids tend to **redistribute** toward the chest and upper body (B). This is responsible for the face congestion. At this point, the body detects a “flood” in and around the heart

c. The body rids itself of this perceived “excess” fluid. The body functions with less fluid and the heart becomes **smaller** (C)

d. Upon return to Earth, gravity again pulls the fluid **downward**, but there is not enough fluid to function normally on Earth (D)
On Orbit — Fluid Shift

- **Total loss of fluid** from the vascular and tissue spaces is about 1-2 liters (about a 10% volume change compared to preflight)

volume = \( \pi h \left( \frac{R^2 + Rr + r^2}{3} \right) \)

where \( R, r = \frac{\text{circumference (c)}}{2\pi} \)
• Microgravity removes the **hydrostatic gradient** in the venous vascular system
• **1-2 liters** of fluid shift toward the head
• Crewmembers sense this fluid shift and describe it as “fullness in the head” or a nasal stuffiness similar to a chronic **sinus congestion**
Ultrasound Imaging

The Heart in Space
• Ultrasound imaging revealed that heart volume first increases, probably because of the increased volume of blood flowing into the heart

• Then the heart volume slowly decreases, ending up smaller compared with its size on Earth, presumably because:
  – The excess blood and fluid have been eliminated
  – The heart does not have to pump the blood against gravity
  – Leg muscles are less used

• Maximal exercise capability (VO₂ max) in orbit is not different from preflight, but is reduced immediately post-flight

• Fit subjects demonstrated larger (16%) reduction in VO₂ max and plasma volume than unfit subjects (only 6% reduction)
During Extra-Vehicular Activity (EVA) astronauts may be working hard for 6 hours in a space suit with mean **metabolic rates** of 800 kcal/hour and 5-10 minute peaks of over 1500 kcal/hour.

Russian cosmonauts lose 0.7-2.2 kg (mostly fluids) during a typical EVA.

The acute dehydration caused by EVA may aggravate an **already deconditioned state** caused by exposure to microgravity.
On Orbit — Heart Rhythm

• Serious heart rhythm **disturbances** were noted during the Apollo program, both during EVA on the Moon and after return to Earth

• Both astronauts were given **excessive work loads** on the Moon, and one had a significant cardiac event 2 years after the mission

• One Mir crewmember showed a sustained 14-beat run of ventricular **tachycardia** after one month in orbit
Re-Entry — Effects of G Forces

- Re-entry forces exerted along $G_x$ axis in capsules — no need for the astronaut to “fly” the vehicle.

- $G_z$ forces in Shuttle. However, 1.5 $G_z$ during re-entry after 16 days of cardio-vascular deconditioning in microgravity may be as provocative as 5-6 $G_z$ in a fighter aircraft.

- Loss of consciousness (syncope) may result from a decrease in blood flow to the brain (cerebral hypoperfusion).
• **Tolerance to prolonged acceleration** depends on:
  – Magnitude
  – Duration
  – Direction of force
  – Restraints
  – Protective systems

• **Individual tolerance** depends on:
  – Age
  – Training
  – Underlying physical condition

• **Space flight** has been demonstrated to reduce tolerance to sustained
  +Gz acceleration (Shuttle) and
  +Gx acceleration (Soyuz)
### Vertical Accelerations

(Gz, up is positive)  

<table>
<thead>
<tr>
<th>Event or Symptom</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>limit of sustained human tolerance, centrifuge</td>
<td>16</td>
</tr>
<tr>
<td>ejection seat</td>
<td>12 - 14</td>
</tr>
<tr>
<td>aerobatic airplane, 2002</td>
<td>11.4</td>
</tr>
<tr>
<td>loss of consciousness</td>
<td>4.5 - 6.3</td>
</tr>
<tr>
<td>complete loss of vision (blackout)</td>
<td>3.9 - 5.5</td>
</tr>
<tr>
<td>partial loss of vision (grayout)</td>
<td>3.4 - 4.8</td>
</tr>
<tr>
<td>rollercoaster, maximum at bottom of first dip</td>
<td>4.5</td>
</tr>
<tr>
<td>congestion of blood in head</td>
<td>-1</td>
</tr>
<tr>
<td>throbbing headache, reddening of vision (redout)</td>
<td>-2</td>
</tr>
<tr>
<td>limit of sustained human tolerance, centrifuge</td>
<td>-5</td>
</tr>
</tbody>
</table>

### Horizontal Accelerations

(Gx, magnitude only)  

<table>
<thead>
<tr>
<th>Event or Symptom</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>“pedal to the metal” in a typical car</td>
<td>0.4</td>
</tr>
<tr>
<td>“pedal to the metal” in a high performance sports car</td>
<td>0.8</td>
</tr>
<tr>
<td>Extreme Launch™ rollercoaster at start</td>
<td>2</td>
</tr>
<tr>
<td>Space Shuttle at takeoff; jet fighter landing on aircraft carrier</td>
<td>3</td>
</tr>
<tr>
<td>limit of sustained human tolerance, centrifuge</td>
<td>8</td>
</tr>
<tr>
<td>tolerance to centrifuge, 5 s duration</td>
<td>31 - 25</td>
</tr>
<tr>
<td>USAF chimpanzee, centrifuge, 60 s duration</td>
<td>40</td>
</tr>
<tr>
<td>chest acceleration during car crash at 48 km/h with airbag</td>
<td>60</td>
</tr>
<tr>
<td>crash that killed Diana, Princess of Wales, 1997</td>
<td>70 - 100</td>
</tr>
<tr>
<td>USAF chimpanzee, rocket powered impact sled, 0.001 s</td>
<td>247</td>
</tr>
<tr>
<td>impact acceleration limit for crash-survivable flight recorder</td>
<td>3400</td>
</tr>
</tbody>
</table>
Impact Acceleration

• **Tolerance** to impact acceleration depends on:
  – Peak acceleration
  – Pulse shape
  – Magnitude, direction, and duration of impact acceleration
  – Characteristics of human subject
  – Subject's restraint system
  – Acceleration history prior to event

• As with entry acceleration, **illness or injury** are expected to be additive with space flight deconditioning in decreasing impact tolerance

• Impact **attenuation** – crew couch
Landing – Orthostatic Intolerance

- 'Ortho' = upright; 'Static' = standing
- 'Intolerance' = Feeling of lightheadedness or fainting associated with upright posture at 1 g
- Tested by completing a 10-minute stand test – failure when patient is forced to sit down to prevent syncope
- Increased risk to crewmembers during entry, landing, and egress
- Affects about 20% of the astronaut population after short-duration (Shuttle) space flight
- Affects about 85% of crewmembers after long-duration (Mir and ISS) space flight
• Both heart rate & blood pressure increase during re-entry
• **Syncope** is caused by a diminished blood flow to the brain when going from sitting to standing
• **Possible mechanisms** – low baroreceptor responsiveness, relaxation of blood vessels, loss of fluids, CNS adaptation
Landing – Decreased Exercise Capacity

- Large decline over first 30-90 days on ISS
- Subsequent improvement may be due to countermeasures
- Early in-flight loss (even with countermeasures) may be related to altered CV control mechanisms/body fluid volumes, and operations
- Aerobic capacity declines again after landing and appears restored by R+30 days in ISS crew
Periodic monitoring to detect manifestation of previously asymptomatic cardiovascular disease
In-flight exercise and Low Body Negative Pressure (LBNP) have a protective effect on the increase in heart rate and fall in blood pressure during standing after flight.

Loading suit (“Penguin”)

LBNP (“Chibis”)

Thigh cuffs (“Brazlet”)

Photos NASA and RSA
Countermeasures — Landing

- Fluid and salt loading
- Anti-G garment
- Liquid cooling garment
- Recumbent seating during re-entry for flights > 30 days

Photos NASA
**The Heart in Space**

**Countermeasures — Spin-Offs**

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Ground-Based Simulation

Bed Rest Studies
(6° head-down tilt)

Photos ESA-MEDES
Bed Rest Model

- Bed rest with -6 deg head down simulates the effects of microgravity on cardio-vascular response
- Within the first week, noticeable atrophy of muscle tissue
- After two weeks, bone density declines as significant amounts of calcium are lost in the urine
- **Exercise** regimens and **LBNP** are evaluated to determine which is more effective at preventing:
  - Cardiovascular deconditioning
  - Orthostatic intolerance
  - Fluid shift
  - Muscle atrophy
Tilt Test After Bed Rest

- After 15-90 days of bed rest, **orthostatic intolerance** is evaluated by suddenly tilting the subject from the supine to the upright position.

- Heart rate increases and blood pressure decreases, causing loss of consciousness (syncope).

- This orthostatic intolerance is similar to that observed in the astronauts when they stand up immediately after spaceflight.
• **Mechanistic studies**
  – Structured to control for many parameters and develop a model of the effects of space flight on cardio-vascular responses (e.g., neck cuff during a bed rest study)

• **Descriptive studies**
  – Cardio-vascular anomalies in one crewmember, which may have operational implications
  – Studies (prospective and retrospective) on a large number of astronauts, which indicate the **risk** or **incidence** of an observed cardio-vascular anomaly caused by space travel

• **Countermeasures validation studies**
  – Conducted after the mechanisms responsible for cardio-vascular deconditioning or pathology are well understood
Current Research Hypotheses

• **Fluid Loading**
  – Loss of fluid contributes to orthostatic intolerance
  – Humoral control (hormones)

• **Alteration of Autonomic Nervous System**
  – In space there is no postural change to stimulate the autonomic nervous system. Therefore its sensitivity is altered. This neural factor could contribute to the orthostatic intolerance

• **Atrophy of the Heart Muscle**
  – Heart does not work so hard in space. This induces an atrophy in heart muscle (the heart pumps less blood), which could be responsible for orthostatic intolerance

• **Decrease in the Sensitivity of the Peripheral Blood Vessels**
Summary

• From a cardio-vascular perspective, there are three phases during space travel

  Pre-flight  

  In-flight  

  Post-flight

• Each of these phases cause adaptive changes in the cardio-vascular responses

• Countermeasures are required to minimize the effects of these three phases

• Cardio-vascular research in orbit and on Earth (bed rest) are needed to better understand the physiological and pathological changes
Reading Material