This master thesis was performed at Architecture and Development Studies at Faculty of Engineering (LTH), Lund University. It is a collaboration with NASA at Johnson Space Center (JSC), Houston and Lund University Hospital with the objective of making an operating table for long term missions like Mars explorations. The Zero Gravity Surgical Workstation (0GSW) is an operating table designed to manage medical traumas in a microgravity environment. It is a part of a contingency plan to enable future interplanetary missions where medical events need to be handled on spot without any support from Earth.

Industrial Design is often associated with compelling aesthetics of products produced in large numbers. It is a tool to improve competitiveness and to promote the company brand, but there is also a wider aspect of industrial design. The 0GSW is neither a consumer product with a focus on styling, nor is it intended for a large scale production. The aim has been to provide an innovative solution with user centred qualities for surgery in deep space. It deals with an environment in which the design is the consequence of the microgravity and the limited space on board spacecrafts.

ISBN 978-91-7740-087-5

0 G Surgical Workstation – Master Thesis by Johan Hägg

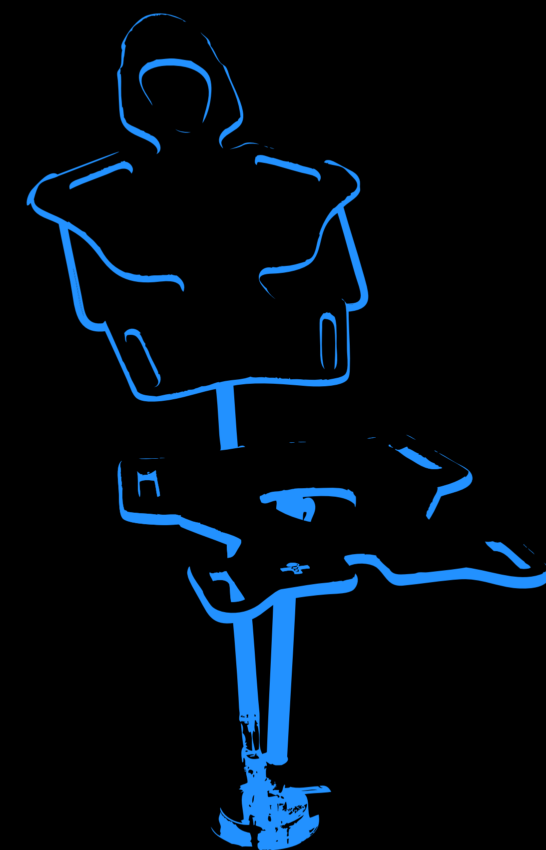
# 0GSW

## 0 G Surgical Workstation

Master Thesis

by

Johan Hägg



LUND UNIVERSITY

# 0 G Surgical Workstation

Printed by KFS AB Lund University 2007



ISBN 978-91-7740-087-5

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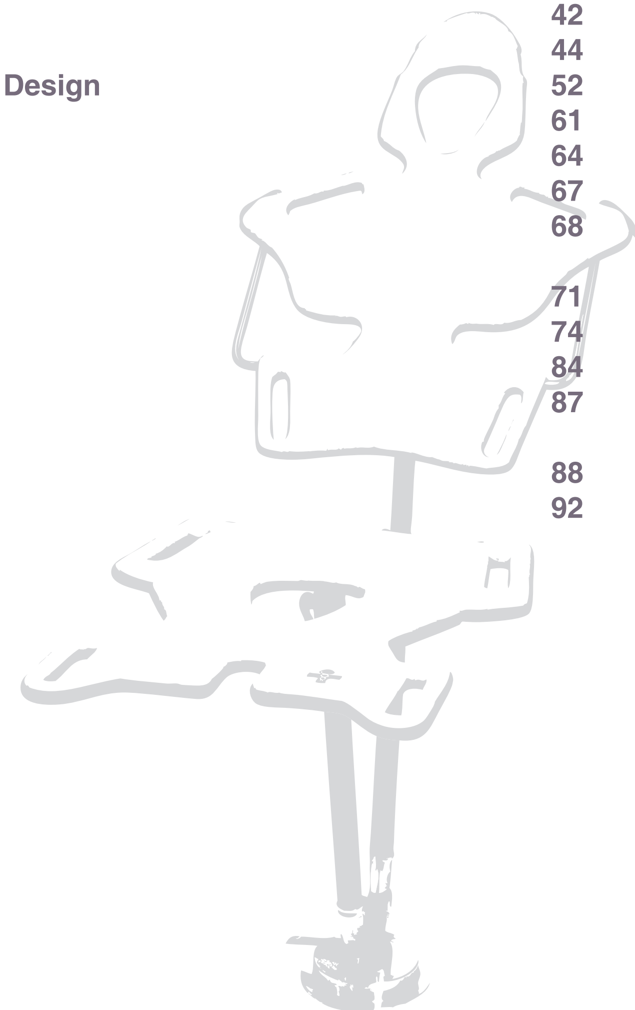

## ACKNOWLEDGEMENTS

Special acknowledgements to my supervisors Gunilla Islander and Marcus von Euler – this thesis could not have been possible without their help. To Gunilla for her tremendous support, feedback and enthusiasm for my thesis. To Marcus for his visionary thoughts and inspiring feedback. This goes to examinator Maria Nyström as well, for persuading me to choose this topic for my thesis in the first place.

Acknowledgements also to various people working for NASA in Houston. These include Larry Toups for his effort in providing me with valuable feedback, contacts and information. I would also like to thank James Flores and Jeffrey Jones.

Bengt Malm and Jan-Åke Larsson (workshop managers at the Faculty of Engineering LTH, Lund University) for amazing assistance and patient in helping me build the mock-up. Catarina Östlund at Architecture and Development Studies for administrative help. I would also like to acknowledge Niklas Lillevars for terrific feedback and linguistic revision. Thanks to design-colleagues Staffan Dahlberg and Daniel Gunnarsson Ohlson for valuable feedback.

Special thanks goes to the Dep. of Anaesthesia and Intensive care (Centraloperation 1) at Lund University Hospital, Practicum, and personnel at the hospital such as Lars Rosberg and Dervla Törnquist. Also all those individuals that have contributed with external medical expertise, including paramedic personnel of Lund Rescue Department, the staff and students of the Faculty of Odontology in Malmö, Corinne Williams at Wyle Laboratories JSC, Jenny Jönsson, Peter Holka at CSK and Andreas Eriksson,

Thanks to all suppliers of material including Kim Sjödahl (Exel), Conny Andersson Barnekow (Herman Anderssons Plåt AB), Michael Uhrmann (AustriAlpin) and JOLIFE AB.

Finally, I which to acknowledge my darling Sofia for her patience during this busy period and for her great support and confidence in me.

**Sponsors:** Exel Oyj, Technipur AB and Herman Andersons Plåt AB


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# SUMMARY

This master thesis was performed at the Division of Architecture and Development Studies (ark3) at Faculty of Engineering LTH, Lund University. It is a collaboration with NASA at Johnson Space Center (JSC), Houston and Lund University Hospital with the objective of making an operating table for surgery in space. Long term missions like Mars explorations will in the future very much depend upon the ability to solve medical problems on location, when the distance from Earth is too far for a rescue mission. This suggests the need of an operating table to manage surgery at least to a certain extent rather than just trying to stabilize the patient, as is the case today.

Surgery in microgravity is in many ways different from the procedure on Earth. If successful operations are to be carried out in space there are essential factors to consider like fluid management, waste disposal, anaesthesia, working positions and restraints of surgeon, patient and operating equipment.

The Zero Gravity Surgical Workstation (0GSW) is an operating table designed to meet the restraint demands, good access for surgeon as well as electrical isolation from defibrillation. The 0GSW is radiolucent* so that the patient can be restrained during radiography. The weight has been reduced to less than 6kg by using light weight materials such as carbon fibre, aluminium and low density polyurethane. The table can be positioned for various operating positions and since it is used in microgravity the surgeon can stand, facing the patient and has full overview while working. The boards easily fold together to reduce space when it is not used. The 0GSW also has mountings for the LUCAS™ system to provide mechanical heart compressions in case of a cardiac arrest.

*For footnotes[1]; see references*
*For asterisks*; see glossary*



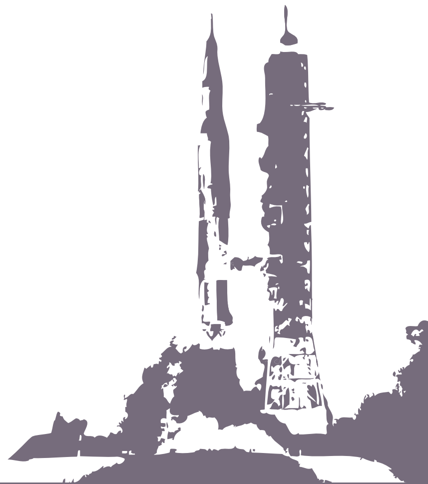
# SAMMANFATTNING

Detta examensarbete utfördes för Arkitektur, Utlandsbyggande (ark3) vid Lunds Tekniska Högskola (LTH). Det är ett samarbete med NASA vid Johnson Space Center (JSC), Houston och Lunds Universitetssjukhus i syfte att utveckla ett operationsbord för rymdkirurgi. Längre rymdfärder som expeditioner till Mars kommer i framtiden att vara helt beroende av förmågan att lösa medicinskt akuta situationer på plats, då avståndet till jorden är för långt för att en räddningsaktion ska vara möjlig. Att resa till Mars skapar ett behov av ett operationsbord för att hantera kirurgiska ingrepp snarare än att stabilisera patienten i fråga, vilket är fallet i dag.

Kirurgi i mikrogravitation är på många sätt annorlunda. Om operationer i tyngdlöshet ska genomföras med framgång, måste flertalet aspekter vägas in, så som hanterandet av vätskor, avfall, anestesi, arbetsställning och fastspänningsanordningar för kirurg, patient och operationsutrustning.

Zero Gravity Surgical Workstation (0GSW) är ett operationsbord som är utvecklat för att klara kraven av immobilisering av patienter, att medge god åtkomst för kirurgen, samt att vara elektriskt isolerande vid defibrillering. 0GSW är också genomlysbar, så att patienter kan röntgas på bordet.

Lättviktsmaterial som kolfiber, aluminium och lågdensitetspolyuretan har använts för att minimera vikten till 6kg. Operationsbordet kan ställas in för flertalet operationsställningar och eftersom det används i tyngdlöshet, så har kirurgen möjlighet att arbeta med patienten stående, vänd mot sig för bättre översikt/åtkomst. Operationsbordet kan enkelt fällas ihop för optimal förvaring. 0GSW har också fästen för LUCAS™ som används för mekaniska hjärtkompressioner vid hjärtstillestånd.



# INTRODUCTION

NASA's plans for the future is to go back to the Moon and eventually to Mars and beyond. By returning to the Moon we can gain more scientific knowledge about the history of Earth and our place in the universe. The strategy of going back to the Moon is also to make preparations for a future Mars mission. This allows NASA to test technologies, systems, flight operations and exploration techniques to reduce the risks and increase the productivity in a cost efficient and safe way.[1]

A crew mission to Mars would require extensive planning. At this point we have investigated the surface of Mars with satellites and robotic rovers. Next step before sending humans will be to launch more scout missions (perhaps airborne devices like planes, balloons) to gather more information about the Martian environment. There will also be missions for collecting geological samples by drilling deep into the ground and bringing them back to Earth for further investigations. This work is scheduled for the second decade of the 21st century.[2] There will probably not be a manned mission to Mars until 2020 at the earliest.

Today astronauts and cosmonauts work at the International Space Station (ISS) in Low Earth Orbit (LEO) to gather as much information as possible about life in space. Understanding how Earth life responds to living in space will prove invaluable for future missions. Space travel will in a foreseeable future continue to be dangerous and expensive. To continue sending humans into space, the goals of these missions ought to be worthy of the cost, the risk and the difficulty. There has to be a greater vision for space exploration than staying in LEO.

The scope of this master thesis is to investigate the medical health care system when it comes to more advanced surgery during long term missions in microgravity. To limit this field the focus has been on developing an operating table, or restraint system, to enable surgery.

Today there is little need to perform surgery in space since a medical emergency on ISS can be treated in a hospital on Earth within 6 to 24 hours. Even from the Moon the time to return to Earth would probably not exceed three days. This means that the patient would be stabilized and brought back rather than performing any surgery. In the future however, health care management of body deterioration (due to microgravity), psychological stress, sickness or trauma might be the most important obstacles to overcome for a Mars expedition or any lengthy stay in space. On these long distance missions there is no possibility to send a rescue team from Earth to evacuate the crew. Also, real time contact with surgical consultants (telemedicine/telementoring) is impossible on interplanetary missions. The crew on a mission to Mars would experience communication delays up to 40 minutes for a round-trip.[3] This means that the crew has to rely completely on their own ability to solve these emergencies.

Historically, mortality and morbidity related to trauma and emergency surgical problems, together with infectious diseases have accounted for more expedition failures on Earth than have defective transportation systems.[4] Our spaceflight experience is still too limited to make any accurate estimations of the risks but spaceflight scenarios can be similar to expeditions to remote and isolate places on Earth such as the south pole.

Surgery in space has never been carried out on a human, but there has been tests performed on manikins, rats, pigs and recently a human in microgravity during parabolic flight* (simulated microgravity onboard an airplane).[4-7] Various tests like endoscopic surgery (laparoscopy, thoracoscopy), haemorrhage control, anaesthesia, aseptic techniques, fluid infusion, intubation* techniques and suturing have been evaluated.

Statistics from 45 years of spaceflight gives us some clue to what medical emergencies we can expect, but no one really knows the long term physiological effect in microgravity. It is known that microgravity alter the immune system and there is also osteoporosis and muscle atrophy concerns. There has to be solutions for managing these effects if a return to Earth is to be possible. The ability to solve medical emergencies is determined by the training level of the crew, access to equipment (surgical, diagnosing, monitoring, life sustaining equipment, drugs etc), and the amount of assisting personnel.

The equipment that is being used on ISS at the moment is a restraint platform to perform cardiopulmonary resuscitation (CPR)* along with a defibrillator, electrocardiograph, heart rate monitor, toxicology and radiation monitoring devices, medical life support packs, oxygen system, respiratory support, infusion pump, equipment for intubation etc.[8] This equipment is not enough to manage any major surgery.

What kind of equipment necessary in the future will be decided by what the chances are to carry out the procedure successfully and the probability of the emergency scenario. It will not be possible to bring everything needed due to weight restrictions and lack of storage space.

Complications are also important to take into consideration. If there are no means to handle intraoperative or postoperative complications it might not be possible to perform surgery in the first place.



# SPACE PHYSIOLOGY

Following sections in “Space physiology” and “Medical procedures in microgravity” describe a broad review of human physiology in space. It is of importance to the reader (physicians, designers etc) to understand the work situation in microgravity and the context in which the 0GSW operates.

The physiological effects from long exposure to microgravity are important to take into consideration if any long term mission shall be possible. Effects from microgravity can have significant impact on future surgical scenarios and will be crucial for any contingency plan.

Initial and prolonged exposure to microgravity can not only increase the susceptibility to injuries but may also aggravate the injury severity and prolong the recovery period. The probability of complications can also increase due to management difficulties. The section below is based on research made by NASA and it describes the mechanisms as they are understood today.

**Cardiovascular effects** has to do with the change of blood volume after entry into microgravity. When large muscles of the lower limbs cease to be opposed to gravity, there is a fluid shift of 1.5-2 litres into the thorax, neck and head. This initiates a diuresis* with a 13% loss of blood plasma volume within the first 2-3 days. As a result of this, a reduction of red blood cells follows over an interval of weeks causing a relative anaemia*. This increased destruction of blood cells is caused by the spleen to maintain a stable haemoglobin concentration as a result of the decreased plasma content.

Losing a litre of blood in microgravity cannot be compared with the conditions of Earth. It is argued that this loss of vascular volume can produce symptoms of a severe haemorrhage.* On the other hand, being in microgravity is some what similar to bed rest which would imply a less severe bleeding.[4]

A haemorrhage following trauma in-flight can reduce the tolerance to increased G-forces associated with the re-entry to Earth which in turn can lead to brain damage.

In case of blunt head trauma the fluid shift may also result in a more severe injury due to higher intracranial pressure.[4] Ordinary symptoms from the fluid shift are dizziness, light-headedness and fainting. They can be treated by fluid loading, exercise, medication, G-suits and liquid cooling garment.[9]

**Space Motion Sickness (SMS)** is a result from the fluid shift and neurovestibular* effects. The symptoms are loss of appetite, nausea and vomiting. SMS affects approximately 79% of all crew members and about 10% of these cases are severe. The incidence is 50% for women and 70% for men. The peak symptoms are at 24 to 48 hours and resolves normally after 72 to 96 hours. The symptoms can be eased with medication and inactivity. 1 G orientation also counteracts SMS along with pre-flight training and prophylaxis.[9]

**Musculoskeletal effects**, along with radiation effects, is regarded as the variable most likely to limit a travel to Mars and beyond. A 20% loss in leg muscle strength has been observed after 1 month in space. This is thought to be the result of atrophy. With the initial fluid shift some muscle groups may lose as much as 50% of their mass within the first days in microgravity. This is a problem even though exercise reduces the overall atrophy. Osteoporosis is also a concern even if a high calcium diet is obtained. The rate of total calcium loss may be 0.5% per month and in some weight bearing bones as much as 5% per month. It has been suggested that only two thirds of the bone loss in-flight is recoverable but the mechanism of bone loss is yet not completely understood.[4]

There is a concern for kidney stones as well, due to the increased urine calcium levels as a result of the demineralization.[9] The osteoporosis suggests that there is an increased risk of fractures. An opposing view is that negligible weight implies negligible risk of injury in a microgravity environment. However, objects in microgravity still possess mass, which, when accelerated, can generate significant force. There is probably a higher risk of injury during Extra Vehicular Activities (EVA) or “space walks”.

The conclusion is that orthopedic injury can prove to be more dangerous than expected because of the calcium loss, affecting the bone healing process in a negative way.[4] It is not certain how to deal with this problem. It has been suggested within the Russian space program that it might be beneficial to choose crew members with a high bone mineral content for long duration space flights. Recent studies have shown that low-intensity pulsed ultrasound accelerates healing of fresh fractures and formation of delayed unions.[10]

**Immune system alterations** is another result of the microgravity environment. In a normal situation when the body detects a virus, 99 genes activate T-cells (a type of white blood cell) which attack the invader. It has been discovered that less than 10% of these genes are activated in microgravity. The reason for this is a specific signal pathway that is not working in the absence of gravity. Furthermore, T-cells do not multiply properly -there are not as many of them as there should be. The only known condition that has this severe effect on the immune system is HIV.[11,12] The limited data available raise concerns about local and systemic infections and decreased ability to heal soft tissue wounds and fractures.

It is known that astronauts are more susceptible to virus infections in microgravity which is why each astronaut undergoes a preflight screening and are placed in quarantine 7-10 days prior a mission.[11] There is however latent viruses such as Epstein-Barr (EBV)* and herpes which cannot be treated (only suppressed by medicine) and might constitute a threat. The level of EBV particles is also higher in microgravity in comparison to Earth.[12]

**Bacterial or viral infections** are important to know how to manage if any surgery is to be performed. It is not possible to “air out” particles and they will not “settle out” by gravity.[4] No one is yet sure whether an astronaut with a suppressed immune system would be able to complete a three-year space mission – the estimated time for a round-trip to Mars.[11]

Scientists have tried different approaches to counteract the effects from microgravity but there has not been a final solution so far. There have been attempts of creating artificial gravity (1 G) from centrifugal forces. The obstacle is that you need a rotating chamber which makes the spacecraft unbalanced and difficult to manoeuvre. There is also a sensory conflict in our neurovestibular system* from the centrifugal force, causing motion sickness. As of today, studies of short radius centrifuges are trying to determine whether or not artificial gravity is an acceptable solution.[13]

**Radiation** might constitute a threat to astronauts. On Earth we are protected from cosmic and solar radiation by layers of atmosphere and the Van Allen belt*, in space however, cosmic radiation can be dangerous to the crew. High levels of radiation can alter the DNA structure and in doing so, change various elements in the blood and tissue. Radiation poisoning often shows long term effects like cancer and reproduction disabilities ranging from reduced fertility to permanent sterility and offspring mutations. Furthermore, ionizing radiation (found in space) can produce damage to the lens of the eye and it is known that high levels of radiation weakens the immune system.[14,15] It has been suggested that microgravity and the extra radiation cause more damage to the immune system together than they do separately, so called synergetic effects.[11]

Spacecraft have previously been coated with heavy metals to shield off the radiation. This is however, not a sufficient approach since it is extremely expensive to send it into orbit. For interplanetary missions it is likely to use a radiation protected compartment for eventual cosmic radiation or solar flares. Radiation dosimeters* placed in various places (including on crew members) can be used as a part of a warning system when the radiation levels are too high.



# EMERGENCIES IN SPACE

### History

In 2005 there had been more than 60 person-year of manned spaceflight involving more than 400 astronauts. There has been 21 fatalities from 5 events during this time. Although most mishaps are related to liftoff and reentry, there has also been in-flight incidents including fire, loss of environmental controls and vehicular collisions.[16]

The table below shows 17 nonfatal severe medical events between 1961-1999:

| | |
|---|---|
| **Cardiopulmonary** | **Internal Medicine** |
| Pneumonitis* 4 | Chronic headaches 1 |
| Arrythmias* 2 | Cellulitis* of arm 1 |
| Reactive airways* 1 | Other unspecified 1 |
| **Genitourinary** | **Trauma** |
| Urosepsis* 2 | Ophthalmology* 1 |
| Prostatitis* 1 | Second-degree burns 1 |
| Urinary retention* 1 | |
| Kidney stones* 1 | |

*Data from article 16) Summers RL, Johnston SL, Marshburn TH, Williams DR. Emergencies in Space. Ann Emerg Med. 2005;46:177-84*

### Risk of an Emergency

First step in a contingency plan is to calculate the risk of an emergency. In the general population, the incidence rate (for a trauma/medical emergency) is normally considered to be 0.06 events per person-year.

From the data shown above NASA estimates the risk of an emergency to 0.02 events per person-year for astronauts that undergo extensive preflight screening.

By using the on-board health maintenance facility (used on ISS for less severe medical conditions) the estimate number can be decreased to 0.01 events per person-year. This estimation is consistent with the extensive data from the Russian space program in which three cosmonauts have been evacuated in 41.5 years of space flight. Mir space station had one medical evacuation in 31 person-years.[16]

For a mission to Mars this means an incidence rate of 0.2 events for an entire eight person crew, with a duration of 2.4 years (0.01*8*2.4). This is of course just a rough estimation. The data is based on statistics from LEO and there is still much to learn about the long term physiological effects of long duration space fights.

**Emergency scenarios**

In designing an operating table for microgravity the emergency scenario has to be considered. To understand what emergency scenarios we can expect it is essential to know a lot about the system as a whole; the space environment and the work on board included. Basically, we can expect the same medical emergencies like on earth but with some additions.

Penetrating injuries, minor injuries and dental injuries represent major causes of lost work days in remote settings on Earth.[4] Methods of dealing with this kind of injuries have to be considered. Previous traumas suggest the need to manage both chemical contamination and burns. There is also a concern for orthopaedic emergencies (especially during EVA's) due to osteoporosis. Furthermore, there are medical scenarios like cardiovascular symptoms (from fluid shift), head injuries, septicaemia,* hernia* etc that needs to be managed on spot.

Appendicitis and inflammation of the gallbladder might need surgery (appendectomy*/cholecystectomy*) if antibiotics fail to suppress the inflammation. The incident rate is very low in both cases, especially for inflammation of the gallbladder. Even though appendicitis is the most common non traumatic surgical event, studies from U.S. Navy submarine and Antarctic experience reported the incidence as one to two cases per 100,000 man days. This would be equal to one to two cases every 45 years in a six man space station.[6]

# MEDICAL PROCEDURES IN MICROGRAVITY

Surgery in space is feasible. Studies have shown that surgery in weightlessness is not all that different from surgery on Earth if there is a method of restraining patient, surgeon and hardware.[5-7,17-19] Furthermore, there has to be solutions for establishing adequate anaesthesia, hemorrhage control, collecting surgical fluids and establishing and maintaining an aseptic environment.

Minimally invasive procedures like laparoscopic and thoracoscopic surgery are attractive in microgravity especially in the ability to prevent cabin atmosphere contamination from surgical fluids (blood, pus, irrigation). Minimally Invasive Surgery (MIS) has also the advantage of smaller incisions, faster recovery and less pain compared to open surgery. Endoscopic instruments use ports which are inserted by small incisions (Fig. 1, left picture). Cameras, fibre optic lightning and specialized endoscopic surgical instruments are then used (Fig. 1). To view the surgical site the surgeon watches a video display from the inserted camera. To improve visualization, the abdominal cavity (in laparoscopy) is insufflated by $CO_2$ gas.

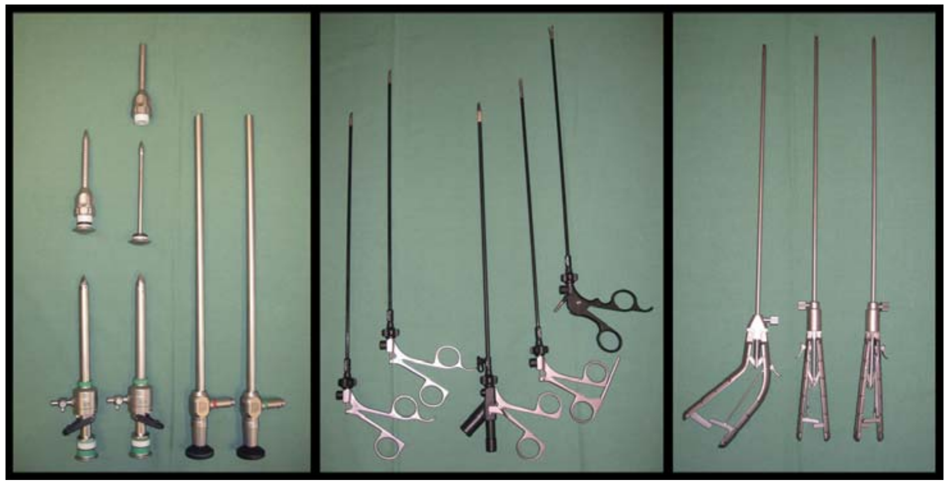


*Fig. 1. Endoscopic instruments. To the left -endoscopic ports, in the middle and to the right -forceps,* hemostats* and scissors.*

From 1993 to 2000, laparoscopy and thoracoscopy were performed on ten anaesthetized adult pigs in the NASA microgravity program during parabolic flight. Laparascopic surgery was successfully performed; visualization was not impaired by the lack of gravitational bowel retraction.

Thoracoscopy proved to be much more difficult. The lack of gravitational lung retraction and the mediastinal structures in 0 G eliminated most of the thoracic domain. Thoracic insufflation appeared to increase the domain but with obvious limitation. More sophisticated techniques such as selective bronchial intubation may improve this further.

Technical advances in endoscopic surgery will probably also make operations like this easier in the future. Video displays will probably be replaced with three-dimensional stereoscopic, virtual reality headgear and telerobotics allowing logarithmic increase in surgical precision (dexterity enhancement).[6]

If endoscopic surgery will be feasible in the future it does not only require sophisticated equipment, but the presence of capable Crew Medical Officers (CMO) with surgical experience.[6] As for today, CMO's are not required to be surgeons, or even physicians. Hand-Assisted Laparoscopic Surgery (HALS) might facilitate MIS in microgravity. It is easier to perform and does not require the surgical proficiency or extensive experience as traditional laparoscopic surgery.[18] An ideal CMO for future, long distance missions would possess basic knowledge in trauma surgery, orthopaedics, anaesthesiology and internal medicine.

Even though MIS has several advantages, open surgery cannot be ignored. MIS is always limited to the instruments being used and some procedures has to be managed through open surgery. Open surgery is more difficult in the way of controlling surgical fluids and establishing a aseptic operating field compared to MIS, but it is possible and can be managed by using an expandable surgical chamber.

A surgical chamber is a kind of inflated glove box made by transparent plastic vinyl which is attached to the patient's extremities, back or upper body. The chamber works like a container and prevents the surgical site to be contaminated as well as atmosphere contamination of the space vessel. The surgical chamber is inflated by a constant airflow which also serves as ventilation to reduce condensation of the chamber walls. Studies in parabolic flight, conducted by NASA in 1987, shows that it might be possible to perform open surgery in expandable surgical chambers. Controlling free floating liquids with sponges was not as difficult as anticipated.[20]

Blood in microgravity will not disperse into the air by itself unless it is an severe arterial bleeding. Because of the surface tension, blood (or any liquid) will stick to objects. A bleeding has been described like a growing dome formation and can be controlled by sponges or a suction device.

Studies of laparoscopic surgery shows that the blood formed large sheets along the abdominal wall and the surface of the organs, but remained mostly around the bleeding site and did not cause any problems.[6]

A special microgravity suction unit has been developed to manage surgical fluids. Regular suction devices depend on gravity to separate fluid from gas in a "drop chamber". However, in absence of gravity, gas stay intermixed in fluids which is why the microgravity suction unit uses a centrifugal separation chamber, connected to a vacuum pump. Additional methods like laser technology, acoustic haemostasis, advanced stapling devices and fibrin sealant foam injected through MIS might facilitate endoscopic suturing to control bleeding.[3,4]

Anaesthesia is complicated in microgravity. It is not clear how intravenous anaesthesia behave in the absence of gravity. A central nerve block might prove difficult in microgravity. It is argued that gaseous anaesthesia might be safer in the hands of an inexperienced CMO than intravenous anaesthesia. Gaseous anaesthesia might, on the other hand, constitute a hazard to the crew in terms of contamination of the cabin atmosphere.

Xenon gas in a closed system with a $CO_2$ absorber has been suggested as a conceivable solution. There is still not enough knowledge about the behaviour and effects of anaesthesia in microgravity to make any adequate recommendations.[4,21-23]

To establish aseptic conditions during surgery is not only vital for the patient but for entire crew. To be confined to a small closed environment like a space vessel requires novel solutions of establishing aseptic techniques and disposal management. In surgery there are "clean" areas that relate to the surgical site (surgeons hands and forearms) and less clean areas which are not in direct contact with the surgical site (operating table, surgeons elbows, upper arm and chest).

In contrast to terrestrial practice, large volumes of liquid (for cleaning) or gravitational force cannot be used in microgravity to manage bleeding.

Therefore, scrub techniques was modified and prepacked, sterile water soaked gauze was tested onboard a KC-135 aircraft during three parabolic flights by NASA in 1992. Surgical supplies such as commercially packed providone-iodine solution on hand scrub brush, squeeze bottles with a sponge at the outlet, surgical gloves and disposable and reusable gowns and drapes was successfully tested.[4]

Drip infusion will not work in the absence of gravity which is why an infusion pump must be used. Infusion pumps have been tested in parabolic flight, pumping liquid from a source bag into a collection bag with good results.[4] The only problem with liquids, as stated before, is that liquids and gas, with different densities, stay intermixed in microgravity which sometimes complicates the procedure. For fluid infusions this means that special filters are needed.

Intubation and airway management have also been investigated in parabolic flight. Restraints were used and stability of operator and patient was not jeopardized during laryngoscopy.* After force was applied to the laryngoscope,* no special restraints was needed.[4] Intubation practice is a part of the basic medical training of the astronauts. Intubation equipment (Fig. 2) can be found in ISS's medical supply.[8]

*Fig. 2. Intubation equipment from ISS: laryngoscope,* laryngeal mask,* syringe and endotracheal tube.**



Restraints of patient, surgeon and equipment are important for most procedures. Various surgical procedures have been performed like laceration closure, tracheostomy,* chest tube insertion, thorascopy and laparoscopy, to test different restraints and supply systems.

Three systems were tested in 2001 by NASA during parabolic flight; a surgical tray, medical sub pack (Fig. 3) and a scrub suit (operating clothes) for the surgeon.[24]

*Fig. 3. Surgical sub pack from ISS containing scalpels, needle driver, forceps, hemostats, surgical gloves, providone-iodine swabs, sterile drapes and strips, sutures, bandage scissors, tape etc.[8]*

A Minor Surgical Kit soft pack (similar to the surgical sub pack) was designed to be deployed to the cabin wall or the floor with Velcro attachments. All pockets open towards a central sterile work field and uses restraints like Velcro fasteners, a magnetic pad for ferrous instruments and elastic straps. The surgical tray was organized in a similar way but mounted on a rigid surface which could be placed closer to the operating site.

The scrub suit is worn by the operating physician and had pockets and restraints placed on the chest for medical supply and instruments. It can be stored in a sterile fashion like an ordinary operating room scrub suit.

For disposal management of wet biologic waste, plastic lined pockets were used. For trash like suture ends a flypaper area was used. Sharp items like blades and needles were secured in a Styrofoam block and placed in a transparent plastic container.

The conclusion of the study was that all methods worked well and they were not much more difficult to perform than in 1 G. The surgical tray was difficult to deploy without the risk of contamination and it could not be stored in an efficient manner due to its rigid construction. The advantage of the surgical tray was that it can be used close to operating site. The scrub suit also had the advantage of being close to the operative field but the access to the supply pockets made it less ergonomic.

The surgeon also had problems getting a clear overview of the instruments. One way to improve this further might be to attach the scrub suit on the assistant.

The minor surgical kit had the best storing capabilities, logistics of the instrument and maintenance of the sterile field. If the minor surgical kit could be deployed closer to the operating site in a similar way to the surgical tray it might be the best solution.[24]

A prototype of a surgical workstation has been developed and tested in parabolic flight by NASA in the early 90's. The operating table had a waist restraint for the patient as well as a restraint on the side for the operating physician. The surface of the table was made of carbon fibre (transparent to radiography) and it had rails along the sides to provide fastening points for life supporting equipment as well as drapes by using clamps. The operating table had two hinges of the boards, one above and one below the patient's buttocks, so that it could be folded in an upright position.

The surgeon was restrained to a floor grid during the test. The deck grid was made by a 12.5 mm thick sheet of aluminium perforated with circular holes. The holes were about 57 mm in diameter to match a plastic hemisphere that was attached by a steel post under each shoe of the surgeon. The shoes could then be hooked into the holes of the grid.

There is little information about the surgical workstation. In NASA's report from October 1992 the conclusion was that the system worked satisfactorily when it comes to the restraints (except for vigorous traction and hands on chest compressions). Nothing is mentioned about the weight or the size of the table. From looking at pictures it looks huge and bulky. There is nothing in the design that would suggest that it could be folded into less spacious dimensions for storage.[4]

In case of cardiac arrest heart compressions need to be managed when defibrillation fails. To provide chest compressions manually are difficult in microgravity. Normally in terrestrial practice the operator use the weight of his upper body to apply the compression force when performing CPR.

This is not possible in microgravity which means that only arm force can be used when doing compressions manually. A nylon strap that goes behind the operators back has been used to manage the counteract force from the patient. This is however a rather inefficient and fatiguing method which is why a lever was designed to attach to the rail at either side of the surgical work station.[4] This procedure might be improved further with a mechanical heart compression device like the LUCAS™* system (Fig. 8).

The crew on a long term mission might also suffer from dental injuries which is why experiments of extraction of teeth from a dental manikin have been made during parabolic flight. The result from the study was successful in that all participants managed to maintain stability and apply the necessary force to extract teeth in all locations of the mouth.[4]

After consulting the Faculty of Odontology in Malmö the conclusion was that dental caries in cavities would (if possible) be scraped off. Caries removal agents like Carisolve® gel (Fig. 27) would then be applied in a similar way to the dental procedures in developing countries, where there are no dental drills. Furthermore, a dental drill would prove difficult to use in microgravity in which small particles of water, debris and biological fluids would easily contaminating the cabin atmosphere.

In case of orthopedic injuries limb traction and immobilization of fractures has to be considered. Traction of limbs have proved difficult in microgravity. It is usually hard for the physician to create enough traction force for placing splints since it is not possible to use the weight of the body to pull. If the operator lacks firm restraints he or she will be pushed towards the patient by reactive forces and it will be difficult to maintain stability.

Results from testing conventional casting and splinting techniques shows that it is much more complicated in microgravity. Handling sharp instruments for trimming the casting devices proved to be difficult as well as preventing droplets of water and plaster from escaping into the cabin.

It has been suggested that plaster castings might be performed in the shower but it would probably not eliminate minor contamination.

Thermoplastic splints was heated by using a microwave oven instead of heating water to 54°C to activate the splint which poses a danger in the microgravity environment. This procedure is, however, still complicated and limited by the size of the splints.

Pneumatic splints were also considered for immobilization but the device in this case leaked in flight and failed the test. There is no report of this being a conceivable solution. or not.

## RESEARCH

The first part of the research was carried out with NASA at JSC in Houston during a period of three weeks. It involved studies of the work and life in space. Also medical hardware was reviewed and discussed with both flight surgeons and medical training personnel.

The research continued in Sweden at Lund Rescue Department where ambulatory equipment like emergency stretchers, first aid supplies and CPR equipment was assessed. The Faculty of Odontology in Malmö was consulted for dental procedures and Kristianstad Central Hospital (CSK) for medical hardware. Most of the work, regarding medical issues, was done at Lund University Hospital, both at the Department of Anaesthesia and Intensive Care (Centraloperation 1) and at Practicum – a training facility at the hospital.

*Fig. 4. CMRS at NASA's training facility at JSC.*

The Crew Medical Restraint System, CMRS (Fig. 4) is a part of the medical equipment on ISS. This stretcher serves as a platform to restrain the patient during CPR and for electrical isolation from the interior of the space station when defibrillating. It is not intended for surgery of any kind.

The CMRS was originally the reason for the thesis; there was a need for improvements of the stretcher which eventually meant designing a completely new system with a focus on future surgery.

The CMRS is quite small; 137.2*35.5*27.7cm when deployed and 69.9*36.2*10.1cm when stowed. The weight is significant considering the size; 18.2kg. The boards are made of a resin called Ultem® 2300 and the legs and attachment points in solid aluminium. The Ultem® 2300 is a rigid, flame resistant material and it has a low dielectric constant.

However, with a density of 1.51g/cm$^3$ the weight is far from optimized for sending into LEO.[8]

*Fig. 5. CMRS seat tracks, restraints and hinge.*

The solid aluminium seat tracks/fastening points of the stretcher (Fig. 5) are normally used for seats in Boeing airplanes according to medical training personnel at Wyle Laboratories* (from personal communication).

The straps of the CMRS are made in Nomex™ webbing. The long strap (Fig. 4) goes behind the CMO's back to counteract the reactive forces created when performing "hands on" chest compressions. When it comes to chest compressions, there was another problem; the hinge in the middle tends to bend down which makes the procedure less efficient.

There is also a concern for pinch injuries from the hinge (Fig. 5) when the stretcher is folded. The board material has good electrical isolating properties which is good for defibrillating patients. A flaw was however discovered in 2002; the boards had cracks in the surface from the screws coming through from underneath, which created a possibility for electrical conduction to the ISS structure. This was temporarily solved by applying Kapton® tape on the on-orbit CMRS.[8]

*Fig. 6. Ambulance stretcher at Lund Rescue Department.*

This ambulance stretcher (Fig. 6) was a part of the equipment of Lund Rescue Department. The legs fold under the stretcher so it may be pushed directly into the ambulance.

The height can be adjusted to various levels and the top stretcher can be lifted off and carried away. The back rest of the stretcher uses gas suspension so it may be raised or lowered into any angle.



*Fig. 7. Spine board.*

*Fig. 8. LUCAS™ heart resuscitation system.*

The spine board (Fig. 7) is a type of rigid emergency stretcher with the possibility to immobilize and move patients with suspected spinal injuries in a safe way. It has several attachment points to make the restraints secure enough to turn the patient upside down in case of vomiting. The attachment points also serve as handles for carrying. Most spine boards are radiolucent so that the patient may undergo radiography without any interference from the board.

The LUCAS™ (Fig. 8) is used to perform chest compressions on adult patients with cardiac arrest. It runs on compressed air and can produce 100 compressions per minute. It uses a suction cup which not only compresses the chest but also lifts it to stimulate the breathing. The ambulance personnel are free to perform medication, defibrillation and ventilation during the transport to the hospital as the LUCAS™ produces chest compressions.

*Fig. 9. Strap arrangement on ambulance stretcher.*

*Fig. 10. Planar operating table at Lund University Hospital.*

The dressed stretcher in figure 9 shows the strap configuration of the spine board and a mattress which also can be used to lift the patient

The research continued in Lund University Hospital at the surgical ward where various operating tables and accessories were studied.



*Fig. 11. Multi purpose operating table with arm rests.*

*Fig. 12. Operating table with leg rest.*

There were three different models in use;

1) figure 10 is a type of planar table. This operating table is made in a one piece slider which makes it possible to set the table in a far out position of the stand.

2) Figure 11, 12 is a multi purpose operating table and it can be adjusted for many operational settings.

*Fig. 13. Leg rests.*

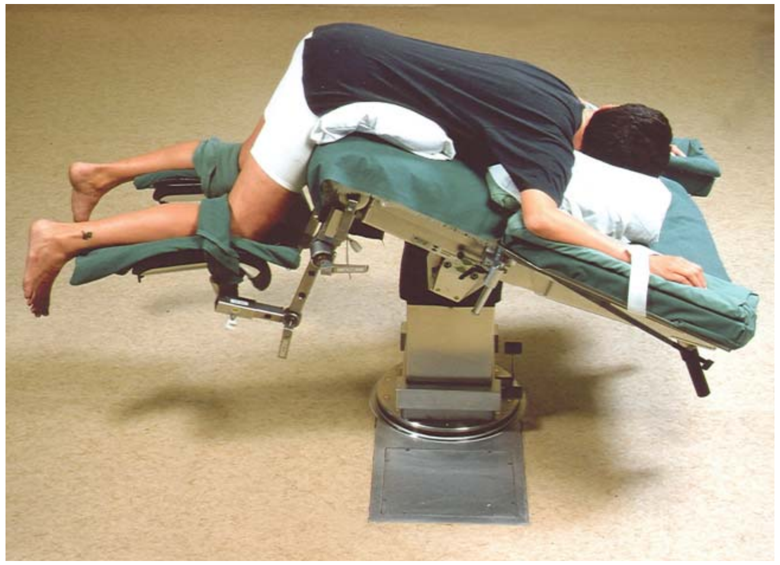


*Fig. 14. Multi purpose table for special operating settings. (Courtesy from Lund University Hospital).*

It can be slanted in the middle and the leg plates can be disassembled and replaced with other types of leg rests (Fig. 13). The leg rests consist of three different types, depending on what table that is being used and the operating procedure.

3) The table in figure 14 is used for special, kneeling, abdominal positions and it is somewhat similar to the second table. It uses a different kind



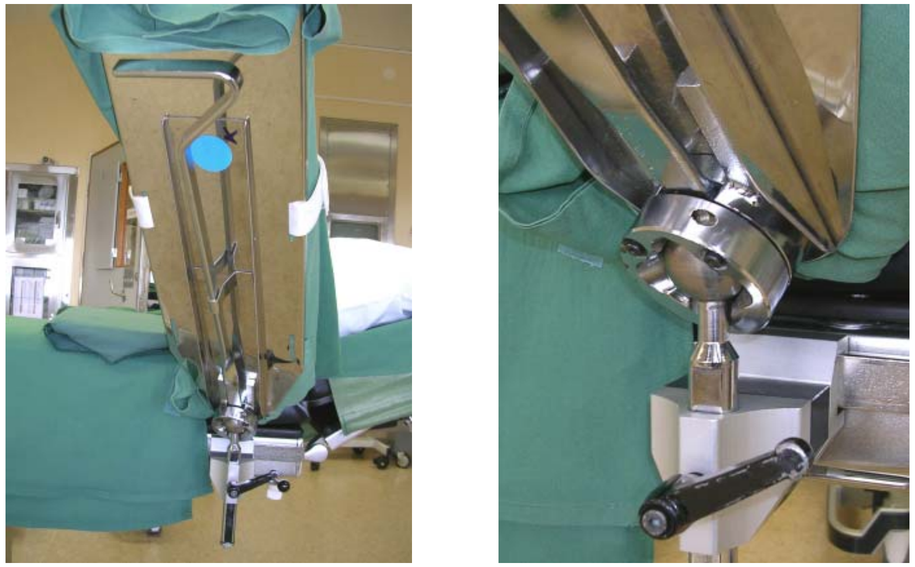


*Fig. 15. Arm rest with quick release ball joint.*

*Fig. 16. Arm rest.*

of leg rests and is primarily used for laparoscopic procedures and surgery of the adrenal glands.* Figure 14 also illustrates a dressed table with padding for the hip, head, arms and legs. This is crucial to avoid any pressure and circulation failure which in turn can lead to severe, permanent neural injuries. The arm rest in figure 15 uses a spring loaded ball joint as a quick lock mechanism for ease of use. Figure 16 is another type of arm rest for forearms, also using a ball joint for quick adjustments.

*Fig. 17. Arm table.*

*Fig. 18. Silicone gel pad.*

An arm table (Fig. 17) was an additional attachment, used to provide better ergonomics for the surgeon when performing arm and hand surgery. The table attaches to the side rail of the operating table.

The silicone gel pad in figure 18 has excellent damping properties and thermal isolating ability. It is used under the patient to prevent pressure damages. This material is used in various shapes like mattresses,



*Fig. 19. Eccentric lever joint.*

*Fig. 20. Eccentric lever joints on operating table.*

lumbar supports, head/neck supports. Figures 19 and 20 show a pair of eccentric lever joints. The lever has got a locking button so it will not unlock by mistake. These types of joints are commonly used in operating tables since they are extremely strong and reliable.

*Fig. 21. Transport trolley for operating table.*

Figure 21 and 22 shows the trolley to transport the operating table. The trolley carries oxygen support and it is designed to place the table on the electro-hydraulic lift (Fig. 10-12, 14). The lift works like a holder/stand for the operating table and can be tilted in various positions by using a remote control.

MIS is a promising operation method for surgery in space and it was important to try out the tools to gather as much information as possible about working positions, workflow and the level of dexterity needed to handle the instruments.

The endoscopic instruments in figure 23 are from Practicum at Lund Unviversity Hospital. The instrument in the left hand is a camera and the one in the right hand is a kind of forceps for grasping. The box simulates an abdomen in this exercise. The camera is connected to a monitor that displays the operating site.

*Fig. 22. Planar operating table on trolley.*

*Fig. 23. Laparoscopic exercise at Practicum training facility.*

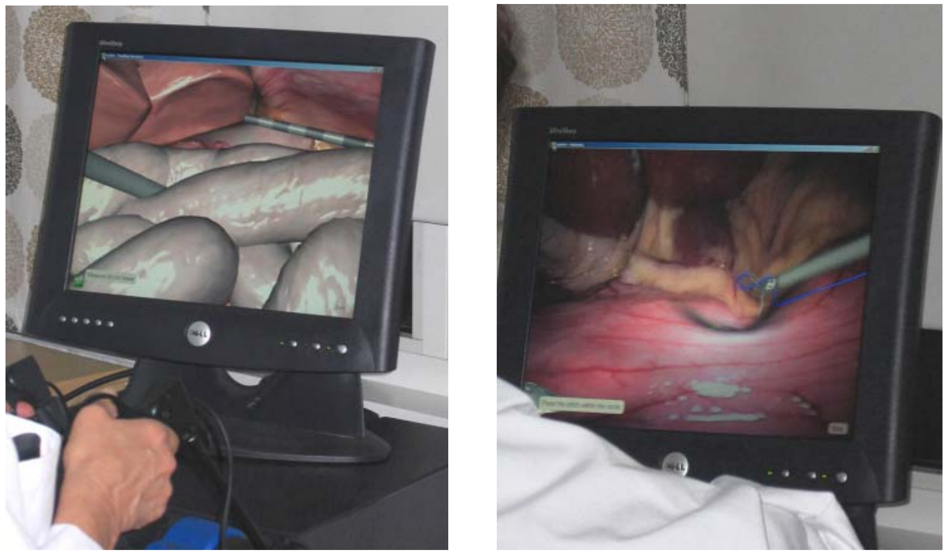


*Fig. 24. Laparoscopic virtual reality simulations.*

*Fig. 25. Dental instruments and tray at Faculty of Odontology in Malmö.*

Virtual reality simulations of endoscopic surgery are also conducted at Practicum (Fig. 24). Different training programs can be uploaded to simulate various operating procedures.

The instrument tray in figure 25 shows dental instruments from the Faculty of Odontology in Malmö. The dental chair (Fig. 26) was assessed along with some of the common, dental instruments (Fig. 27) that might be



*Fig. 26. Dental chair.*


*Fig. 27. Common dental instruments and Carisolve® gel.*

used in microgravity. The conclusion after reviewing the equipment was that their function would have little impact on the design of the operating table. Dental injuries would constitute a minor roll in the overall picture and would not imply any particular quality of the design.

# OPERATING POSITIONS

The reasons for a particular operating position can be many. The safety of the patient is perhaps the most important aspect, especially if the patient is under anaesthesia and unable to reposition himself. If a patient is subjected to a hard surface, it can restrict blood circulation and cause severe neural injuries. This can be avoided by using cushioning in exposed areas and not placing the patient in an unnatural position.

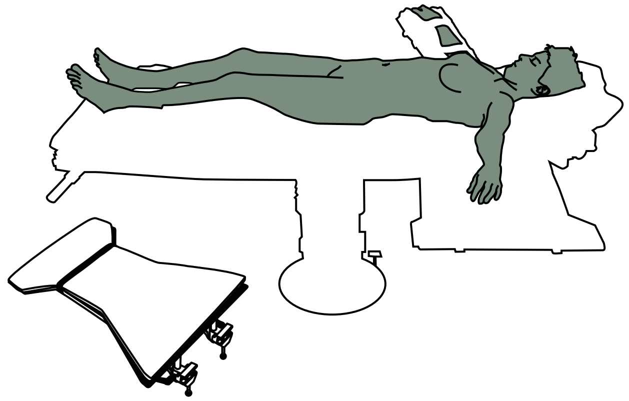
The operating position must also provide good accessibility for the surgeon. Some operating positions manipulate the body of the patient into a particular physiologic posture to facilitate the procedure. One example of this is the Trendelenburg position (Fig. 28) where the patient is placed in an inclined position. This position can be used for laparoscopic surgery in the lower abdomen to retract the intestines to improve visualization. It can also be used in order to prevent an air embolism* from reaching the brain.

The Trendelenburg position uses gravitational force and is therefore ineffective in microgravity. There are also operating positions like the sitting position (Fig. 28) which is normally not used in 1 G practice nowadays. The reason for this is a concern of air embolism formation due to the pressure differentiation of the heart area in contrast to the area above the heart, when sitting in a upright position.  This condition will not cause any problem in microgravity.

It is important to learn those differences in order to understand the design potentials in microgravity.

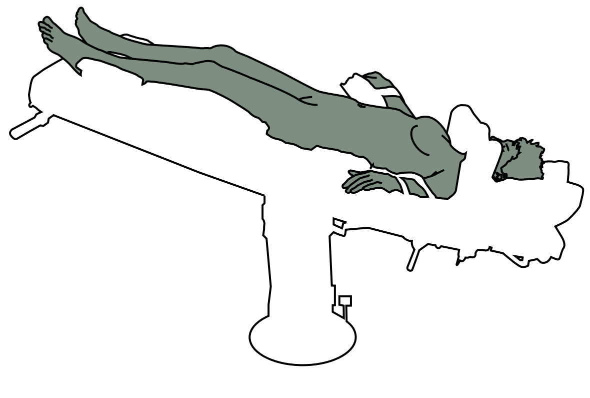
The working position of the surgeon is also important to establish the best ergonomic posture throughout the procedure. Equipment like the arm table (Fig. 17) make long operating times more comfortable.

Equipment like x-ray tools, orthopaedic accessories for traction treatment etc, might also influence the position of the patient as well as the function of the operating table. The Rizzler bows in the slanted, supine* position (Fig. 28) for example are used to fasten surgical hooks to retract tissue during open surgery.



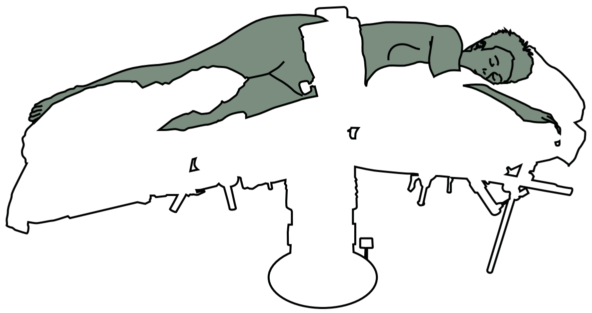
**Supine position with arm table.**

**Slanted, supine position with Rizzler bows.**

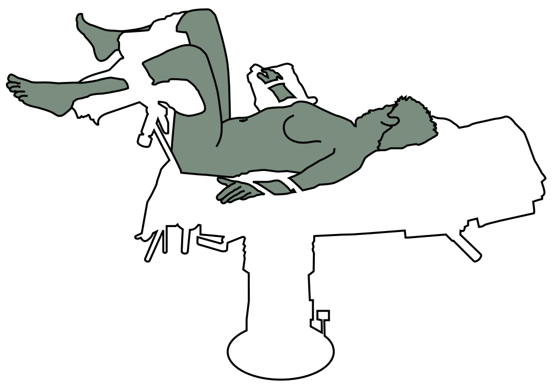


**Trendelenburg position.**

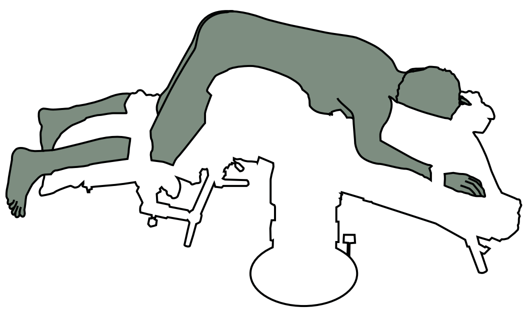
*Fig. 28. Examples of different operating positions of patient in terrestrial practice.*



**Lying on the side.**



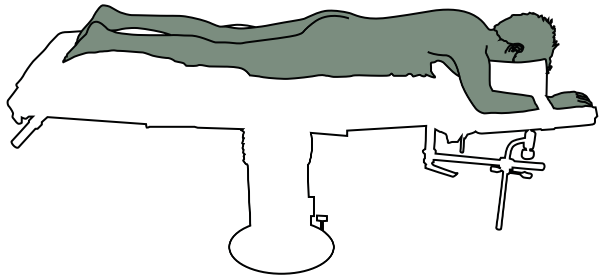
**Urologic or gynaecological position.**



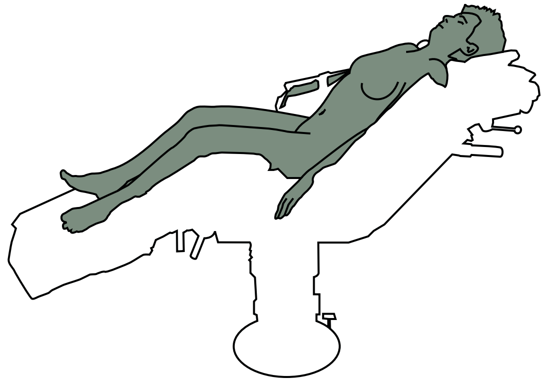
**Proctology prone or “A la Vache” position.**







**Abdominal position.**



**Sitting position.**

# FUNCTION ANALYSIS

In order to summarize the information of the research, a function analysis was made. By doing this it is possible to highlight a number of qualities and compare them to make a conclusion of their importance of the design.

**Patient restraints.** Above all, the purpose of the 0GSW is to restrain the patient in microgravity. This might be in similar way to the CMRS but with a focus on surgery.

**Ergonomic qualities** both for the patient to minimize the risk of injuries, and to make a comfortable working position of the surgeon. The operating table also needs to be adjustable for different body sizes (according to NASA standards).

**Easy to use.** The table has to be easy to use so it can be deployed in a quick way. Adjustment for body size, procedure and equipment has to be intuitive.

**Operating position.** The table must allow adjustments for the required operating positions and be compatible with additional medical equipment.

**Lightweight construction.** Lightweight materials are important to minimize the cost of sending the equipment into orbit.

**Good storage capability** is of major importance since the compartment on board the spacecraft is very limited.

**Aseptic qualities** must be obtained by using aseptic materials and surfaces which are easy to clean. This is an important quality to avoid bacterial contamination during surgery.

**Electrical isolation** of the table is important when performing defibrillation to prevent charges from getting in contact with cabin interior.

**NASA regulation** of equipment in flight needs to be fulfilled. This means that the table needs to be rigid enough to withstand a load of 60kg and that it has to be flame resistant.

**Radiolucent.** There might be a need to perform radiography with the patient restrained on the table. In this case the OGSW has to be radiolucent.

**Spinal stabilization** is also a desired quality in case of a injured back or neck. Orthopaedic procedures might require immobilization of the body in a similar way to the spine board.

## SKETCHES

*Fig. 29. Concept A, mounting scenario.*

The following section explains the initial phase of the design process by sketching. These first sketches (concept A) show an idea of making a stretcher-like table made of several pipe modules that are tied together with a kind of lacing (Fig. 29). It consists of a stretcher construction and a mattress top (similar to a Therm-a-rest® mattress) which is lightweight and not too soft for CPR. It can be dismounted and rolled into a flat package for storage (Fig 30).

The drawback of this concept is the weak construction when performing chest compressions even with the reinforcement beams. The procedure to deploy it is also far too complicated in an emergency situation.

*Fig. 30. Concept A with mattress.*

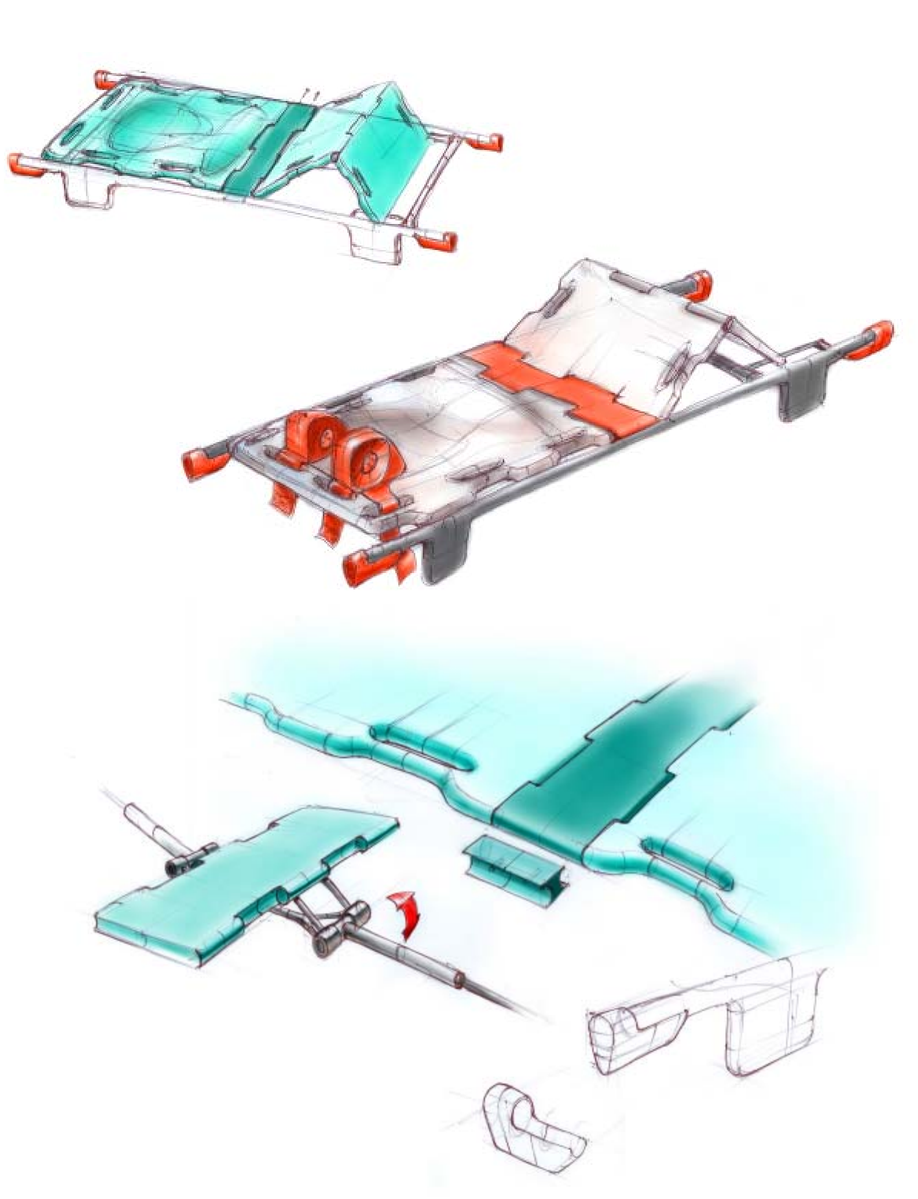


*Fig. 31. Concept B.*

Concept B (Fig. 31) is basically a foldable spine board. The function is similar to the ambulance stretcher in that it can place the patient in an upright position by using gas suspension for the back and leg boards.

This concept was refined into concept B2 (Fig. 32) where the handles form a continuous frame around the board. The conclusion was that handles are only practical for lifting in 1 G, not in microgravity. The B2 concept can be attached to the wall by a sliding beam mounted on the



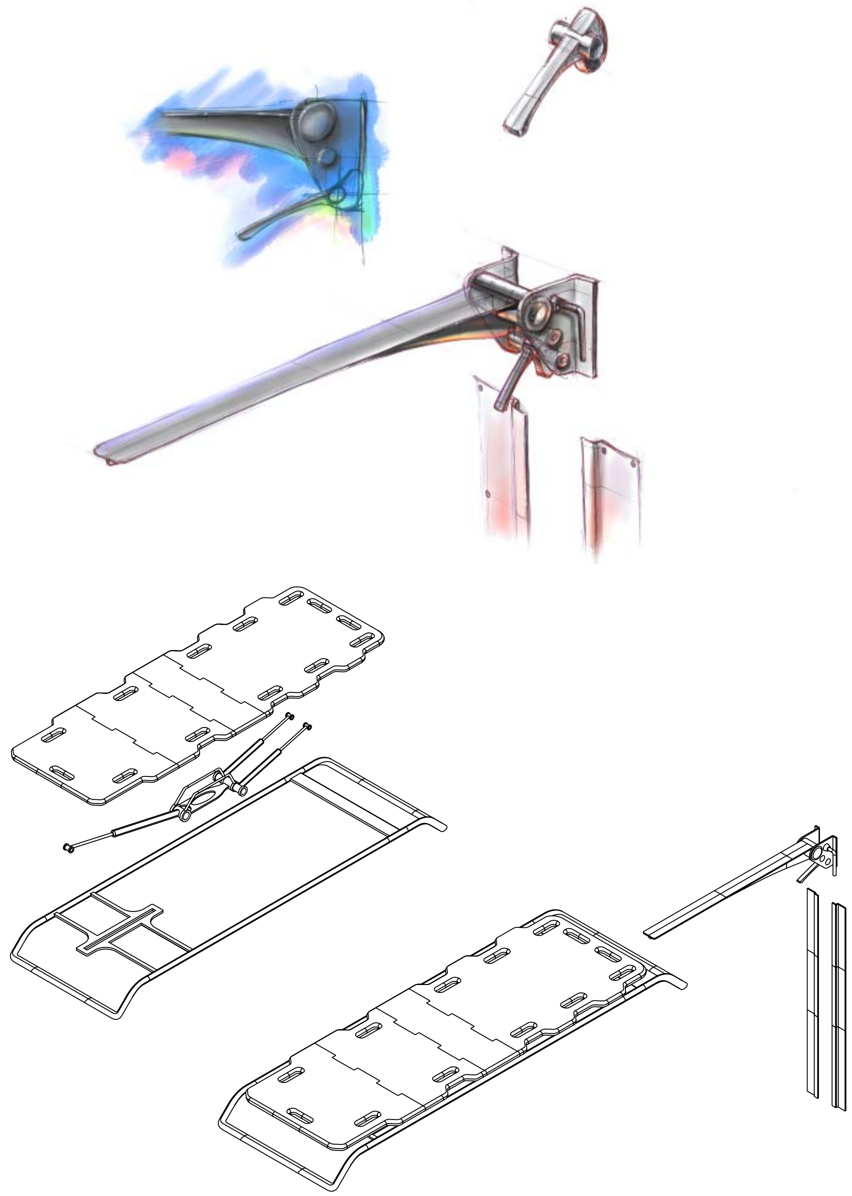
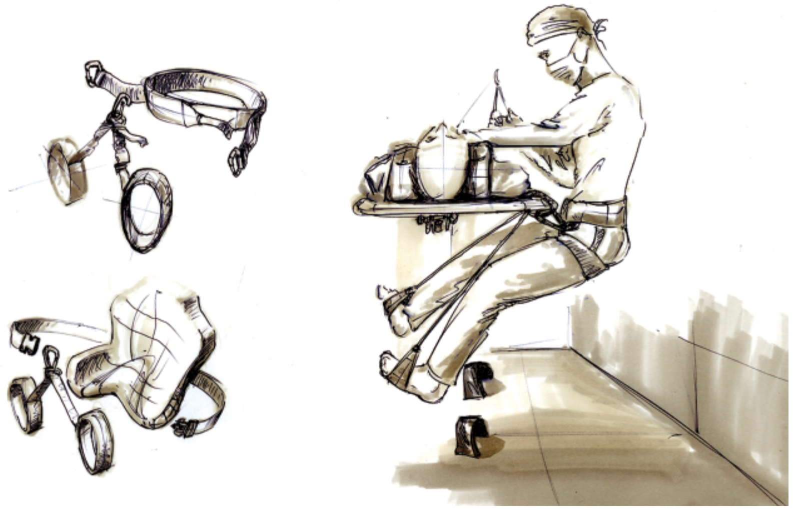


*Fig. 32. Concept B2 with sliding beam.*

wall (Fig. 32). The beam moves along a track so the height from the floor to the table can be adjusted.

The disadvantage by this concept is its size since it cannot be disassembled or folded into a small package. It resembles a stretcher rather than an operating table which makes it unsuitable for some operating positions. It is also good if hinges can be avoided because of the pinch hazard and the difficulty to clean.



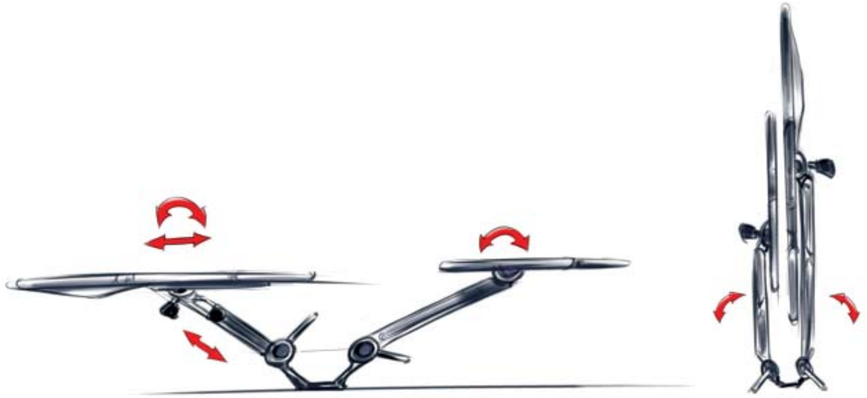


*Fig. 33. Operating scenario for concept B2.*
*Fig. 34. Concept C, degrees of freedom.*

The first sketch illustrates an operating scenario of concept B2 where the surgeon is restrained to the side of the table by a harness (Fig. 33).

The idea behind the next concept (C) (Fig. 34) was to strip the operating table of as much material as possible to make the construction smaller and lightweight. This was accomplished by not having any board material for the legs or the lumbar back. The design is essentially a two point restraining platform for chest and hip.

The table is divided into two boards; one for the bottom and one for the head and shoulders. The sketch shows the adjustment directions of the two boards which is important for the table to fit different body sizes. This design will also fold which makes it a lot smaller than previous “stretcher-like” concepts. The detail sketches (Fig. 35) show different proposals



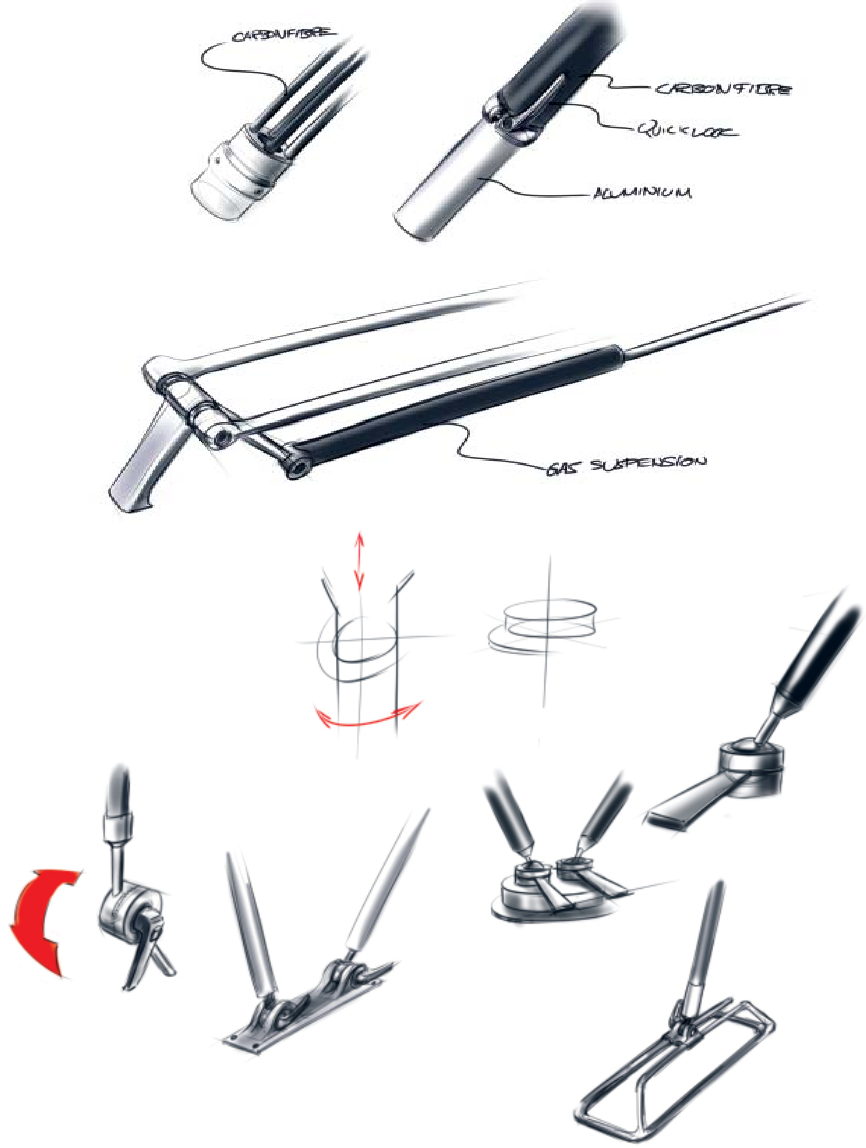



*Fig. 35. Arms and joints for concept C.*

for mechanical solutions of the “arms”, fastening point and joints. Gas suspension of the arms might allow good adjustment. However, if any part breaks there will be little room for spare parts. Carbon fibre rods or tubes are on the other hand both strong and light.

Ball joints with a quick lock mechanism were proposed for easy adjustment of the arms. The problem with a ball joint was to create enough friction to make the joint strong enough for this application. A joint of this type would be too big and heavy. An eccentric lever joint (Fig. 19, 20) proved to be a better solution in this case.

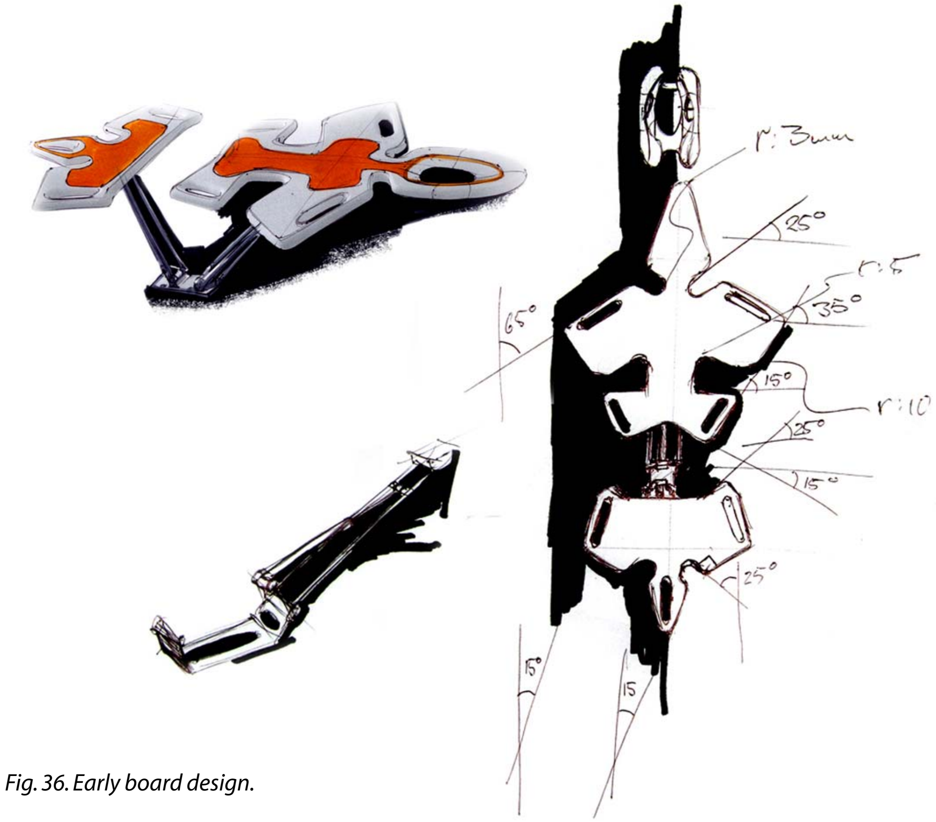


*Fig. 36. Early board design.*

Concept C was refined and the contour of the boards (Fig. 36) was designed with the restraints and the human body in mind. A lot of the material has been cut off to minimize the weight. It is basically using the same restraining principle as the spine board. A small sketch model (Fig. 37) in polyurethane foam and aluminium was made to try out the optimal length and angle of the arms in a planar and upright position.

The upright position requires a longer arm of the back board compared to the planar position. To allow this extension, the arm can be telescopic or/and by using a guide rail on the back board.

Some sketches were also made of the restraints as well as some cushioning of the boards (Fig. 37). Cushions can be added as attachments or it can be fully integrated into the board. However, by using integrated padding it might prove difficult maintaining a sterile surface. Furthermore, padding might not be as important in microgravity as in 1 G. The only force the boards oppose to the body in microgravity is the reactive force from the restraints.

Some sketches were also made of head and neck support although this might be considered as additional equipment.

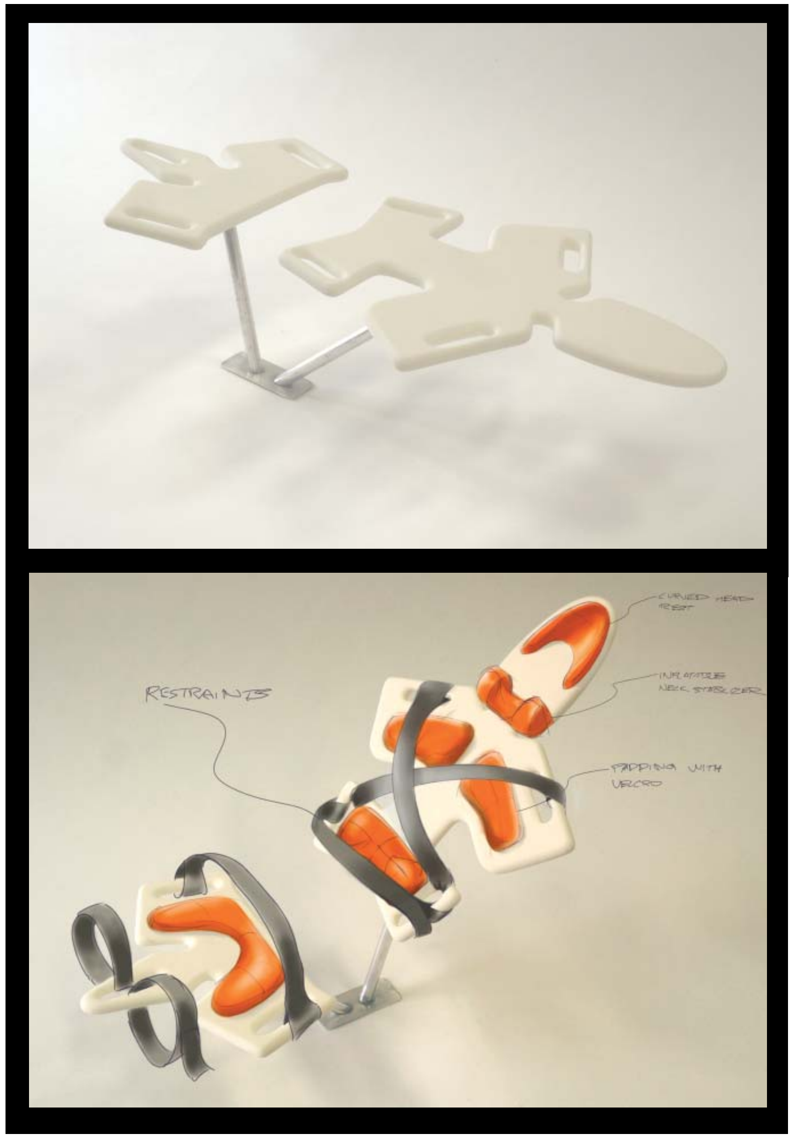



*Fig. 37. Sketch model with straps and paddings.*

Equipment like life monitoring equipment, infusion pumps, respiratory support etc is sometimes attached along the sides of the operating table.

This is practical when moving the patient, but on board a space vessel this type of equipment would probably be stored in a medical rack in a similar way to the one on ISS. This means that no side rails to attach additional equipment is needed.

# 0 G SURGICAL WORKSTATION DESIGN

To optimize the shape of the boards, seven design proposals (Fig. 38) were made before finding a final solution. The original shape of the sketch model concept 1 (C1) evolved to a design with a leg board, C2.

The reason for this is to enable immobilization of the legs in case of fractures. Arms can easily be immobilized along the body. Leg fractures are however more difficult to handle without any rigid support from the table. The leg board can be detached so the patient can be placed in a prone position. The inward curve of the middle board, when the leg board is detached, allows better access during urology/proctology exams.

C1 has an oval hole for the nose and mouth to allow insertion of respiratory tubes in an abdominal position. C2 has a larger opening to avoid pressure damage to the eyes. This was refined into a triangular shape in C3.

The  design of C3 also has a slightly curved top of the seat board which matches the shape of the back board in C4.

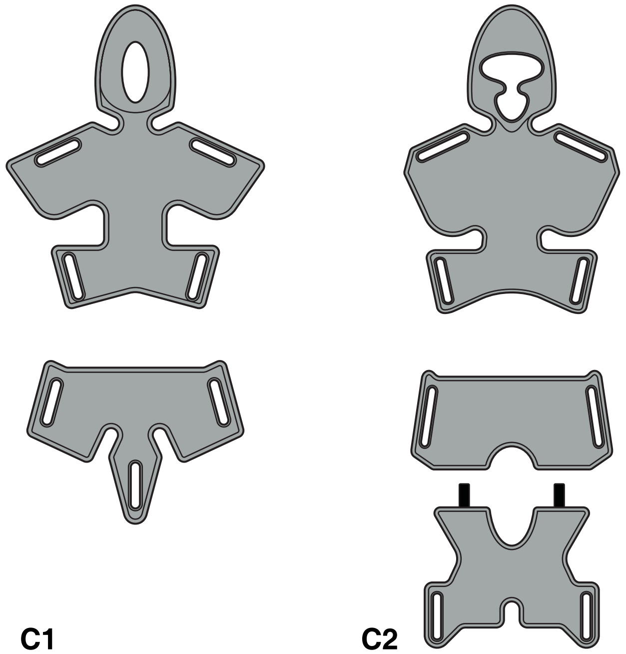



*Fig. 38. Board design.*



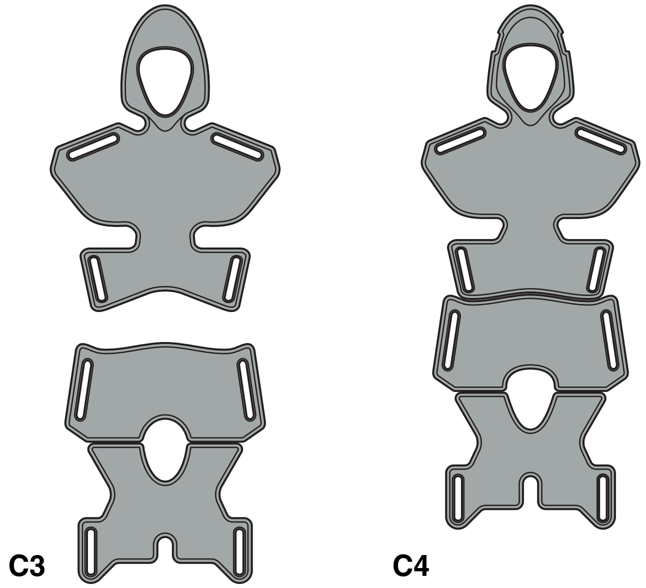



*Fig. 38. (Continued).*

The shape of the head piece in C4 has been modified to attach a head support or padding. The neck area is also a bit wider in C4 than in C3 to make the board stronger.

The hole for the face in C5 was made slightly smaller after it was tried out in scale 1:1. The back board has an inward curvature to make it more comfortable around the shoulders. At this stage there was an idea of integrating the LUCAS™ system to manage CPR. This is why the design of C6 has the widest back board to accommodate fastening rails for the LUCAS™. It was eventually narrowed down in the final design (C7) to fit the actual rail distance.

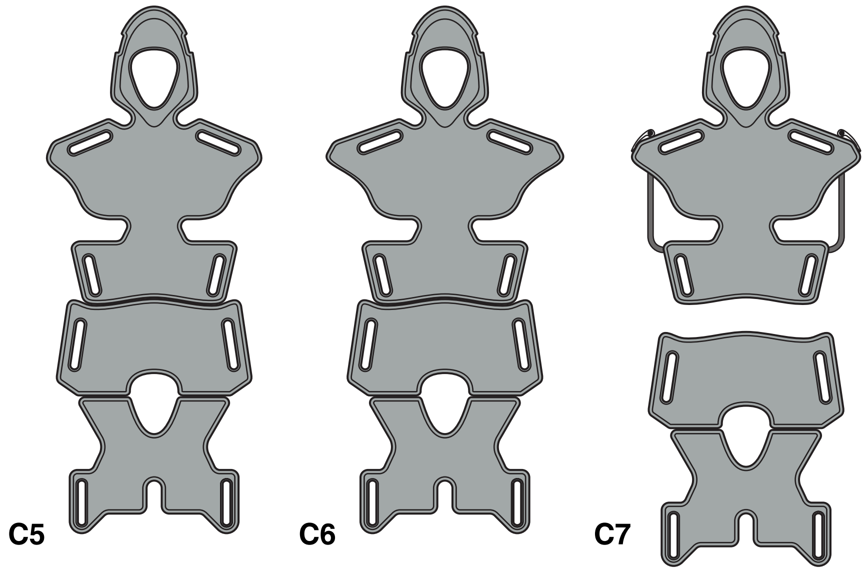



*Fig. 38. (Continued).*

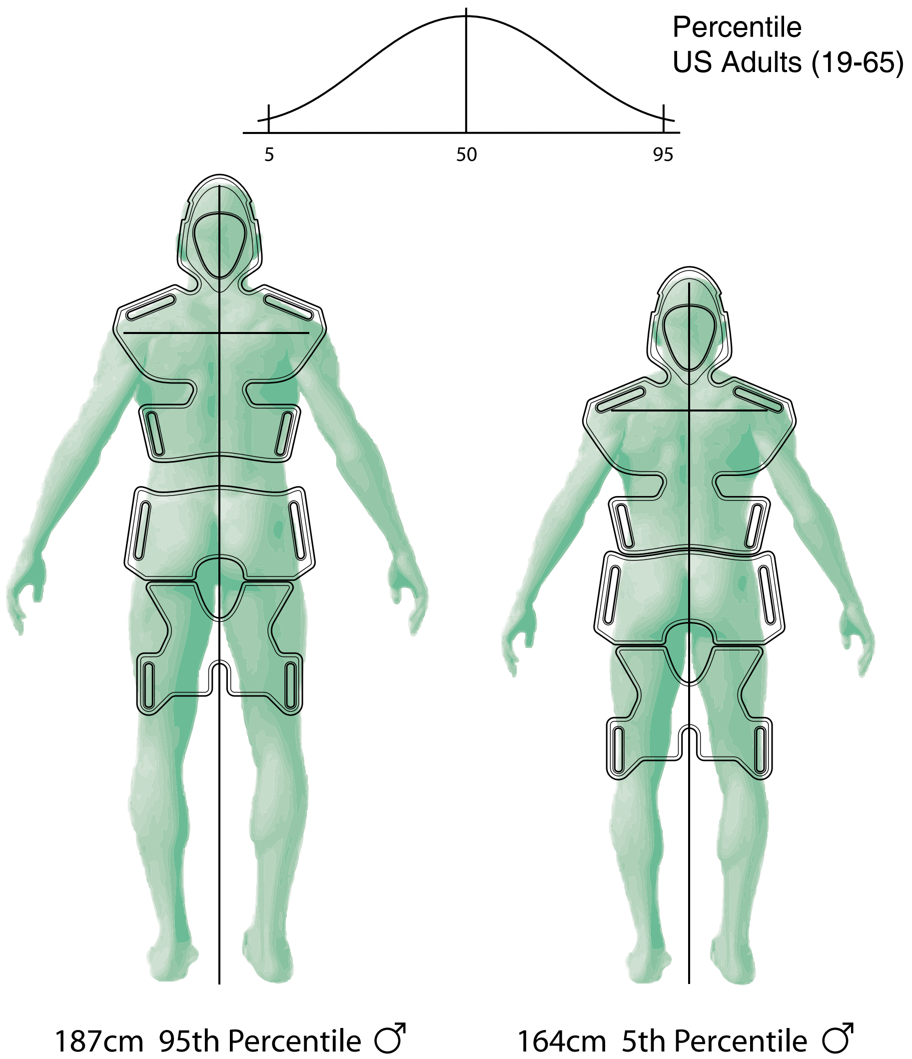



*Fig. 39. Anthropometric study for the C4 concept.*

An anthropometric* study was made to determine the shape, proportion and size of the boards. The statistical data for the study was based on American, male adults in the age of 19 to 65 years, from the 5th to the 95th percentile according to NASA standards.

The main measurements for the boards were the stature, biacromial shoulder width and to some extent the width of the pelvis (biiliac width).

The stature of the 5th percentile is 164cm and 187cm of the 95th percentile. The shoulder width for the 5th percentile is 36.5cm and 43.5cm for the 95th percentile. About 20 percent of all astronauts are women which have to be considered for the design as well.



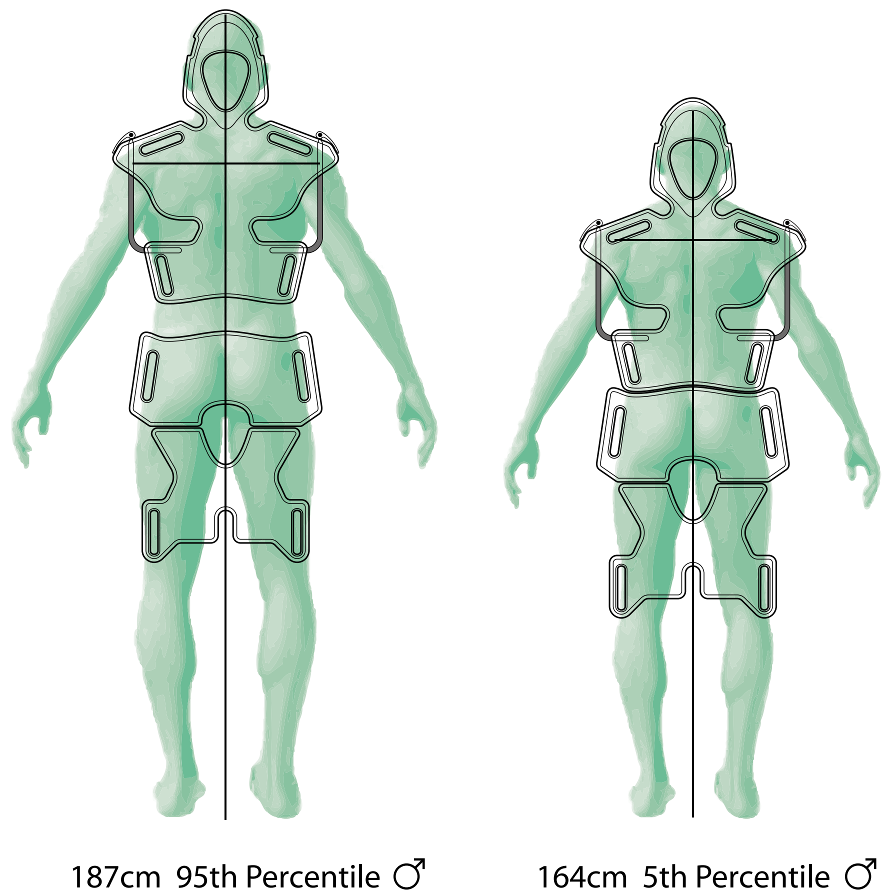



*Fig. 40. Anthropometric study for the C7 concept.*

The conclusion from reviewing the anthropometric data was that the dimensions of the 5th percentile males are basically the same as the 50th percentile females (with the exception of the hips).

The figures show the difference of C4 (Fig. 39) and C7 (Fig. 40) in relation to the human body. The cut for the shoulders of the C7's back board makes it more ergonomic, especially for an abdominal position were the edges of the C4 design could cause damage to nerves and reduce blood circulation.

The fastening tracts for the LUCAS™ does not pose any discomfort for arms or shoulders since they are detachable and used only for CPR.

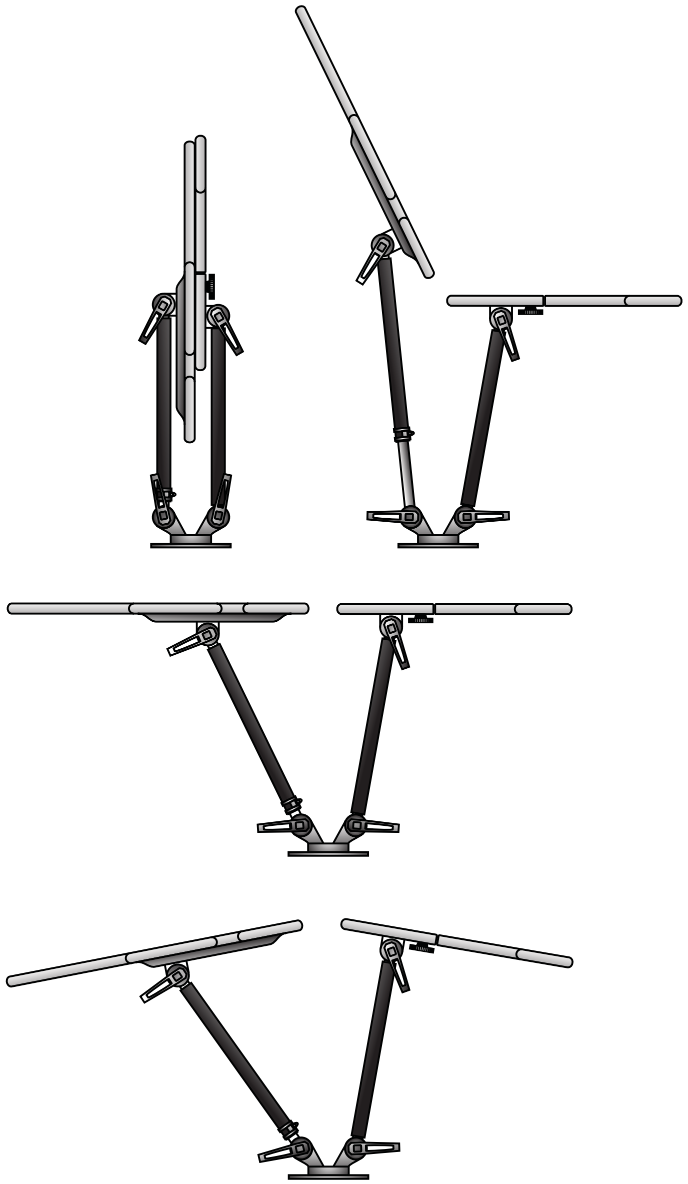


*Fig. 41. Board positions.*

Since it is not known what kind of operating scenarios there will be in the future, it is important to make the 0GSW as versatile as possible.

The back board can be folded upwards to place the patient in an upright position (Fig. 41). When folded, the dimension of the 0GSW is 170*523*978mm and about 523*600*1220-1470mm deployed in planar position (Fig. 42).

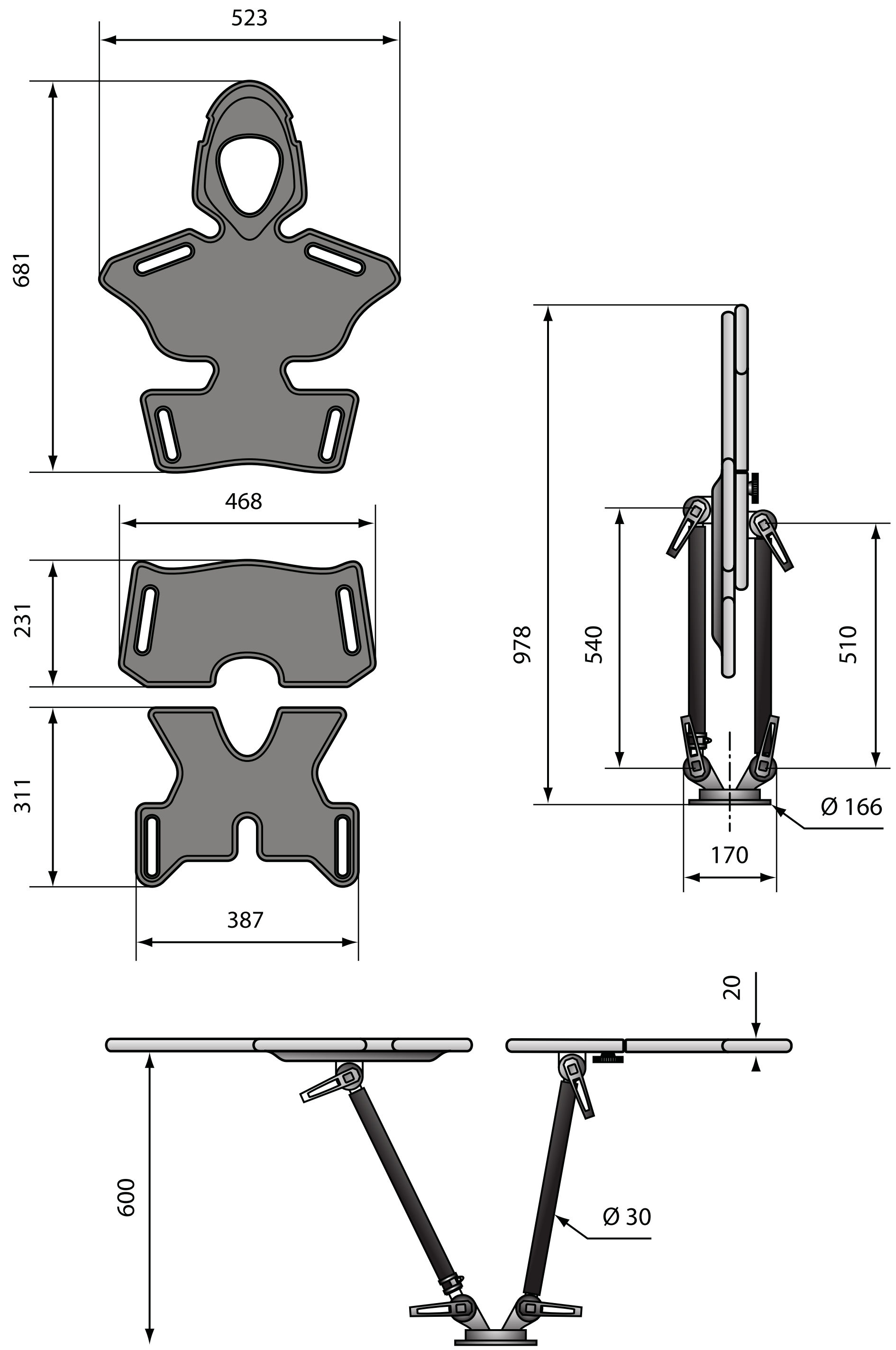



*Fig. 42. 0GSW technical drawing.*

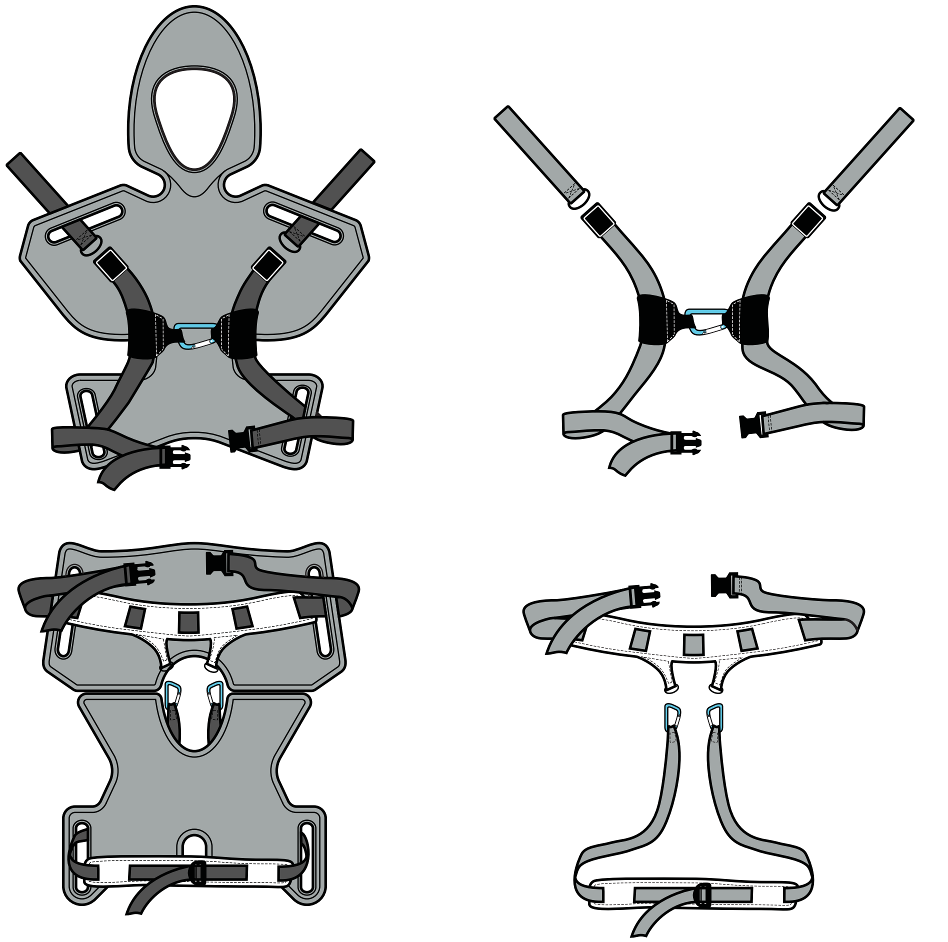


*Fig. 43. 0GSW strap configuration.*

The straps of the board are divided in two restraints; one for the upper body and one for the hip and legs (Fig. 43, 44). The straps of the upper body are similar to the ones on a rucksack and can easily be repositioned depending on the type of procedure. For instance, the carabiner/snap buckle over the chest can be open to clear the chest area for thorax surgery. The strap over the belly can be placed under the table to make room for abdominal surgery, the straps for the legs can be detached along with the board when its not used.

Figure 43 shows the original design of the restraints. This was later refined into the design on the next page. The final design uses Velcro, nylon straps with more secure snap buckles (Fig. 44).



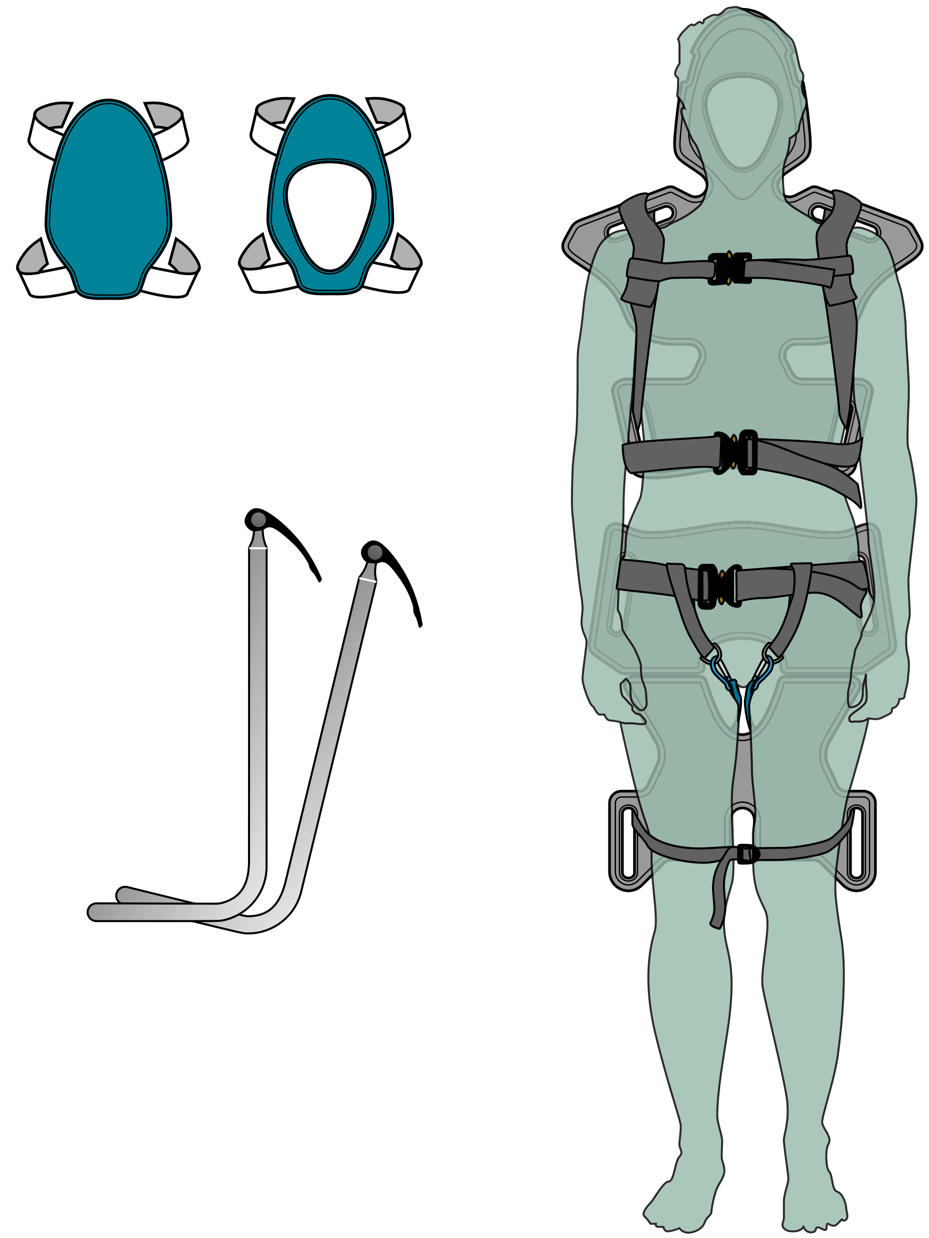


*Fig. 44. Final straps, gel pad and fastening rails for LUCAS™.*

Some padding for the head was also designed in the same material as the silicone gel pads found at the hospital (Fig. 44). The padding sheets are attached around the table with Velcro straps.

Fastening rails for the LUCAS™ were also equipped with quick release skewers to attach to the back side of the board (Fig. 44).

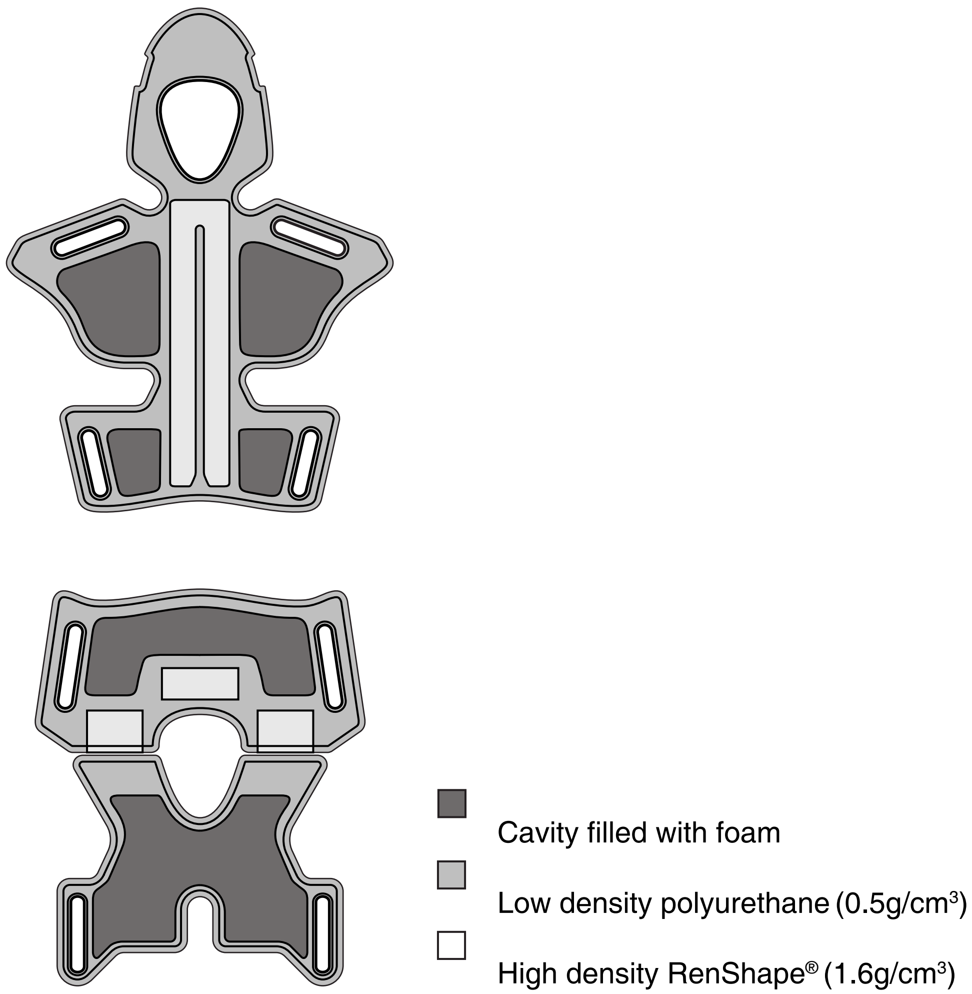



*Fig. 45. Board material.*

The boards of the prototype consist of three different materials to optimize the weight (Fig. 45). The base material for the boards is a polyurethane material with a density of 0.5g/cm$^3$. For areas under great stress like the T-profile guide rail on the back board, slider and joints, a high density, polyurethane material called RenShape® of 1.6g/cm$^3$ was used as reinforcement.

To make the boards lighter the dark gray areas were milled out and filled with construction foam to create a sandwich construction. Rohacell® foam or honeycomb structures will not only make the boards lighter but also stronger. Using a thermoset like the polyurethane/RenShape® material with a low conductivity, the boards are also good for electrical isolation.

## RADIOGRAPHY

*Fig. 46. 0GSW in radiography.*

One other important quality of the boards was for them to be radiolucent to x-rays if the patient would be restrained to the table during the procedure.

Carbon fibre is normally used in tables designed for radiography. Carbon fibre on the other hand, is a highly conductive material and will not be suitable for electrical isolation.

To understand how the polyurethane would behave in radiography, a chest x-ray of the back board was performed at the department of radiography at Lund University Hospital (Fig. 46).

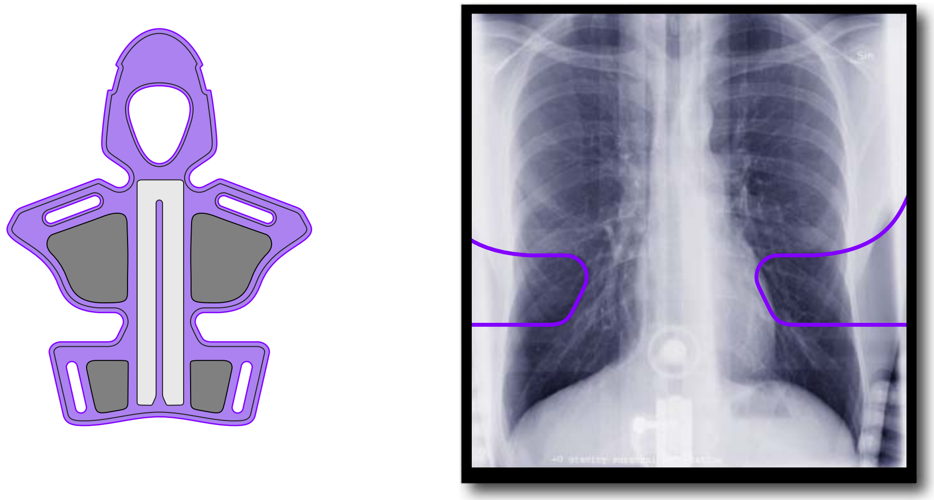


*Fig. 47. Radiography – low density polyurethane.*

The base material of the board displays the contour of the board (Fig. 47). Even though it is visible on the x-ray image, it does not impair the visibility by much.

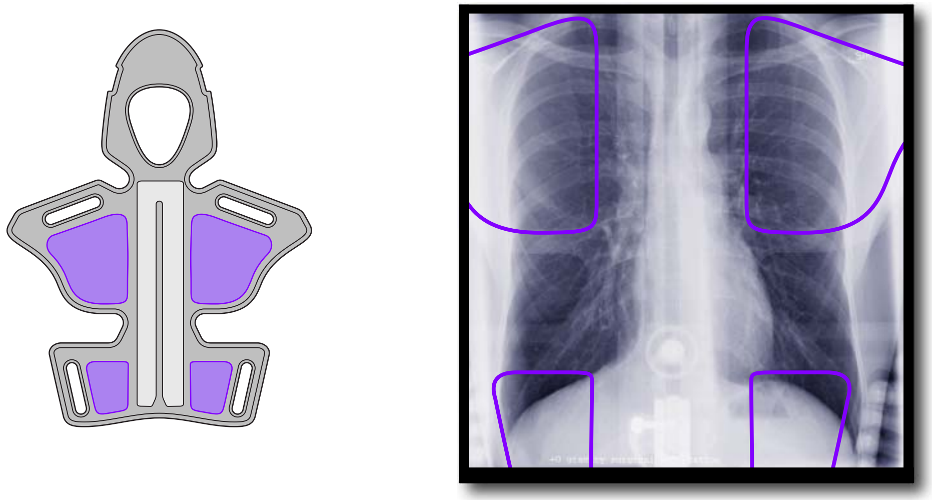


*Fig. 48. Radiography – low density foam.*

The board areas that are filled with foam are almost invisible on the x-ray image allowing even more accurate diagnosing (Fig. 48).



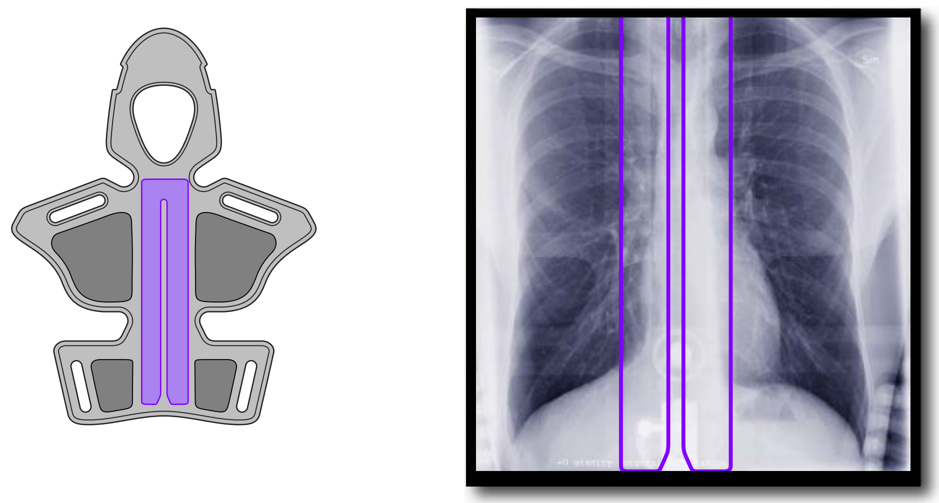


*Fig. 49. Radiography – high density RenShape® polyurethane.*

The high density RenShape® (used in the guide rail) is obviously more visible, showing lighter areas in the image (Fig 49). There is still an advantage to use this material compared to metals which are completely opaque to x-rays. One example of this are the white areas in the lower end of the guide rail that shows the steel and aluminium parts of the joint.

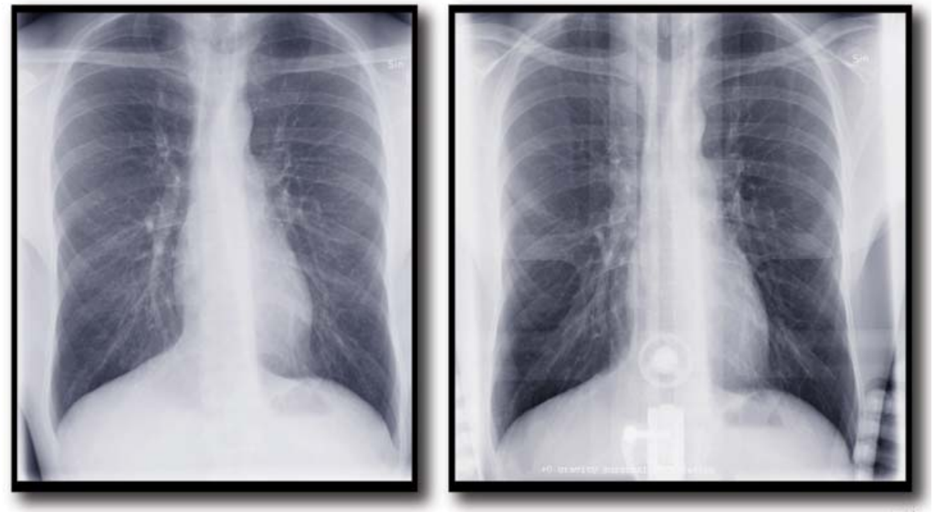


*Fig. 50. To the left; radiography without the 0GSW. To the right; radiogrphy with the 0GSW.*

The conclusion of the experiment is that it is possible to use this kind of board material in radiography. A comparison was made to one image without the board (Fig. 50). The opinion from the medical personnel at the hospital was that the radiolucency is good enough for diagnosing.

## LUCAS™

The LUCAS™ system might be particularly interesting for practice in microgravity since it is not depending on gravity, assuming the patient is restrained to the backboard. As for today, there is no method that can produce chest compression in space as effective as the LUCAS™.

To include the LUCAS™ in the design, a specimen (Fig. 51) was borrowed from Jolife AB, the company that produces the system. The distance between the fastening rails and the placement of the LUCAS™ was adjusted to fit the human body. The rails have the same diameter as the fastening points on the original back board.

The LUCAS™ slides along the fastening rails so that it can be positioned in the right location of the patient. This is an important feature since it is difficult to reposition a patient who is strapped on to the board.

*Fig. 51. LUCAS™ system attached to the 0GSW.*

## GRAVITY STAND

The 0GSW is first and foremost designed for use in microgravity.

However, a stand (Fig. 52) was designed as a complement to the table in low gravity environments like the Moon (1/6 G) or Mars (1/3 G). The design was inspired by telescopic tripod stands.

The advantage of using a construction like this is that it is possible to make it lightweight and small. Because the legs folds against the arms of the table, it will not consume more space than it normally would.

*Fig. 52. 0GSW stand for low gravity procedures.*

## GUIDE RAIL

A double, T-shaped guide rail was designed as a proposal to fasten the 0GSW on the floor or on the wall (Fig.53). The idea was for the operating table to move along the rail to change the height of the table to fit the surgeon in a good way. Since the lower stand of the table is cylindrical, the table can also be rotated on the guide rail which allows the operator to position the patient in a favourable manner.

The construction is essentially made up by two guide rails; one for the stand and one for a slider that locks the stand in position when the lever is pushed down.

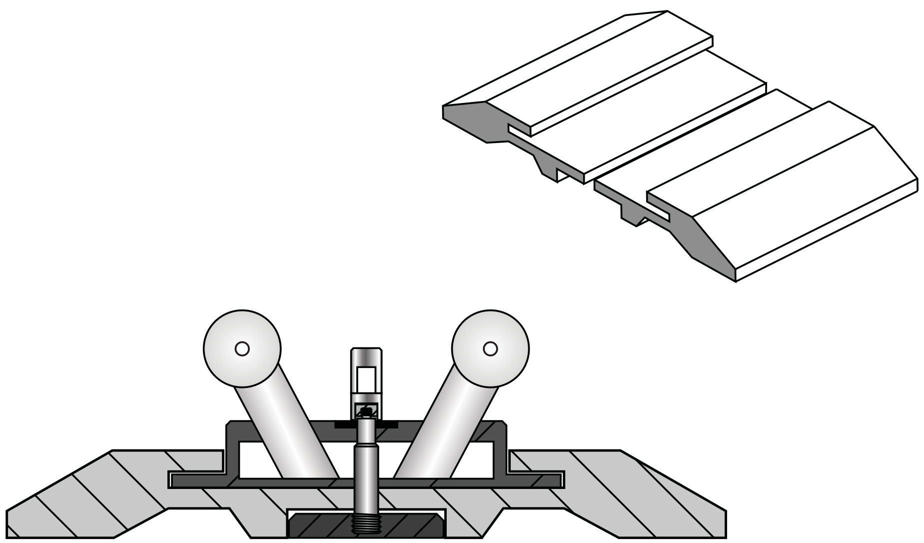


*Fig. 53. Cross section of the guide rail.*

## USAGE SCENARIO

In microgravity there is neither up nor down, no ceiling or floor unless the interior suggests so. The aim was to take advantage of this situation, and try to incorporate it into the design. Figure 54 shows an idea of having the patient facing the surgeon. This would give a better overview of the operating site for the surgeon instead of leaning over the patient.

What kind of padding is required remains to be seen. It depends on how much pressure is generated from the restraints. This must be evaluated in microgravity before any conclusions can be made.

Operating cloths have to be customized for the table to make standard surgical procedures possible. Additional equipment would be confined to the medical rack rather than be attached to the table where it might interfere with the procedure or compromise the sterile field.

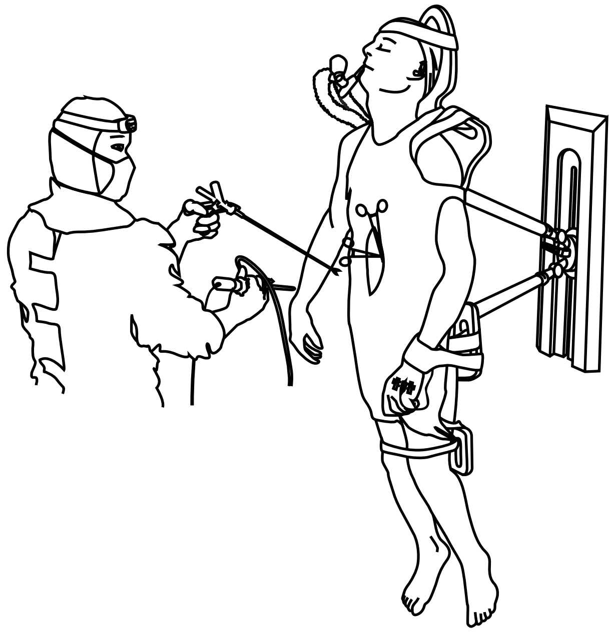
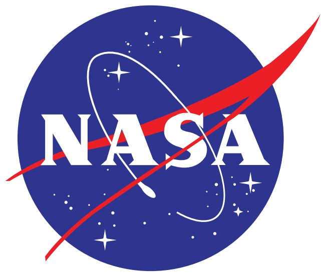


*Fig. 54. Example of 0GSW usage scenario.*

## GRAPHICS

The logotype used by NASA today is the NASA insignia in figure 55 (also known as the “meatball”). It is the original logotype which dates back to 1959. It was replaced by the “worm” logotype (Fig. 55) in 1975 but was reinstated again in 1992. The NASA insignia was difficult to use in its original colours on the 0GSW.

The idea was to show the actual product and not put too much emphasis on the NASA logo. The boards of the 0GSW are painted in a light, blue-gray colour to give a sense of aseptic cleanness. In order to make the logotype gain a subtle appearance a number of colour proposals were composed (Fig. 55, 56). The final concept in figure 56 is in gray scale and with enough contrast not to blend in on the board. On the other hand, it is not strong enough to “jump out”.




*Nasa insignia (meatball).*


*Worm logotype.*

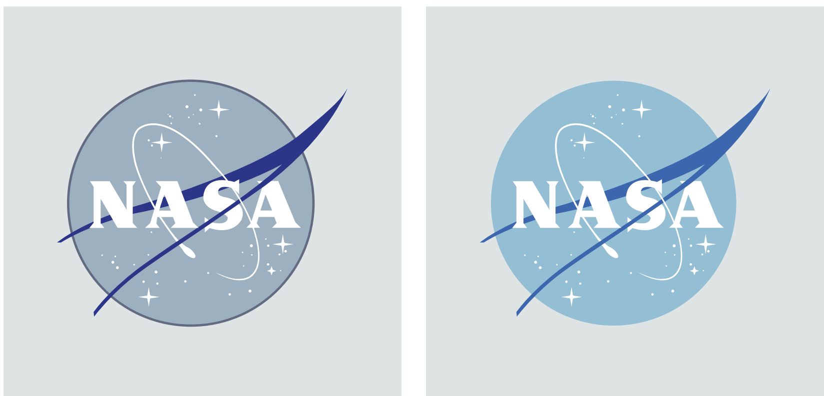
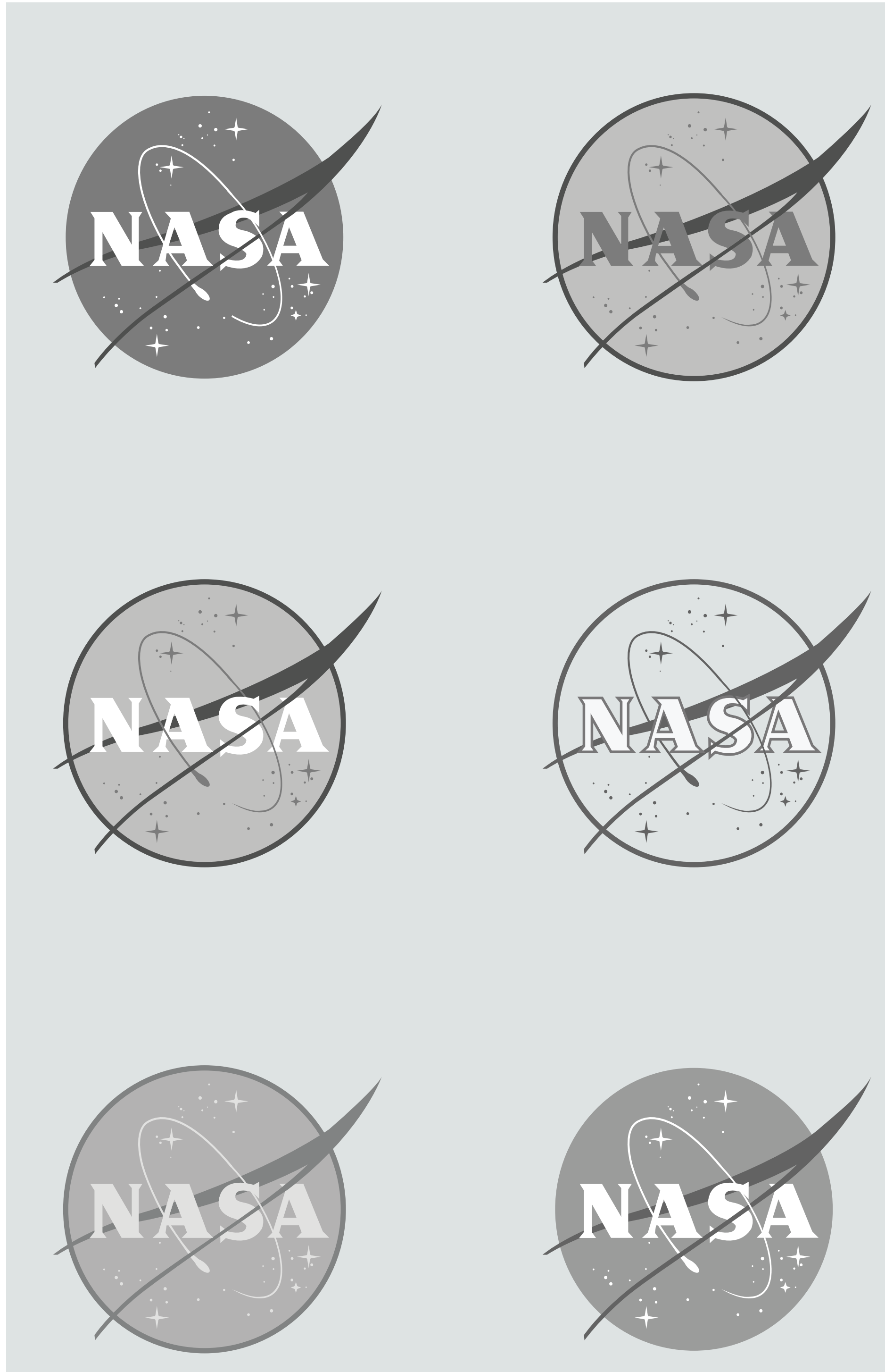



*Fig. 55. Nasa logotypes and the Nasa insignia in blue scale.*




*Final proposal.*

*Fig. 56. Variations in gray scale of the Nasa insignia.*

Inspired by NASA mission marks, a logotype was also designed for the 0GSW (Fig 57). The outer shape of the logo (with the up pointing arrow), represents the astrological symbol of Mars.

The serpents are commonly used in medicine emblems such as the rod of Asclepius* in medicine, and the bowl of Hygeia* in pharmacy. The red cross is also a strong symbol of health care and was included in the design to make an even stronger medical impression. The first design in red was later replaced by a gray one to match the board and the other graphic elements.

Additional text graphics and the designers logotype was placed on the back side of the backboard (Fig. 57).

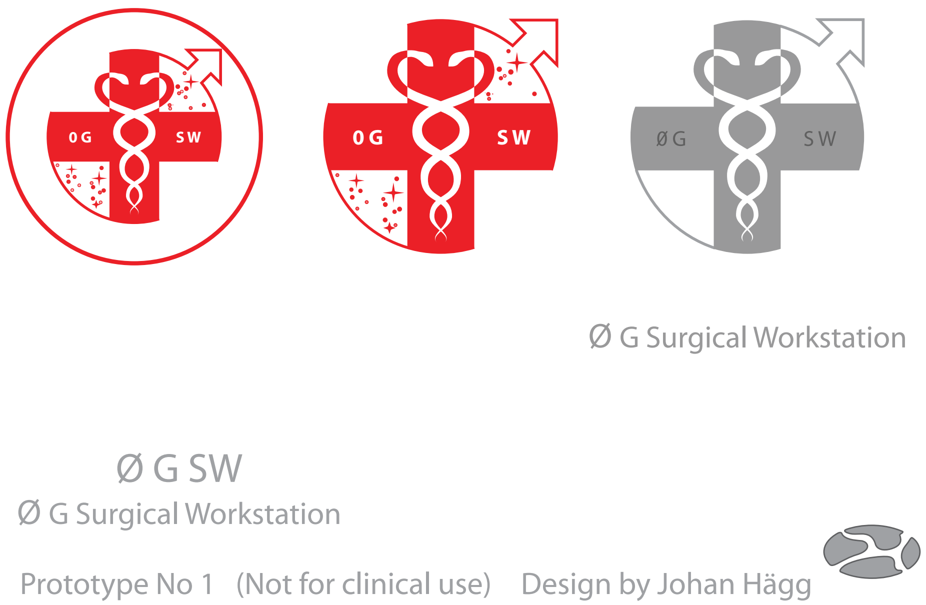



*Fig. 57. 0GSW logotype and additional graphic elements.*

## MOCK-UP REALIZATION

The mock-up/prototype was built over a period of ten weeks in the workshop of Ingvar Kamprad Design Centre (IKDC) at Faculty of Engineering LTH. All work was done in the workshop except for the water-jet cutting of the boards and the paint job. Figure 58 show the boards after the water cutting and after the core was milled out.

The thickness of the boards were about 18mm at this stage and the top boards had a thickness of about 7mm. Before the boards were glued together to form a sandwich construction, the milled areas were filled with a construction foam, shown in figure 59, and after hardening, cut off, shown in figure 60.

*Fig. 58. Boards after milling the compartment for the foam.*

*Fig. 59. Expanded foam.*

*Fig. 60. Foam cut off.*

In figure 61, the tracks for fastening the leg boards are milled. The beige object sticking up on the seat is a part of the joint made in the high density Renshape® material.

After the foot piece was turned, holes were milled to accommodate the two joints for the carbon fibre arms of the table (Fig. 62).

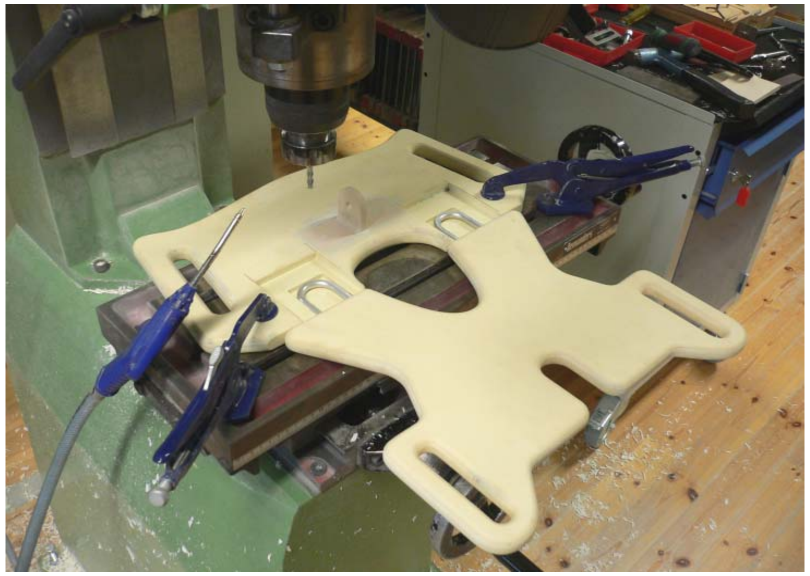


*Fig. 61 Milling operation for seat and leg board.*

*Fig. 62. Milling operation for foot piece.*

# MOCK-UP ILLUSTRATIONS


*Graphic elements.*


*Snap buckles from AustriAlpin.*

*LUCAS™ fastening rails in aluminium.*

*0GSW foot piece.*

*Aluminium locking knob for the back board guide rail.*

*Aluminium locking knobs for the leg board.*

*Joint detail of the foot piece.*

*0GSW in slanted, supine position.*

*Leg board with the 0GSW logotype.*

*0GSW in folded position, showing the guide rail of the backboard.*

*0GSW in folded position.*

*0GSW in an upright position.*


NASA

# DISCUSSION

The conclusion after reviewing the articles in space medicine is that surgery in space is possible if there are methods for handling fluids, waste, anaesthesia, diagnosing equipment as well as restraints of operating equipment, surgeon and patient.

There is additional equipment, as well as procedural management that need to be investigated for the future. However, this does not fall under the specification of this master thesis; the scope has been on developing a basic operating table for microgravity use.

Operating positions in microgravity will be somewhat different from terrestrial practice. Gravity is used to facilitate many operational settings on Earth like the Trendelenbourg position (Fig. 28) which become inefficient in space. There are however some advantages of performing surgery in the absence of gravity. Even though restraints are needed, the surgeon can position himself or the patient in virtually any desired position.

This can by far improve the visibility and access during the procedure compared to 1 G orientation. The sitting position (Fig. 28) is normally avoided in 1 G except for dental procedures. It can prove useful in microgravity for regional anaesthesia. In case there is a lack of assisting personnel the sitting position is favourable, allowing assistance from the patient in minor operations.

Many procedures will not be possible in a foreseeable future though, without medical specialists, operating team and advanced (large, heavy) equipment. As of today, no one can be really sure of what emergencies we can expect, or what the chances are that we may solve them without support from Earth. Even though advanced surgery like managing a ruptured aortic aneurysm* never will be a reality on a Mars mission, the aim has been to make the 0GSW as all-round as possible.

Storage problems for additional equipment for the 0GSW like padding, leg- and arm rests has to be solved in a clever way, for instance by using the existing, on board equipment. One example of this is the gynaecological position. It can be managed by using a strap around the patient's legs and the back of neck in order to lift the legs to the correct position (this is possible in microgravity since the body has a tension in it self) instead of having "one purpose"– designed leg rests. Additional equipment like the Rizzler bows (Fig. 28) need substitutes to facilitate surgery.

The 0GSW mock-up is the first step towards a working prototype, but there have to be several refinements in the design before it can be used clinically.

Because the 0GSW is designed for microgravity, the construction is much lighter than a traditional operating table – 6kg compared to 312kg for a regular mobile table. For the design, lightweight usually means weaker construction. If polyurethane will be used as board material it needs to be reinforced. This can possibly be accomplished by a fibre composite matrix, molded into the boards. The carbon fibre tubes also need to be more stable, possibly by using a wider diameter of the existing tubes, or by using multiple tubes and thus creating a framed structure.

The straps of the 0GSW are manufactured in a static nylon fabric. The restraints might be improved further by using a material with a superior aseptic quality. The straps need to be firm, yet stretchable over the chest to enable breathing. The steel snap buckles from AustriAlpin are among the most durable and strongest available on the market. Plastic buckles are not as durable, but they will probably sustain temporary, emergency usage. Plastic also has the advantage of being radiolucent.

Eccentric lever joints (Fig. 19, 20) were difficult to come across in the making of the mock-up. Despite the weight, these joints are certainly a better alternative compared to the quick release skewers used on the 0GSW mock-up.

The LUCAS™ system might be promising for microgravity use but it would likely need some design changes to work properly. The weight has to be reduced, it needs to be smaller and will probably be powered by electricity (using the on board electrical system) instead of compressed air. There have been reports of the LUCAS™ causing damage in terms of fractures and internal bleedings related to extended operating times (information from personal communication). There is a great fracture concern due to the osteoporosis in microgravity so there has to be a careful evaluation before any adequate recommendation of the device can be made.

Much of the equipment and procedures on board a spacecraft will be quite primitive. Sometimes the old fashioned way might be the less complicated and the most effective way of doing things. In fact, the environment on board a space vessel has a lot in common with developing countries. The crew needs to be self-sufficient despite the minimal supply available.

There will not be room for any unnecessary items, designed for one particular thing. It is often the simple, well experienced solutions that are the most effective.

The 0GSW design is the result of the microgravity environment. The operating stand (Fig. 52) was eventually designed as a complement to enable surgery in low gravity environments. Perhaps in the future the design of the 0GSW can spawn a mobile operating table for remote places or in depressed areas of the world. To design for life in space requires a completely new way of looking at the most fundamental things in life we normally take for granted. At the same time it also brings us closer to our own being and helps us understand our basic needs for survival.



# CONCLUSION

The 0GSW fulfills the restraint requirements stated in the function analysis in the ability to immobilize the patient and reposition the restraints to suit several operating procedures. The guide rail of the back board makes the distance to the seat adjustable to fit body sizes from the 5th- to the 95th percentile men. The distance between the boards can also be modified by increasing/decreasing the angle of the arms. The arm of the backboard is telescopic which makes it possible to set the table in an upright position. By using quick release skewers for the joints, the 0GSW can be deployed in a fast and simple way.

The seat can be rotated around the x-axis while the back board rotates around both x- and y-axes. This enables a variety of operating positions including sitting position, supine and slanted supine position. Even “A la Vache” and gynaecological positions are possible since the leg board can be detached from the seat.

The guide rail on the wall enables rotation of the whole table to improve accessibility. The distance/height of the table (depending on the position of surgeon) can easily be adjusted by sliding the table along the guide rail. Due to the microgravity it is possible to use the 0GSW in unique positions compared to Earth. Assuming restraints for the equipment are managed in a satisfying way, the microgravity might in fact facilitate some surgical procedures by enhanced visibility and access.

The boards are made in a thermosetting plastic, which is heat resistant and good for electrical isolation (from defibrillation). The 0GSW is also approved for radiography due to its radiolucent board material. The operating table uses aseptic materials, with flat surfaces and edges with big radii to make cleaning easier. To optimize storage, the 0GSW can be folded, making it smaller.

The weight of the 0GSW has been reduced to 6.48kg (including straps of 0.57kg) by using lightweight materials. The price associated with sending 1kg into LEO is approximately 22,000 USD. The cost of sending the 0GSW into orbit is consequently 142,600 USD (997,900 SEK) -almost three times less than the CMRS.

# GLOSSARY

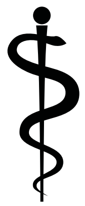
**0GSW** – Zero Gravity Surgical Workstation
**Adrenals** – SE: binjurar
**Anaemia** – SE: blodbrist
**Aneurysm** – An aneurysm is localized, blood-filled bulge of a blood vessel. The bulge can burst and lead to death at any time.

**Anthropometry** – Studies of human body measurements in order to understand physical variations.

**Appendectomy** – Surgical removal of the appendix in order to treat appendicitis. (SE: Blindtarmsoperation)

**Arrythmia** – A group of conditions in which the electrical activity of the heart is irregular or is faster or slower than normal.

**Asclepius** – The rod of Asclepius is a symbol used by many medical organizations. It is an ancient Greek symbol which symbolizes the healing arts by combining the serpent, which in shedding its skin is a symbol of rebirth and fertility, with the staff, a symbol of authority befitting the god of Medicine.



**Cellulitis** – Bacterial infection of the skin as well as its underlying tissue.

**Cholecystectomy** – Surgical removal of the gallbladder. Open- or laparascopic surgery.

**CMO** – Crew Medical Officer
**CMRS** – Crew Medical Restraint System
**CPR** – Cardiopulmonary resuscitation (SE: HLR: Hjärt och Lung Räddning)

**Diuresis** – Increased urine production by the kidney. In microgravity, the diuresis is the result of the body trying to decrease the amount of fluid of the upper body caused by the fluid shift.

**EBV** – Epstein-Barr Virus causing e.g. mononucleosis (SE: körtelfeber). EBV infections can be latent in the body.

**Endotracheal tube** – A tube which is inserted into a patient's trachea in order to ensure that the airway is not closed off and that air is able to reach the lungs.

**Embolism** – An embolism occurs when a object/embolus migrate and block a blood vessel. (SE: propp )

**Endoscopy** – Means "looking inside". Endoscopy refers to a minimally invasive diagnostic procedure by an insertion of a rigid or flexible tube into the body for visual inspection.

**EVA** – Extra Vehicular Activity
**Forceps** – Handheld, hinged instrument used for grasping and holding objects. (SE: griptång)

**Haemorrhage** – SE: blödning
**HALS** – Hand Assisted Laparoscopic Surgery
**Hemostats** – Similar to forceps but with a locking clamp. Hemostats are commonly used in both surgery and emergency medicine to control bleeding, especially from a torn blood vessel, until the bleeding can be repaired by stitches or other surgical techniques. (SE: peang)

**Hernia** – A protrusion of a tissue, structure, or part of an organ through the muscular tissue or the membrane by which it is normally contained. (SE: bråck)

**Hygeia** – The bowl of Hygeia is often used by the pharmacy. In Greek mythology, Hygeia was the goddess of health, cleanliness and sanitation. Unlike her father Asclepius, she was associated with the prevention of sickness and the continuation of good health.

**Intubation** – Insertion of a tube into the windpipe in order to protect the patient's airway and provide a means of mechanical ventilation.

**ISS** – International Space Station
**JSC** – Lyndon B. Johnson Space Center. NASA's center for human spaceflight activities in Houston.

**Kidney stones** – Or Renal calculi, are solid concretions of dissolved minerals in urine; calculi typically form inside the kidneys or ureters. If stones grow to sufficient size (from at least 2-3 millimeters) before passage they can cause obstruction of the urinary tract (SE: njursten)

**Laparatomy** – Open surgery in the abdomen.
**Laparoscopy** – Minimally Invasive Surgical technique in the abdomen. Tubes/ports are inserted through small incisions of the abdominal wall. Optics and surgical instruments are then used to perform the surgery. $CO_2$ is used to inflate the abdomen to improve visibility.

**Laryngeal mask** – A tube with an inflatable cuff, used for airway management. They cause less pain and coughing than an endotracheal tube, and are much easier to insert.

**Laryngoscope** – A hook like device that consists of a handle, a light source and a blade, designed to push down the tongue and lift the epiglottis in order to open up the throat.

**Laryngoscopy** – Procedure that include the usage of a laryngoscope and insertion of tubing into the patient's airway.

**LEO** – Low Earth Orbit. 200 – 2000km above the Earth's surface.
**LUCAS™** – Swedish heart compression device, used for CPR. It can create up to 100 mechanical chest compressions per minute and stimulates airways by lifting the chest of the patient. The device is powered by compressed air.

**MIS** – Minimally Invasive Surgery. Procedure that involve the use of endoscopic instruments through small incisions of the body.

**Muscle atrophy** – Permanent loss of muscle mass.
(SE: muskelförtvining)

**NASA** – National Aeronautics and Space Administration
**Neurovestibular system** – Sence of balance. (SE: balanssinne)
**Ophthalmology** – Branch of medicine which deals with the diseases and surgery of the visual pathways, including the eye, brain and areas surrounding the eye, such as the lacrimal system and eyelids.

**Osteoporosis** – SE: benskörhet
**Parabolic flight** – Simulated microgravity on board an airplane. The airplane is performing parabolas in 25 second intervals of 0G. The gravity during each parabola range approximately from 0G (fall) to 2G (pullup).



**Pneumonitis** – Inflammatory reaction in the lungs. Pneumonia is one example, caused by an infection. (SE: lunginflammation)

**Prostatitis** – Any form of inflammation of the prostate gland.
**Radiation Dosimeter** – Radiation detection device.
**Radiolucent** – Transparent to electromagnetic radiation/ greater transparency to X-ray photons. (SE: genomlysbar)

**Reactive airways** – Asthma like syndrome developing after a single exposure to high levels of an irritating vapour, fume, or smoke.

**Septicaemia** – Blood poisoning/sepsis are often related to the underlying infectious process. A septicaemia may progress to dysfunction of the circulatory system and, even under optimal treatment, may result in the multiple organ dysfunction syndrome and eventually death. (SE: blodförgiftning)

**SMS** – Space Motion Sickness
**Supine position** – SE: Planläge
**Thoracoscopy** – MIS procedure in which an endoscope is inserted through the chest wall in order to examine the lungs or other structures in the chest cavity, without making a large incision.

**Tracheostomy** – Surgical procedure performed on the neck to open a direct airway through an incision in the trachea (windpipe, SE: luftrör). Tracheostomy can be used when tracheal intubation fails or when long term mechanical ventilation is needed.

**Urinary Retention** – Lack of ability to (partially/fully) empty the bladder. (SE: urinstämma)

**Urosepsis** – Septicaemia or systemic shock that originates from the urinary tract.

**Van Allen belt** – Two torus shaped belts of charged particles (plasma), trapped by Earth's magnetic field, that works like a shield/magnetic mirror to cosmic rays.

**Wyle Laboratories, Inc.** – Privately held provider of specialized engineering, scientific and technical services to the Department of Defence, NASA and a variety of commercial customers primarily in the aerospace industry.

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