During orbital spaceflight, the acceleration of gravity is reduced from one-G on the Earth’s surface to about $10^{-6}$-G in orbit. Nevertheless, the head accelerations associated with changing direction and with turning are unaffected. Therefore, the body must selectively adapt to the relative absence of gravity. As a result of this reorganization, astronauts frequently exhibit difficulty with balance upon landing that could pose a serious problem if they had to function efficiently in a gravitational environment immediately after a long-duration spaceflight. They can also become disoriented when in motion. These deficits are as yet incompletely understood. The otoliths, located in the inner ear, sense head accelerations and generate reflexes to the eyes and postural muscles that maintain gaze and posture when moving in a gravitational environment. They are also directly involved in sensing the direction of gravity and contribute importantly to the sense of spatial orientation. It is likely that changes in otolith-mediated reflexes that occur as a result of adaptation to microgravity could be responsible for postflight problems with gaze and balance.

The purpose of two Neurolab experiments (see science reports by Moore et al. and Clément et al. in this publication) was to study how spatial orientation and reflexes originating in the otolith organs might be affected by adaptation to microgravity. Flight and ground-based instruments were developed for the Neurolab mission to study how orienting otolith-ocular reflexes and the perception of the spatial vertical are changed by adaptation during spaceflight. These instruments included a flight-rated centrifuge that delivered measured amounts of linear acceleration along different body axes in flight, a functionally equivalent centrifuge to do ground-based testing, and an apparatus that statically tilted the head and body with regard to gravity before and after flight. The static tilt apparatus allowed the teams to obtain data that could be compared with the results of centrifugation. Binocular, infrared video-oculography, a noninvasive technique, was utilized to measure eye movements in three dimensions while the astronauts were being centrifuged. Equipment was also developed that could deliver visual stimuli to calibrate the induced eye movements and to induce optokinetic nystagmus (OKN) and ocular pursuit during centrifugation and static tilt. This report describes the development and use of this equipment. This unique hardware performed flawlessly in flight, provided the first inflight “artificial gravity,” and advanced the technology of eye movement recording.
HARDWARE DESCRIPTION

To perform the experiments on the mission successfully, the equipment had to be able to generate controlled accelerations to the inner ear, present moving visual patterns to the test subject, and record eye movements during the stimuli. To accomplish these goals, the following equipment were developed:

- Ground and flight centrifuges,
- Tilt chairs for postflight use,
- A visual display,
- An eye movement recording system, and
- A videotape processing facility.

Centrifuges

One technique for producing accelerations to the inner ear in space is to rotate subjects about a distant axis in a centrifuge to generate centripetal linear acceleration. Until the present experiments, the response to this kind of centrifugation had not been formally studied during spaceflight. Two centrifuges were developed for these experiments. The flight model was built by the European Space Agency (ESA) (Figures 1-3), and a ground centrifuge based at Johnson Space Center (JSC) in Houston, TX, that was built by Neurokinetics Inc., Pittsburgh, PA, was used for pre- and postflight studies (Figure 4). Both centrifuges were functionally identical. Subjects were seated with the body vertical axis parallel to the axis of rotation at a radius of 0.5 m, and were oriented facing or back to the direction of motion (tangentially) either left-ear-out (LEO) (Figure 2) or right-ear-out (REO) (Figure 4). In this configuration, rotation at a constant velocity of 254 degrees/second and 180 degrees/second provided one-G and 0.5-G, respectively, of centripetal acceleration along a line joining the ears (the subject’s interaural axis). Accelerations at the onset and end of rotation were 26 degrees/second². Subjects could also be positioned lying-on-back (LOB) (Figure 3) so they lay supine along the arm of the centrifuge with their heads 0.65 m from the axis of rotation. In the LOB configuration, rotation at a constant velocity of 223 degrees/second and 158 degrees/second provided centripetal acceleration along the subject’s body vertical axis with a magnitude of one-G and 0.5-G at the level of the interaural axis, respectively. Because the center of rotation was about an axis approximately through the navel, the centripetal acceleration was directed down (toward the feet) at the head and up (toward the head) at the feet; i.e., toward the center of rotation. Thus, there were potentially conflicting estimates of the direction of the accelerations from some of the tilt receptors in the body and the otoliths. A restraint system, consisting of a five-point harness—thigh, shoulder, and neck pads—and a knee strap held the body firmly in place (Figure 1). A custom-made facemask, consisting of a fiberglass front and back shell that was molded to the bony features of the skull, restrained the subject’s head. The subject held handgrips, mounted on either side of the chair, that incorporated a push button used to calibrate the video system (see below) and an emergency rotation-abort switch. The subjects wore a set of headphones to provide a masking noise that eliminated external auditory cues.

Tilt Chairs

The centrifuge used for ground-based testing at JSC was also used as a static tilt chair (Figure 4). With subjects in the REO orientation, the centrifuge chair assembly could be tilted about an
axis located underneath the subjects’ seat. As a result, subjects were tilted in roll at angles between zero degrees (upright) and 90 degrees left-ear-down. A digital inclinometer was used to set the angle of tilt. A second tilt chair, built by Leigh McGarvie and Nicholas Pasquale of the Mount Sinai Medical Center, was used to test the response of the astronauts to static tilt on the day of landing at the Kennedy Space Center (KSC), Cape Canaveral, FL (Figure 5). For this, subjects were seated in an automobile racing seat and firmly held in place by a five-point safety harness, adjustable padded shoulder and neck supports, and a fiberglass back shell to support the head. Subjects could be tilted in roll from the upright (zero degrees) in 15 degrees steps to 90 degrees left-ear-down about an axis behind their head. A pin mechanism locked the chair in place at each angle. A three-meter-diameter white hemisphere, centered at eye level, was positioned in front of the subjects to display points of light and optokinetic stimuli. A static five-point display, consisting of a center point and four eccentric points at ±10 degrees horizontal and vertical gaze angles, was used to calibrate eye movements.

Visual Display
A visual display, consisting of a 158×167-mm liquid crystal display screen and associated optics and electronics, was mounted in a box directly in front of the subject’s face on the centrifuge chair (Figures 1-4). The visual display had a field of view of ±44 degrees horizontally and ±40 degrees vertically, and presented black dots on an amber background. This was used to display a sequence of dots at known gaze angles to enable calibration of the eye movement monitor. The display was also used to present optokinetic patterns (sequences of five-degree stripes that moved horizontally, vertically, and diagonally across the screen at 30 degrees/second) and smooth pursuit targets (small dots that moved horizontally...
and vertically across the screen). Optokinetic patterns were presented for 20 seconds in each direction (up, right, down, left). During smooth pursuit, the target was stationary at the center of the screen for a period ranging from 1.8 to 2.4 seconds, then stepped five degrees to one side. The target then moved at a constant speed (20 degrees/second) in the direction opposite to the step to a final position ranging from 25 degrees to 35 degrees. The duration for presentation of the target at zero degrees and the final position of target varied randomly to avoid anticipation by the subjects. The size of the step was adjusted so that the image of the target was on the fovea at the onset of pursuit. There were four trials in each direction (up, down, left, and right) in random order. The various visual stimuli were perceived at about the same viewing distance—i.e., about 60 cm—for all subjects. The pattern illumination was adjusted for each subject for best viewing of pursuit and calibration targets.

Eye Movement Recording

Binocular video recordings were obtained using two miniature NTSC video cameras that were mounted on the visual display unit (Figure 1), which provided video images at a frame rate of 30 Hz. Two rectangular banks of nine infrared (IR) light-emitting diodes (LEDs) (wavelength 950 nm), attached to each camera, were used to illuminate the subject’s eye. The LEDs were not visible to the subject. Images of the subject’s eyes were directed onto the charge-coupled device of the video camera via an IR beam-splitter mounted on the visual display unit, which was transparent to light in the visible range and allowed the subject a clear view of the visual display. The horizontal and vertical camera position and focus could be adjusted manually, by the operator, using a small video monitor as a guide, to obtain clearly focused images of the subject’s eyes. Two custom-made Hi-8 video cassette recorders (VCRs), mounted on the opposite end of the rotator beam to the subject chair, were used to store the video images of the eyes. Several experimental parameters, such as centrifuge velocity and timing information, were also recorded onto the Hi-8 videotape along with the image of the eye. Only one eye was recorded in the tilt apparatus shown in Figure 5.

Tape Processing Facility

Following the Neurolab mission, ground and inflight Hi-8 videotapes were dubbed onto Betacam SP tapes for post-processing. The tape processing facility consisted of a Betacam VCR (Sony UVW-1800), an IBM-compatible personal computer (PC) fitted with custom-made video digitization and display hardware, and a video monitor. Processing of the video data was automated, with two seconds of images digitized and stored in the PC. The digitized video images were then processed field by field (where a single field consisted of either the odd or even lines from a complete video frame), providing a sampling rate of 60 Hz.

The coordinates of the pupil center in the image field were calculated using a partial ellipse fit based on the work of Zhu et al. (Zhu, 1999). Location of the center of the pupil at 25 known gaze positions, obtained during calibration (see visual display above), formed the basis of a three-dimensional (3D) spherical model of the eye, which was used to determine horizontal and vertical eye position from the pupil center of subsequent images. Torsional eye position was obtained using the gray-level intensity information of the iris (Iral signatures) obtained from a circular Iral sampling annulus centered on the pupil (Figure 6). A reference Iral signature was sampled from images acquired while the subject fixated on the center point of the calibration display. Pattern matching of the reference signature with Iral signatures obtained from subsequent images provided a measure of torsional eye position (Moore, 1996). Improved accuracy of torsional computation was achieved using geometric algorithms that compensated for the eccentricity of the Iral sampling annulus according to eye orientation (Moore, 1996). Eye position in head coordinates was represented as Euler angles in a Fick (yaw, pitch, roll) rotation sequence.

APPLICATION

There were a number of innovations in the research equipment developed for this flight. Firstly, the precisely controlled human centrifuge allowed study of the effects of sustained levels of 0.5-G and one-G of side-to-side and head-to-foot linear acceleration on otolith-induced orienting eye movements. The effects of “artificial gravity” on otolith-induced orienting
eye responses in space had not been determined before. Secondly, this was the first use of binocular 3D video-based eye movement recordings during controlled vestibular stimulation in space. Finally, this was the first use of visual stimuli for study of visual-vestibular interactions during centrifugation, either on Earth or in space. The development of this technology has been invaluable for testing the otolith tilt-translation hypothesis (see science report by Clément in this publication) and has facilitated study of vestibulo-sympathetic reflexes (Kaufmann, 2002). It will also provide the means for evaluating the efficacy of artificial gravity as a countermeasure to deconditioning of vestibulo-ocular and vestibulo-sympathetic reflexes during long-term space travel. In clinical medicine, the acceleration provided by centrifugation in darkness with concomitant visual stimulation may be a useful test of vestibular function. There may also be value in using centrifugation in the rehabilitation of patients who have had the inner ear removed on one side.

REFERENCES

