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MEDICINE ON MARS

How sick can you get during three years in deep space?

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The rocket science will be the easy part. With a projected launch date of 2020, NASA is planning to send astronauts on a three-year mission to Mars—including six months in transit each way—and its technicians are reasonably confident about the mechanical aspects of the trip. The truly vexing problems are turning out to be the medical ones. Can human beings survive long-term exposure to deep-space radiation and zero gravity? Can astronauts who have medical emergencies be treated en route? What about the psychological effects of the stress and confinement? These are questions that various officials at NASA—along with a number of consulting experts—are trying to answer.

Four years ago, NASA realized that it didn't have the resources to deal with the medical challenges of deep-space exploration. In part, this deficiency is due to the complexity of what happens to the human body in space, but it also reflects the fact that the life sciences have long been treated like a stepchild in an agency dominated by engineers and physicists: last year, medical research received less than two per cent of NASA's annual budget. The agency, recognizing this problem, decided to "outsource" some of the work to a nonprofit consortium of twelve university laboratories. The consortium is known as the National Space Biomedical Research Institute, and has its headquarters at Baylor College of Medicine, in Houston.

Recently, I visited the NASA physiologist Dr. John Charles, in Houston, to discuss these matters. Dr. Charles is the scientist responsible for what the agency refers to as the "Critical Path Road Map"—the strategy for developing the medical research and technology that will be necessary for travel to Mars and beyond—and he does not minimize the difficulties involved. Across from his office on the Johnson Space Center campus, beyond the grassy quadrangle and pond, stands a tall limestone building whose top floor serves as the living quarters for the astronauts. Charles's brief is, ultimately, to protect their well-being. A towering man with a salt-and-pepper buzz cut and radiant blue eyes, he holds a doctorate in cardiovascular physiology and has worked at NASA for sixteen years. "We've gotten away with past space flights because of hubris and luck—and because we put very fit astronaut bodies out there," Charles said.

In 1997, teams from NASA and the N.S.B.R.I. reviewed the experiences of the two hundred and seventy-nine men and women who had participated in space missions between 1988 and 1995. They discovered that all but three of them suffered some sort of illness during the trip, and a hundred and seventy- five biomedical risks were subsequently identified. Four were classified as Type I, meaning that they are grave, that they are highly likely to occur, and that there are no protective countermeasures for them. “Each of these could easily be a showstopper,” Charles said. All the same, he says, “It’s inevitable that we will go to Mars—if not the U.S. now, then someone else will, maybe the Chinese.” He pointed out that there was already a long list of astronauts eager to make the trip. “These people are explorers,” he added. “No explorer has ever been guaranteed a return ticket.”

A number of the biomedical risks are simply the result of living without gravity. “You are basically taking healthy individuals and putting them into a sick environment—space,” Charles explained. Human beings evolved over millions of years in the grip of gravity; the fluid and small bones of the inner ear, which make up the vestibular system, sense its steady tug. In the absence of gravity, people are without the signals that they depend on for orientation and balance.

The first medical problems occur right after liftoff. Even seasoned astronauts frequently vomit, overcome by vertigo and nausea. It takes a few days for the vestibular system to adapt. During that time, the astronauts take anti-emetic medication and move in slow, deliberate ways; even minor changes in position—say, turning one’s head too quickly—can trigger a bout of space sickness. (Among astronauts, missing the emesis bag is very bad form, since the vomitus floats through the cabin and has to be chased by a crew member and trapped, glob by glob, with a sponge.) Even when the dizziness abates, some astronauts find themselves unable to sense the location of their hands and feet.

The absence of gravity also wreaks havoc on the circulatory system. Normally, blood pools in your legs and lower torso; when you enter weightless space, that blood is released and rushes up like a geyser. You can feel as if your head is being hit by a hammer, and your heart beats rapidly to expel the incoming excess of blood. Then your body is fooled into thinking that it has a fluid surplus, and typically two pints of water will be lost in two to three days. As a result, you quickly become dehydrated, which in turn makes your blood thicker. The thickened blood cues your body to stop producing red blood cells, and over the coming months in space you will become mildly anemic.

On Earth, our musculoskeletal system is kept intact by working against gravity, a biological process called remodelling. In weightless space, this process slows down, and a person loses one to one and a half per cent of his bone mass per month; even tendons and ligaments progressively deteriorate. Since there is no resistance to motion, and objects have no weight, muscles atrophy: it’s like being on complete bed rest in a total body cast. The risk of bone fracture during a three-year mission to Mars is estimated to approach twenty to thirty per cent. Relatively minor stresses could cause the supporting ligaments and muscle to tear like tissue paper. Crew members on Mir have tried to prevent this process through physical exercises, but without success.

Once the body has acclimated to weightlessness, returning to gravity is equally traumatic. In 1989, one of the shuttle astronauts, Manley (Sonny) Carter, described it as the most wrenching physical experience of his life, and for the first time NASA began seriously to consider the limits that human biology might impose on space travel. “We got religion from Sonny’s observation,” John Charles said. But, even now, countermeasures are rudimentary and not very effective: NASA provides a G-suit, with inflatable pockets that compress the legs and abdomen to sustain the astronaut’s blood pressure, and a regimen of salt tablets and water to replace lost fluid.

Astronauts are reluctant to talk about such physical ailments, and NASA has been equally reluctant to publicize them. To preserve the dignity of astronauts returning from missions, the Kennedy Space Center transports them from the spacecraft with mechanical people movers, and the catwalk leading from the capsule is shrouded by a curtain so no one outside can see the astronauts staggering. I prevailed on Andrew Thomas, an astronaut who spent a hundred and forty-one days on Mir in 1998, to describe what it was like to return to Earth after some five months in zero gravity.

“I landed lying down on my back and reached for my camera—it felt amazingly heavy, like a huge fifty-pound lead dumbbell,” he recalled. He was overcome by vertigo, and—when he was helped to his feet and supported on both sides by the ground crew—by gravity, too. “It was incredible. Just putting one foot in front of the other required tremendous effort.” His balance was poor, and he staggered forward, listing to the side. Over the next few days, he recounts, “I had to walk slowly with a wide-based gait. Fine-balance skills took several weeks to return. When I walked with my eyes closed, I still veered to the side and walked into the wall.” Thomas underwent many weeks of rehabilitation, as is standard practice, with graduated exercises, guided movements in a warm swimming pool, and massage. Even after a month, however, he couldn’t jog without becoming short of breath.

How will debilitated astronauts who have been in deep space for six months adapt to Mars, which has a gravitational force almost half as powerful as Earth’s and more than twice as powerful as the one the Apollo astronauts encountered on the moon? “The real problem will be to get used to the surface of Mars, where there will not be a rehab program waiting for the crew,” Andrew Thomas pointed out. “If we need to take emergency action, abort the landing, or escape the hatch, there would be the potential for disaster.”

Since zero gravity is so destructive, the solution would seem to be artificial gravity, which can be generated by centrifugal force. That’s the force we know as the tug from an object spinning in a circle, like the pull of a bola in the hand. But creating artificial gravity with centrifugal force in a space-ship is difficult. One idea under consideration is to rotate the entire spacecraft, which would make the level of G equal throughout the cabin. Some engineers have proposed that the ship be built in the shape of a dumbbell, with two parts connected by a long tubular bridge; the entire ship would then spin around its central axis. Unfortunately, a ship of this design would be more likely to break in two if there was a mechanical failure, or if space debris crashed into the bridge. Another possibility would be to create artificial gravity in a single room of the spacecraft, which would be rotated like a small centrifuge. But this would result in a highly unequal distribution of force: there would be zero G at the astronaut’s head and one or two G at his feet, so he would be light-headed while his legs would feel as if they were dragging ankle weights.

At present, NASA is experimenting with a G chair, which Charles offered to show me. We walked across the campus to a windowless structure that was built to receive the Apollo astronauts after the lunar missions and now houses several research laboratories. In a brightly lit room crowded with equipment, Dr. William Paloski, the chief of life-sciences research at NASA, demonstrated how he was simulating different states of artificial gravity. A large padded black chair, such as might be found in an old-time barber shop, was mounted on a huge turntable and surrounded by monitoring equipment. As the chair spins at different speeds and tilted at different angles, Paloski studies the reactions of astronauts, as well as healthy volunteers, strapped in it. “If we could successfully create artificial gravity, then this single countermeasure will cover all the problems associated with weightlessness,” Paloski explained. “Artificial gravity would be a prescription during a long-duration space life”—that is, “taken” for a specified amount of time and at a certain G level.

Paloski is studying whether such a prescription is feasible, since it requires the brain and the vestibular system to be trained for what is termed “dual readaptation.” He has in mind something like the ease with which you put on and take off your glasses. The brain is familiar with both states of vision, and adjusts quickly: you don’t experience the dizziness or headache you might have had when you first wore the glasses. Paloski wants to train the astronauts’ brains to feel settled in either gravitational state. So far, he admits, he hasn’t figured out how.

The dangers posed by cosmic rays are even more daunting: we have neither biological nor mechanical defenses against them. These rays are deflected from the Earth by a surrounding magnetic zone, but beyond this zone they are commonplace. Composed largely of iron particles travelling at speeds that approach that of light, they penetrate deeply into the body, even through the skull. When the speeding particles pass through the tissues, they trigger what is, in essence, a nuclear reaction.

“Normally, on Earth, we suffer tiny breaks in one strand of our DNA from UV sunlight and X rays,” Dr. Francis Cucinotta, the manager of NASA’s Space Radiation Health Project, explained. “But with the kind of high energy deposited from cosmic rays, there are multiple breaks in both strands of the DNA helix, and we haven’t evolved natural repair mechanisms to restore them.”

A special accelerator at Brookhaven National Laboratories, on Long Island, is being upgraded to enable it to mimic cosmic rays by generating speeding iron particles. Cells in culture, as well as mice and rats, will be exposed and extensively studied to measure the rays’ effects. The evidence we already have is discouraging: researchers have exposed rodents to these high-energy iron particles and found significant changes in their cerebral dopamine pathways, as well as consequent behavioral changes, such as apathy and decreased memory. Autopsies revealed that the rodents’ brains were riddled with microscopic lesions from the radiation, as if they had been hit by buckshot.

Cosmic rays could also cause dangerous mutations in the bacteria and fungi that normally colonize our skin, mouth, and intestine, as well as the ambient ones within the spaceship. As Dr. Duane Pierson, a NASA microbiologist, explained to me, microbial flora could change into virulent pathogens that might not respond to antibiotics. The risk of infection is compounded because the immune system also appears to be altered in space. Astronauts who have been isolated on analogue missions in Antarctica have suffered from T-cell deficiencies, and Pierson has found instances in which latent viruses, such as Epstein-Barr and cytomegalovirus, have been reactivated. On a prolonged mission, these viruses could easily spread in the cabin.

What's more, exposure to cosmic rays greatly increases one's likelihood of getting cancer. Studies on astronauts such as those on Mir, who have gone into orbit around the Earth, are instructive: the number of chromosomal breaks they had correlated with the level of radiation they'd encountered during their flight. Experts estimate that these astronauts have a one to two per cent increased lifetime risk of cancers—a level of risk which is considered acceptable by the Occupational Safety and Health Administration. But a recent review by the National Research Council indicated that the increased lifetime cancer risk for astronauts on a voyage to Mars could be as high as forty per cent—more than ten times higher than the level deemed acceptable. In other words, it is currently illegal for NASA to send men and women to Mars, and, presumably, it will remain so until adequate protective measures have been devised.

NASA believes that an acute medical crisis—a bleeding ulcer, say, or a broken limb—is very likely to occur during a Mars voyage. Data on long-duration missions in close quarters, such as submarines, show that in the course of a year there is a six-per-cent chance that a person will have an accident requiring emergency care. If the Mars crew was composed of six astronauts, for example, at least one such emergency would be likely to occur over the three-year voyage. This prediction, of course, extrapolates from data on Earth; the risk in deep space would be even greater, given the debilities imposed by zero gravity and cosmic rays.

Dr. Jon Bowersox, a surgeon at the University of California, San Francisco, who works with N.S.B.R.I., is a former Army flight surgeon and an expert on adapting surgery to the battlefield. He says that an injured astronaut in deep space presents a similar challenge—except that "evacuation is not feasible." Of course, the doctor on board will be trained in general surgery and emergency-room technique, but in space even routine surgery becomes daunting. Blood aerosolizes into the cabin's atmosphere and creates a wafting fog. The scalpel, clamps, and other instruments have no weight in the surgeon's hands. Tissues lose their normal density. Blood flow, wound healing, and anesthesia could all be different, so doctors will not be able to rely on their experience and knowledge of surgery on Earth. Furthermore, surgical decisions will have to be made on the spot; because of the long time delay of transmissions between Mars and Earth—up to forty minutes—emergency treatment cannot be directed from Mission Control in Houston.

Bowersox and other N.S.B.R.I. experts believe that training prior to the voyage will probably occur in a "virtual" environment, with simulators that will challenge each crew member to provide emergency medical treatment in a setting similar to that of the spacecraft. Because a surgeon at zero G loses what Bowersox calls his “intuitive and natural cues,” experts are designing special sensors that, combined with artificial intelligence, will monitor the operation.

The N.S.B.R.I. members have proposed the creation of a “digitized virtual astronaut.” This would be a computer representation of the entire physiology of the crew member which is updated in real time, using input from a comprehensive bank of sensors. Whether these sensors would be placed over different parts of the body or be embedded near certain vital organs is a matter of contention. Astronauts have always bristled at being overly monitored on voyages. “There is a taboo against planting sensors in astronauts, as there is in soldiers,” Bowersox said. “It is a fear of Big Brother. But it’s a fallacy. We should be able to implant them for the good of the crew. There are now ways to coat such sensors with fibrin”—the protein material that forms clots—“so that they’re biocompatible and can be placed below the skin and last for months.”

There might also be a “virtual mentor”: a computerized database whose artificial intelligence will assist the onboard physician in diagnosis and treatment. “For example, astronaut John Doe has a fever, and pain in his right lower abdomen,” Bowersox says. “The virtual mentor instructs the doctor to perform an ultrasound, with voice and image overlay, all the while comparing the new ultrasound data with baseline data. Appendicitis, which is the likely diagnosis, would be best treated with intensive antibiotics, given the difficulties of operating in zero G. Surgery is a last resort.”

When surgery could not be avoided, it would be performed by the doctor, coached by the virtual mentor and aided by robotics. The virtual mentor would provide a physiological assessment, advising about blood volume if there is hemorrhage, oxygen needs, and electroshock to stabilize the heart rhythm. What Bowersox has in mind is an advanced version of systems currently in development on Earth which use remote-controlled robotics, with fibre-optic feedback, to perform certain cardiac and abdominal procedures. On a Mars mission, sensors attached to the surgical instruments—scalpels, clamps, retractors—could supply immediate information about the physiology of the tissue undergoing repair.

Surgery would still be a great risk, especially if it involved procedures of any intricacy. Bowersox believes that significant trauma to a limb, for example, would probably be treated with immediate amputation rather than arduous repair. Even harder to manage would be a head trauma. “People run out of steam in talking about CNS injury,” Bowersox says. “Neurosurgery at zero G is unimaginable to most experts.” Given the lengthy delays characterizing transmissions to Mission Control, the ship’s commander will have to choose when to offer continued support and when to let a suffering astronaut die.

Finally, NASA must protect the psychological and social well-being of the crew. Chris Flynn, a NASA flight surgeon who worked on the Mir mission, is chief of psychiatry at the Johnson Space Center. He served nearly eight years on active duty in the U.S. Air Force and is now in the Air National Guard. “After a pilot had a psychiatric event, I was one of the doctors who decided whether he should ever fly again with nuclear weapons,” he explained. Flynn conceded that the psychiatric concerns raised by a prospective Mars mission—a mission that will, in all likelihood, have an international crew—are daunting. “Of course, you can’t depend on self-reporting. Astronauts are hard-charging people, guys who won’t stop. People who fly don’t ever want to admit they’re ill.”

The normal circadian rhythm and restful REM sleep are often lost during space travel, which can seriously affect not only one’s mood but one’s ability to think clearly. Astronauts on a Mars voyage will also be confined to a cabin the size of a dorm suite for roughly three years; once they reach their destination, they will be more than a hundred million miles from home. All this could cause members of the crew to become unstable and turn against one another. Moreover, the time delay in radio communication would prevent a psychiatrist on the ground from engaging in the kind of dialogue which would ordinarily reveal changes in a person’s state of mind. “We need to develop objective physiological measures to monitor mood, anxiety, and depression,” Flynn said. The difficulty of this task will be compounded by the culturally variant views of psychological syndromes and therapies among the crew. And yet it is vital to develop these measures, he continued, given the likelihood of anxiety and depression when “someone is put in a can and flies away for three years.”

In addition to experiencing monotony, claustrophobia, and sleep deprivation, the crew will be deprived of the daily intimacies that help to maintain our psychological health. “It’s not just sex,” Flynn said, “but that sense of loving that sustains our social connectedness.” During analogue missions in harsh, isolated environments, more than ten per cent of the subjects develop serious psychological adaptation problems, and up to three per cent experience symptoms of frank psychiatric disorders like major depression. Flynn envisions the virtual projection of family members to the crew as a central element in psychological support in deep space. This would involve technology that permitted exchanging audiotapes, recent photographs, and video clips with family members. All this might help alleviate some of the effects of isolation, and can be tested in an Antarctica analogue mission.

Exhaustion in space is particularly dangerous, because it can impair an astronaut’s judgment. To combat this problem, NASA has developed an instrument to measure cognition, the so- called S-CAT, or Spaceflight Cognitive Assessment Tool, which was used on the Mir missions. This is a test that is taken before the flight to establish baseline values, and then retaken periodically by the astronauts during the flight; a comparison of the scores shows the crew member when, and how, his cognition is impaired. Artificial intelligence will likely be developed to aid the crew if they flag from overwork. A virtual mentor might regularly assess the performance of tasks and the results of the S-CAT; if it appears that an astronaut is losing cognitive abilities, the virtual mentor could instruct him in the work and recommend countermeasures to avoid accidents.

Happily, many of these technologies will have applications on Earth as well. For example, computer-based “surgery simulators” could be of great benefit for training interns and residents: mistakes in a virtual environment do not result in debility, death, and lawsuits. Virtual mentors could be especially helpful for complex neurosurgical procedures, cardiac repair, and abdominal or pelvic laparoscopies. Right now, such systems are being tested in the emerging field of intrauterine surgery: during operations performed to repair congenital defects, doctors place microsensors in the amniotic fluid. The kind of sensors that Bowersox imagines being used on a Mars mission could equally serve to monitor immobile patients with chronic illness: while they stayed home, their vital signs could be transmitted directly to the physician's office. Even the A.I. feedback systems that are being developed to monitor fatigue and stress could be adapted for pilots, operators of heavy machinery, air-traffic controllers, and workers in nuclear facilities, as well as medical interns and residents on call—in short, for anyone in a job where fatigue can lead to serious mishaps.

The technologies introduced in the next decade by NASA and N.S.B.R.I. will be field-tested in an international space station, which will be ready to receive long-term crew members this fall. Astronauts and cosmonauts will be sent there for periods of three to six months. "Successful work on the space station will allow astronauts to get their tickets punched to go to Mars," John Charles said. He also hopes that useful data from monitoring large numbers of astronauts will be gained from these space-station missions.

"It's a difficult road to Mars," Charles said. "There are many years of hard work ahead of us." Already, though, there's active discussion within NASA about what kind of astronaut would be best prepared for deep space. "If young," he continued, "they may be the most fit. But then you run into the problem of radiation, which could zap their gonads, so they would not be able to have kids." A case could also be made for choosing older astronauts, seasoned by previous missions, for the first Mars voyage. And if the radiation exposure caused cancer after a decade or so, an older crew would have fewer years to lose.

Charles also told me about a recent informal poll of NASA astronauts taken to help formulate a list of the skills most necessary in the ideal Mars crew. "They all would be remarkable people," he said, "all cross-trained. Everyone would have emergency medical skills, basic training in engineering and navigation. But the first priority on everyone's list was a handyman, someone who is a crackerjack mechanic who can fix whatever is broken." Even then, Chris Flynn observes, "There is a very small E.R. up there. What we can do, even as a physician on board, is quite limited."

Are the risks worth it? "A deep-space mission to Mars is a focus for the new century," Bowersox told me. "It's like westward expansion—the effort and journey will spark creativity and imagination." That does seem to be how the astronauts feel. I asked Bonnie Dunbar, an astronaut who has completed five missions in space, if she would go to Mars. "Absolutely," she said in a gleeful voice. "I think of my grandfather who came from Scotland. He had a dream to come to America, took a rickety boat across the sea, and went west into wilderness. Did he stop because of the risks? I'll be fifty-one this year. I've spent my life training to go into space. If my life ends on a Mars mission, that's not a bad way to go."