Chapter 32

Non-Invasive Monitoring of Ocular Health in Space

32

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This chapter addresses the following

Key Concepts:

- Vision is the most relied on of the human senses, and one of the most critical tools used by astronauts in the performance of mission duties.
- The absence of gravity in space affects human physiology in a number of ways. Deep space travel will also expose astronauts to high levels of radiation for extended periods of time.
- The needs of astronaut health can be met by effective, non-invasive miniaturized systems for monitoring health via telemetry.
- The eye represents a useful site for non-invasive access to the body. It also contains structures that are representative of nearly every tissue type in the body, enabling broad-spectrum monitoring of ocular and systemic health.
- A head-mounted apparatus equipped with several non-invasive optical diagnostic technologies, and technologies based upon skin contact and proximity to the brain, is under development at NASA.

32.1 Introduction

Interest in space travel and planetary exploration is gaining momentum. On 13 October 2003, China successfully launched a man into space and it seems that Japan and India are not too far behind. On 4 October 2004, a non-governmental American civilian rocket (Space Ship One) entered the edge of space (100 km above the Earth's surface) for a short duration, winning the 10 million USD Ansari X-Prize [1].

On a larger scale, on 14 January 2004, United States President George Bush announced that the National Aeronautics and Space Administration (NASA) would revive efforts to send a manned mission to the moon and mars. It should be noted that a round-trip mission to Mars will take approximately three years to complete. This includes from nine months to one year travel time from earth to mars, a one-year stay, and another nine months to one year for return travel to earth.

Maintaining good ocular health is essential to the completion of this mission. In spite of advanced automation in manned space exploration, vision is the most relied upon of all the human senses and one of the most critical tools used by astronauts in the performance of mission duties. For example, astronaut pilots land space shuttles with exacting precision nearly completely dependent upon vision.

32.2 Ocular Health and the Harsh Environment of Space

Both the moon and mars have extreme conditions for human survival. For example, the moon has no atmosphere while mars' atmosphere is highly rarefied (1/150th of earth), with a composition of about 95% carbon dioxide, 3% nitrogen, 1.6% argon, 0.15% oxygen, and 0.03% water vapor. The surface temperature on the moon can be as low as –240°C in the shade, with the average temperature on mars around –60°C.

32.2.1 Environmental Factors

The amount of ultraviolet light on mars is about 800 times greater than that on earth. The gravity on the moon is one sixth, and on mars it is one third that of the earth.

Recently the martian rovers Spirit and Opportunity recorded dust storms on the martian surface with wind speeds in excess of 100 miles per hour. Fine dust particles have been found to irritate the eyes and lungs of astronauts on the lunar surface during the 1970s short walks [2].

32.2.2. Gravity Concerns

In addition to these harsh environmental factors, the absence of gravity in space affects human physiology in a variety of ways. Immediately upon entering this environment, astronauts experience shifts in fluid distribution to upper parts of the body, and in the elimination of weight-bearing forces. This causes head congestion, face puffiness, and leg shrinkage. The only reliable way to sense motion is via the eyes since the otoliths in the inner ear respond differently to fluid motion. This altered sensory input confuses the brain, causing disorientation. Since weight-bearing forces are eliminated, the bones and muscles deteriorate and the kidney filtration rate increases, causing kidney stones.

32.2.3 Radiation

Lastly, but perhaps most importantly, deep space travel will expose astronauts to high levels of radiation for extended periods of time. As a result, long-duration space travel will likely prove to be rigorous for the human body. The long-term effects, which are hitherto unknown, may involve changes at the cellular and molecular levels due to all of the aforementioned conditions. Thus important systems such as the vestibular, cardiovascular, renal, musculo-skeletal, brain, and eye could be affected. Table 32.1 lists potential ocular risk factors. In two recent studies, relatively low doses of space radiation were found to cause an increased incidence and early appearance of cataracts in astronauts [3, 4].

32.2.4 Aging and Health

In the absence of effective countermeasures, the untoward effects of space travel could accelerate aging as well as introduce new pathologies. Assuring astronaut health is thus a major priority in planning missions to the moon, mars, and beyond. Constraints in available room onboard vessels such as the International Space Station and deep space voyage crafts, as well as limitations in the availability of in-flight medical expertise, add to the challenge of meeting health care needs during missions that will last years. These needs can, however, be met by effective, non-invasive miniaturized systems for monitoring astronaut health via telemetry.

32.3 Using the Eyes as a Window to the Body

The eye is a unique part of the body in that it is largely transparent and therefore represents a useful site for non-invasive access to the body using light that readily enters the eye. Since incident light is scattered back out of the eye, this organ represents a location where analysis of the back-scattered light could provide useful information regarding internal structures, fluids, and tissues.

The eye is further unique in that this relatively small organ contains structures that are representative of nearly every tissue type in the body. The cornea is a typical extracellular matrix composed primarily of collagen. Aqueous is an ultrafiltrate of blood, containing most of the molecules found in serum at concentrations that are reflective of systemic levels. The lens is a highly organized array of crystalline proteins. Vitreous is very similar in nature to joints. The retina and optic nerves are in fact part of the central

Table 32.1. Potential ocular risk factors in long-duration space flight and on the Moon and Mars

Condition	Possible cause(s)	In-Flight	Moon	Mars
Cataract	Radiation	Yes	Yes	Yes
Ocular hypertension and glaucoma	Reduced gravity	Yes, particularly with borderline/pre-glaucoma astronauts	Likely	Likely
Transient vision changes of unknown etiology	Reduced gravity	Yes	Not known but likely	Not known but likely
Macular degeneration	Radiation (free radicals)	Possible	Possible	Possible
Keratoconjunctivitis	Air quality Fine dust	Yes (depending upon proper functioning of air-filtration systems)	Yes	Likely
Photopsia	Radiation (retinal light flashes)	Yes (but no known dangers on short-duration flights)	Likely	Likely
Choroidal engorgement	Reduced gravity	Likely	Likely	Likely
Macular nutrition (decrease in caretonoids levels)	Radiation and reduced gravity	Possible	Possible	Possible
Ocular ischemia	Reduced gravity	Possible	Possible	Possible
Trauma or physical injury	Foreign objects hitting or imbedded in the eye	Possible (bungee cord injury has occurred previously with serious consequence)	Possible	Possible

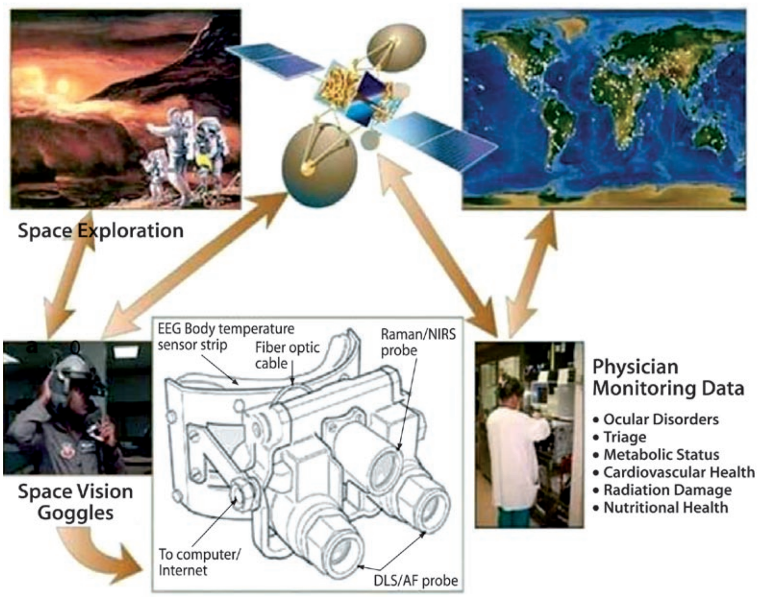
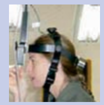
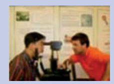
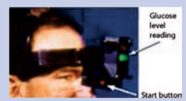


Fig. 32.1. Concept of a head-mounted goggles-like teleophthalmology apparatus

Table 32.2. Non-invasive optical technologies for monitoring astronaut health, early detection of ocular and systemic diseases and to enable early countermeasures

Technologies and readiness level	Diseases/studies	Instruments
Dynamic light scattering (DLS) in clinical/experimental use [8, 9]	– Corneal diseases and wound healing (LASIK) – Lens aging and cataract – Uveitis, glaucoma, Alzheimer's – Vitreous aging and lysis studies – Drug efficacy studies, cholesterol – Studies on effects of radiation, hyperbaric oxygen and other conditions on eye tissues – Diabetic vitreopathy	
Corneal/lens autofluoresence used in clinical study [10]	– Radiation induced biological effects – Diabetic retinopathy	
Laser-Doppler Flowmetry (LDF) Flown on KC-135- NASA's Microgravity airplane [11]	– Physiological circulatory changes – Hemodynamic response – Choroidal blood circulation – Age-related macular degeneration – Diabetic retinopathy	
Raman carotenoid pigment dispersion analysis used in clinical studies [12, 13]	– Lack of nutrition (luetin/xeaxanthin) – Age-related macular degeneration – Skin cancer – Stress status of living plants and plant products	
Ocular polarimetry in laboratory use; clinical system under devel-opment [14]	– Blood-glucose sensing	

Tissue oximetry flown on KC-135- NASA's Microgravity airplane Ocular oximetry (in design stage)	▪ Hyper-/hypo-tension ▪ Blood circulation in head and muscle tissue ▪ Functional imaging of brain ▪ Occult blood loss ▪ Bed rest/exercise studies ▪ Cardio-pulmonary surgery (operating room/intensive care unit)	
Ocular capillaroscopy (in design stage for use in conjunctiva)	▪ Micro-circulation/blood vessel tortuosity (long-duration confinement/bed rest/exercise, immune system) ▪ Functional imaging of blood flow	
Celestial and terrestrial teleophthalmology: all of the above in a telemedicine integrated head-mounted goggle-like diagnostic device (under development)	▪ Various ocular and systemic diseases using the eye as a window to the body	

cause(s) are yet to be determined. To do so will require the use of advanced non-invasive technologies in preparation for the use of such technologies during long-duration flights in space.

32.3.2.1 Proof-of-Concept Experiment

A proof-of-concept experiment, using a head-mounted compact laser Doppler flowmeter, was recently conducted on-board NASA's KC-135 airplane. This wide-body airplane, dubbed the vomit comet or weightless wonder, creates conditions of weightlessness or zero gravity during freefall lasting 25 to 30 s, and about twice the Earth's gravity during the climb phase of the parabolic flight trajectory shown in Fig. 32.2.

In this experiment, we measured choroidal blood flow in 25 volunteer human subjects. The experimental setup onboard KC-135 is shown in Fig. 32.3. The preliminary results can be found in previous papers [6, 7]; additionally, the detailed study is about to be published. The goal of this study was to evaluate choroidal blood flow in response to changing fluid levels in weightless conditions to help find the etiology of changes in vision of astronauts in orbital flight.

32.3.2.2 Choroidal Blood Flow

Choroidal blood flow plays a major role in the regulation and supply of nutrients to the photoreceptors and pigment epithelium since every 20 min, 100% of the body's blood volume flows through the eye, while 85% of that blood flow goes to the choroid and only 4% to the retina. We found that mean systemic blood pressure decreased by about 19% but choroidal blood flow increased by about 22% in zero gravity, compared to earth's gravity. Future studies will confirm if the blood flow and volume will stabilize and self regulate in long-duration missions.

32.4 Conclusions

The eye is a window to the body. Fully utilizing the opportunities provided by this fact promises insights into easily and accurately assessing

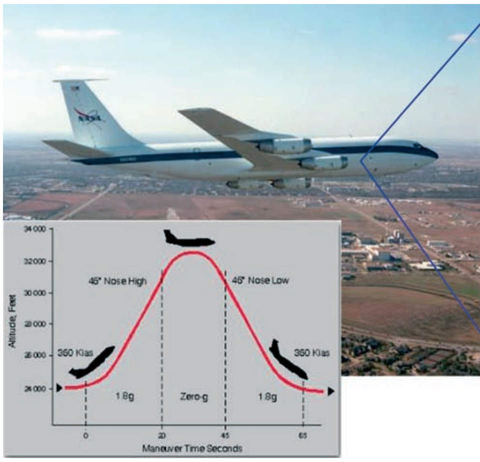


Fig. 32.2. NASA's KC-135 zero-gravity airplane and the parabolic flight trajectory

Fig. 32.3. Laser-Doppler flowmetry measurements in the choroid on-board KC-135

health, and diagnosing departures from health early in the natural history of disease. Regarding the rigors of deep space travel, this capability will create opportunities to detect a number of potentially debilitating diseases before the onset of irreversible damage.

We have presented the concept of an advanced instrument that integrates several non-invasive optical techniques that have been successfully demonstrated, or are currently under development in clinical and/or laboratory settings. These techniques are readily interfaced with the computer technology that by transmitting information from remote sites makes celestial teleophthalmology a reality.

Early diagnosis and prevention (rather than just cure) of disease is a critical direction for medicine in the 21st century. Technologies that are found to be useful in monitoring astronaut health in space may have great utility and value on Earth. In addition to the celestial teleophthalmic applications described above, it is possible that our compact, non-invasive, and multi-purpose diagnostic devices will be used for regular health monitoring by today's health-conscious consumers in settings of their choice, such as homes, offices, gymnasiums, drive-throughs, and shopping malls. Governments and health care agencies may further find useful applications for using such devices to extend health care to under-served areas of the world. This form of terrestrial teleophthalmology will also provide a powerful device for use in identifying diseases not adequately diagnosed and/or treated (e.g., diabetes in the US) in so-called advanced care settings.

References

1. Rutan B (2005) Rocket for the rest of us. National Geographic 207(4):28–35
2. Bell TE, Phillips T (2005) En route to Mars, the Moon; Why colonize the Moon before going to Mars? NASA scientists give their reasons. http://science.nasa.gov/headlines/y2005/18mar_moonfirst.htm?list915919. Cited 4 Oct 2005
3. Cucinotta FA, et al. (2001) Space radiation and cataracts in astronauts. Radiat Res 156(5):460–466
4. Rastegar et al. (2002) Radiation induced cataract in astronauts and cosmonauts. Graefes Arch Clin Exp Ophthalmol 240(7):545
5. Ansari R, Singh B, Rovati L, Docchio F, Sebag J (2000) Monitoring astronaut health at the nanoscale cellular level through the eye. In: Proceedings of Nanospace 2000, Houston, TX
6. Ansari R, et al. (2003) Measurement of choroidal blood flow in zero gravity. Ophthalmic Technologies XII, In: Manns F, Soderberg PG, Ho A, (eds) Proc SPIE 4951:177–184
7. Hatcher M (2003) Flowmeter tests eyes in zero gravity; NASA scientists probe changes in astronauts' vision with a laser Doppler flowmeter. http://optics.org/articles/news/9/3/14/1. Cited 4 Oct 2005

8. Ansari RR (2004) Ocular static and dynamic light scattering: A noninvasive diagnostic tool for eye research and clinical practice. J Biomed Opt 9(1):22–37
9. Sebag J (2004) Seeing the invisible: the challenge of imaging vitreous. J Biomed Opt 9(1):38–46
10. Rovati L, Docchio F, Van Best J (2004) Autofluorescence methods in ophthalmology. J Biomed Opt 9(1):9–21
11. Geiser MH, Diermann U, Riva CE (1999) Compact laser doppler choroidal flowmeter. J Biomed Opt 4(4):459–464
12. Gellermann W, Bernstein P (2004) Noninvasive detection of macular pigments in the human eye. J Biomed Opt 9(1):75–85
13. Ermakov I, Ermakov M, Bernstein P (2004) Macular pigment Raman detector for clinical applications. J Biomed Opt 9(1):139–148
14. Ansari R, Bockle S, Rovati L (2004) New optical scheme for a polarimetric-based glucose sensor. J Biomed Opt 9(1):103–115