Dental Treatment during a human Mars Mission with remote support and advanced technology

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Health issues of astronauts or cosmonauts are of high importance prior to launch and during the space mission. A wide range of medical examinations are carried out as part of the astronaut selection process and during training to ensure the best possible health status of each crewmember at the time of launch. For treating pain and dysfunction that could occur during a mission, a set of basic medication and medical equipment is available onboard. Astronauts are also trained to handle some of the most likely medical emergencies.

Although occurrences of dental injuries have been minimal so far, they are expected to rise significantly on long-term missions to the Moon, Mars and beyond. Reasons for dental injuries accompanied by severe pain and dysfunction are manifold. A replacement of a lost dental restoration and/ or a stabilization of fractured teeth and jaws can be important to prevent further damage to human health, to limit the loss of manpower, and finally to ensure mission success.

This paper deals with an ongoing research project that combines the technical feasibility of 3D technology in combination with dental methods. To demonstrate the workflow of a dental treatment with remote support, the developed technical procedure has already been successfully simulated under 'Mars' conditions during the 'AMADEE-15 Mission'. The authors will give an introduction to the historic background and rational for dental emergency situations. They will further outline a possible scenario of detecting, diagnosing and treating a dental problem during a human mission, including advanced manufacturing methods for dental treatment. Furthermore, the results of the simulation as well as future prospectives will be discussed.

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I. From the Past to the Future: Space Dentistry and Dental Emergencies

Health issues of astronauts are of high priority, especially on long term missions. It is important that astronauts stay healthy and come back in good shape. This is the reason why spaceflight medical systems have evolved from a few medications and monitoring devices to advanced life support hardware. Space dentistry, as part of space medicine, is an emerging field. Major milestones and available associated equipment are introduced in the following for each manned mission up today.

Apollo Missions

While the medical kit for each of the six piloted Project Mercury flights (1961-1963) included just an anti-motion-sickness drug, a stimulant, and a vasoconstrictor to treat shock, the medical accessory kits for the Apollo missions contained medical supplies and a small amount of medical equipment.

During the Apollo program, no dental problems with an impact on the missions with a maximum duration of 18 days (Apollo 17) occurred. Nevertheless, during the 3 month preflight period, five of the 33 Apollo astronauts needed dental treatment. One pulpitis (a severe inflammation of the dental nerve) occurred preflight and post flight (Johnston RS et al. 1975).

Skylab Missions

The Inflight Medical Support System (IMSS) for Skylab was designed to provide the on-board physician or Scientist Pilot with medical equipment adequate to make a diagnostic assessment of those injuries or illnesses most likely to occur in the Skylab environment. The Inflight Medical Support System contained equipment and medical kits with over 1300 different items, and for the first time, a dental kit. It also included a manual with line drawings of complete intraoral radiographs of each crewmember as well as integrated, illustrated diagnostic and treatment procedures. Figure 1 shows Skylab 2 commander Charles Conrad during a dental examination by medical officer Joseph Kerwin in the wardroom of the Skylab station.

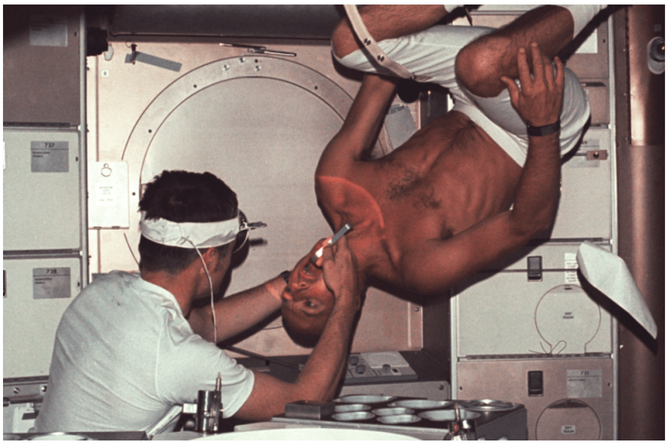

Figure 1. Skylab 2 commander Pete Conrad undergoes a dental examination by medical officer Joseph Kerwin. *In the absence of an examination chair, Conrad rotated his body to an upside down position to facilitate the procedure.(image credit: NASA)*

Salyut and Mir Missions

During Salyut and Mir missions lost fillings and crowns were reported, which were caused by launch vibrations. One case of dental caries was reported from the Mir space station. It was treated with a temporary filling from an available dental kit (NASA [Dental Emergencies] 2012).

It is reported, that Russian cosmonaut, Yuri Romanenko, had a severe toothache during the 96-day flight of Salyut 6 in 1978. Romanenko tried to keep that secret from ground control, but due to extreme pain, other crewmembers asked for help. During that time, the Soviet program unfortunately had no "*contingency plans for dental emergencies*" (Seedhouse 2011 p. 31) and the only advice he was given was "*to take a mouthwash and keep warm*". Romanenko had to wait two more weeks before his mission ended. He took "*overdoses of pain killers to deaden a toothache that was causing his eyes to literally roll with pain*".

State of the Art: International Space Station Missions

Currently all crew members receive preflight medical examinations, including a dental check and preflight medical training. Examinations are performed 10 days or less prior to the mission. Two astronauts of each Expedition Crew receive additional training as *Crew Medical Officer* (CMO). This training includes "*cross training in different disciplines so that they could provide surgical assistance, anesthesia support, and diagnostic capability* […]" (Clément 2011, p.296). Inflight the CMO conducts regular medical examinations as well as radiation monitoring and physical fitness tests. In addition, crew conferences with ground specialists can be arranged.

Onboard the International Space Station, medical equipment and instruments are available for a number of likely medical procedures. Set procedures with detailed instructions on how to use the available equipment for dental emergencies concern the following incidents (NASA [Medical Checklist] 2001):

- Crown Replacement
- Total Avulsion / Complete Tooth Loss
- Exposed Pulp
- Injection Technique
- Temporary Filling
- Tooth Extraction
- Toothache

The procedure for 'Dental – Crown Replacement' (p. 525) notes that "*if there is no pain, especially when eating or drinking"* astronauts shall *"stow crown in secure location and crown can safely be placed upon return."* Astronauts shall "*perform crown replacement procedure in event of pain and discomfort."* This shows that a crown displacement on orbit is prevented as long as possible. In case of an emergency, pain can or should be suppressed until medical help back on Earth is available. In case of an extreme emergency, tools are available to extract the tooth.

Future Missions and Outlook

Summarized, the dental experiences made in an oral health and preventive dentistry program during the early days of US spaceflight showed that the probability of a severe dental emergency is roughly 1:9000 man-days. The probability of a dental problem that causes at least significant discomfort is 1:1500 man-days. These figures fit the probability of dental emergencies recorded for Navy personnel on long-term submarine missions (Johnston RS et al., 1975). Thus the probability of the need of inflight dental treatment increases with the duration of the mission and the number of crewmen.

It is likely that a dental emergency or at least dental caused discomfort will occur during a long-term Mars mission and "*dental emergencies can become true medical emergencies*" (Hodapp 2008 p.554). Further, on outbound flights for example to Mars, all emergencies have to be handled by the crew itself. Currently no procedure or technology is available to sustain and restore teeth for long-term missions.

II. A Fictional but Likely Emergency Case on Mars

If somebody on Earth, suffers from tooth pain, he or she will turn to a dentist for help. For example, if a tooth filling is lost, a clinical crown[4] of a tooth is fractured, or dental cavities occur as a result of caries, the dentist may propose to repair the tooth using an inlay[5], onlay[6] or crown. Those are manufactured by trained dental technicians in an especially equipped laboratory. State of the art equipment includes especially designed workspaces and furniture, as well as a number of suites of special equipment and machinery (Fig. 2). But most of the production process is still genuine handwork (Fig. 3). The dental product is made according to the patient needs and is finally inserted by the dentist.

[4] A crown is the topmost part of a tooth. An artificial or clinical crown is a metal, porcelain, or plastic reproduction of a crown affixed to the remaining natural structure of a tooth (Miller-Keane Encyclopedia and Dictionary of Medicine, 2003)
[5] An inlay (in dentistry) is a filling made outside the tooth to correspond with the cavity form and then cemented into the cavity (Miller-Keane Encyclopedia and Dictionary of Medicine, 2003)
[6] An onlay is a cast metal restoration that overlays cusps, thus restoring the occlusal and proximal surfaces and lending strength to the tooth. (Miller-Keane Encyclopedia and Dictionary of Medicine, 2003)

Figure 2a. Technical workspace and machine room of a state-of-the-art dental laboratory. *(image credit: Meusburger Dentaltechnik)*

Figure 2b. Computer workspace for digital modelling *(image credit: Meusburger Dentaltechnik)*

Figure 3. Dental technician 'finishing' a crown made of ceramics *(image credit: Kainerstorfer)*

But what would happen, if an astronaut on a long-term outer space mission suffers from dental and/ or jaw problems that can not be treated sufficiently by pain medication?

In contrast to low-Earth-orbit missions, outer space missions will not allow evacuation of a sick or badly injured crewmember (e.g. fractures of jaw bones and/or teeth by trauma). Therefore long-term missions to the Moon, Mars and beyond require both specific equipment and astronauts with basic theoretical and practical knowledge to deal with dental and/or jaw problems that are accompanied by inflammation, pain, dysfunction and/or severe discomfort. Although occurrences of dental accidents have been minimal so far, they are expected to rise significantly on long-term missions (NASA [Dental Emergencies] 2012; Hodapp 2008).

A. Selected Scenario

From a long list of potential dental problems that can occur, *"such as caries, pulpities, abscesses, fractures, and crown displacement"* (NASA [Dental Emergencies] 2012 p. 3), the two most likely scenarios have been selected for further studies and simulations. Scenario 1 deals with the replacement of a lost dental restoration (crown, partial crown or filling'. Scenario 2 deals with the manufacturing and incorporation of a stabilization splint.

<u>Scenario 1: Replacement of a lost dental restoration (crown, partial crown or filling)</u>

A dental crown (Fig. 4) is a tooth-shaped 'cap' that is placed over a damaged and prepared tooth. Although there is no written report of an in-flight dental emergency with US astronauts, there has been at least one account of a NASA astronaut temporarily repairing a crown displacement. Also cosmonauts have reported lost fillings and crowns during flight (NASA [Dental Emergencies] 2012 p. 6).

Scenario 2: Fabrication and insertion of a stabilizing splint

Given the oral and dental status of the crew is almost perfect on launch day (due to prior medical examinations) and the inflight oral hygiene is carried out in an exemplary fashion, it is more likely that trauma and stress induced bruxism will be main causes for dental problems and orofacial pain, rather than caries and periodontitis.

An occlusal appliance[7] (Fig. 5) is used after trauma and/or stress induced bruxism (grinding and/or clenching of teeth) as mechanical bandage. It can be of help to stabilize the maximum occlusion and to reduce hyperactivity of the masticatory muscles. This can result in a reduction of myofascial[8] and/or temporomandibular[9] joint pain (Lotzmann 1983, Bumann and Lotzmann 2002)

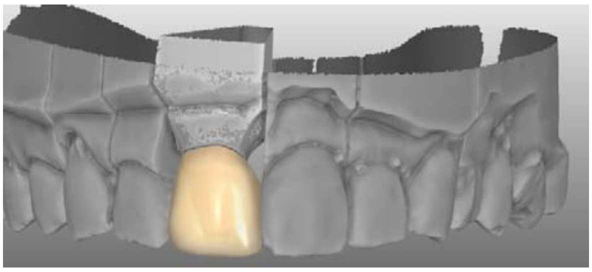

Figure 4a. 3D model of a crown

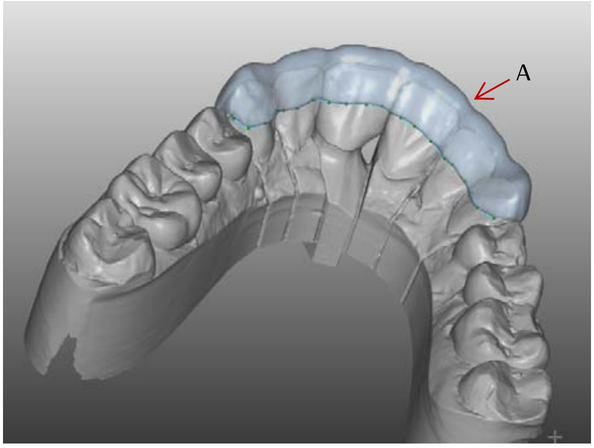

Figure 4b. 3D model of a fitting positioning guide (A) for a correct intraoral placement of the crown shown in Fig 4a. *(image credit: Meusburger Dentaltechnik)*

Figure 5a. Partial crown made from ceramics on a model. *(image credit: Meusburger Dentaltechnik)*

Figure 5b. Stabilization splint with anterior guidance inserted on the lower teeth of a patient who is pressing and clenching with his steeth and suffers from pain of the temporomandibular joint. *(image credit U. Lotzmann)*

[7] An occlusal appliance or splint is an removable intraoral device to stabilize and optimize the dental occlusion or to eliminate contacts of the posterior teeth for reducing muscular hyperactivity.
[8] Pain associated with inflammation of muscle and/ or fascia surrounding the muscle.
[9] Pain associated with inflammation of the jaw joint.

Both scenarios have been tested under laboratory conditions and found applicable. Scenario 1 has been chosen to be further elaborated and to be tested in a Mars simulation mission. Scenario 2 still has to be further examined.

Since the usual procedure on Earth is not subject to the same conditions and restrictions as a future space mission (due to remoteness, availability of equipment, etc.) it has been adapted accordingly. Table 1 shows the exemplary treatment sequence for the replacement of a lost dental restoration (e.g. a crown) (Scenario 1).

Table 1: Exemplary treatment sequence for the replacement of a lost restoration, as partly tested during the *Amadee Mars simulation.* Further testing has to be carried out under conditions of microgravity.
(1) Clinical situation by the outset: Toothache, discomfort and/or dysfunction caused by a loss of filling, partial crown or crown. (2) Intraoral scanning of the teeth and if necessary further dental diagnostics (e.g. digital x-ray). (3) Transmission of the 3D scanning data back to Earth for diagnostic support by experts. Virtual, computer-aided design of the restoration and the fitting positioning guided by the Earth-based dental lab. (4) Transmission of the 3D data files of the designed restoration and its positioning guide to the space base. (5) 3D milling or printing of the restoration and the positioning guide ibidem. (6) Insertion and fixing of the restoration using the positioning guide for the exact placement of the restoration. (7) Checking the fixed restoration by a crewmember. If necessary removing of surplus cement and occlusal adjustment (8) Intraoral control scan for documentation

The assumed scenario for the replacement of a dental restoration is based on the fictional accident of an astronaut during a Mars Mission. As he tumbles during a routine work, he injures his jaw. The impact also causes the loss of a crown and he needs immediate medical help (Fig. 6).

Figure 6. Caused by an accident astronaut Sirius M. has lost one of his dental restorations. He is instantly suffering from severe pain and cannot carry out his duty anymore. *(image credit: space-craft Architektur, D. Krljes)*

The proposed procedure, following a medical check and diagnosis, is a combination of 3D technology with high-end dental manufacturing. Fig. 7 shows the intraoral scanning done by the injured astronaut or one of his crewmates. In the following scenario, the 3D data is transmitted to Earth, where a team of dental experts approves the data and designs a virtual crown and a positioning guide (Fig. 8). These data sets are then transmitted back to the Mars habitat. There, a 3D-printer is used to manufacture both the crown and the positioning guide (Fig. 9). Our fictional astronaut Sirius M. or a crewmate inserts and fixes the crown. If necessary he removes surplus cement and occlusal interferences (Fig. 10).

Figure 7. Sirius M or a crewmate is scanning his upper and lower teeth with an intraoral scanner. The 3D data set is transferred to Earth*(image credit: space-craft Architektur, D. Krljes)*

Figure 8. On Earth dental experts approve the data and design a virtual restoration and a fitting positioning guide. The data is sent back to the Mars base *(image credit: space-craft Architektur, D. Krljes)*

Figure 9. On the space base, the restoration and the positioning guide are manufactured using a 3D printer *(image credit: space-craft Architektur, D. Krljes)*

Figure 10. After the successful insertion of the crown, Sirius M. is back on duty. "Houston, the dental problem is solved". *(image credit: space-craft Architektur, D. Krljes)*

B. Simulation of the selected scenario

Following a theoretical and practical simulation under normal laboratory conditions, the proposed procedure (as listed in Table 1) has been partly simulated during a Mars simulation mission.

The experiment 'Dental Treatment on Mars' was among the selected experiments for the two-week mars simulation mission of the Austrian Space Forum in August 2015 (OEWF 2015). The objectives were to demonstrate the workflow of the selected scenario with remote support and advanced manufacturing techniques.

Two slightly modified scenarios were tested: One simulation with a test person and an assisting person; and one with a test person, conducting all sequences by himself (Fig. 12). Selected sub-sequences were tested with an analog astronaut (Fig. 11). The whole simulation, except one dry run, was subject to the conditions of the larger Mars simulation (time delay, procedure protocol).

During the simulation it became evident, that the inclusion of a positioning guide would greatly improve the process. As a result point (5) and (6) were adapted accordingly.

Figure 11. Analog astronaut uses the intraoral scanner and scans the affected area himself during the simulation. (image credit: Meusburger)

Figure 12. Testperson controls the inserted crown by himself using a mirror. (image credit: P. Santek, OEWF)

III. Scientific, Technical and Operational Challenges

There are a number of challenges in order to avoid and prepare for in-flight dental emergency events. Aside from the selection and the development of the procedure, materials and technologies for treating dental emergencies as well as strategies for their prevention, a number of scientific, technical and operational challenges apply. Discussed below are some of the most relevant.

A. Technology and Materials

For the simulation of the procedure, the following hardware has been used: An intraoral scanner (GC AADVA IOS™), a computer station, and a dental kit and associated equipment. The intraoral scanner AADVA IOS ™ presents a new development. It includes a free-moving hand-piece with integrated optics. Also included is an anti-shake protection. The scanner produces high quality real-time images. (Logozzo et al. 2014)

Modern dental technologies allow intraoral 3-D scans of the teeth and surrounding soft tissues. This 3D scan data set could be transmitted to Earth. In our assumption, a trained and experienced dental technician would do a virtual 3D- model of the required dental splint, crown or dental prosthesis that fit the needs of the suffering crewmember. The data set of this 3D-treatment appliance is transmitted back to the spaceship, where an onboard 3D printer or milling (if available) is used to manufacture the model from ceramics, resin or another useful material automatically. A trained crewmember will then help the injured crewman to insert the splint or partial crown and if necessary do the final adjustments. In October 2015, it was demonstrated that a 3D printer with a low-temperature plastic feedstock can function in space. A 3D printer is seen as "*a critical enabling component for deep-space crewed missions and in-space manufacturing*" (NASA [3D Print] 2015).

The material used for the simulation was from the Shera Dental product series (Methacrylat Oligomere). Those are high quality, light curing adhesive synthetics. Depending upon the final product, a variety of 3D-printable materials are available. The development of materials in this area is a fast-growing field. For future space flight applications, it is most likely that materials to be used will be produced in-situ. This issue will need further attention.

B. Gravity Influences

Dental emergencies in space have been rare and the only planned and well documented oral examination in space dates back to 1973 (Skylab 2 mission). It is discussed that microgravity and radiation during long-term missions might lead to an increase of oral diseases like caries, periodontitis, jaw fractures, tooth pain, salivary duct stones and cancer (Rai B and Kaur J. 2011). However, the long-term effects of space flight on the masticatory system with its oral cavity and teeth are not really known and understood. Further research is necessary in this field.

Besides the direct physiological impact on the human body, a change in gravity affects a wide range of human activities, like body movement, posture and locomotion and provides a dramatic challenge to human physiology (cf. Clément 2005; NASA [Research] 2015). Selected sequences of the treatment would need to be tested in micro gravity to ensure a smooth working flow.

C. Restraints

As implicated in Img. 1, special procedures and/or additional restraints may be needed to complete certain activities. Simple procedures can become a major challenge, simply due to 'Newton's Laws', as for every action there is an equal and opposite reaction. As learned from the Skylab missions *"Man uses his arms and legs to complete a force coupe in zero-g much the same as he does on Earth. The major differences occur in how the man is restrained. On Earth, he has gravity holding his feet to the floor. In zero-g he must have restraints for that purpose"*. (NASA [Bull.7] 1974 p. 2)

A routine oral examination may be done without the aid of restraints. But as soon as forces are applied (eg. by pressing or pushing), restraints will be needed to support the astronaut. There are multiple kind of restraints already available on orbit. Those possibilities and the needed type of restraint for the selected sequences need to be further explored in the future. According to Taddeo and Armstrong, "*the ideal medical restraint would accommodate the neutral body posture assumed in microgravity and would support basic procedures […] This restraint would incorporate interfaces for medical equipment and medical waste management* […]." (Clément 2011 p. 70)

D. Extended Medical Training

For long-term missions, pre-flight medical training will need to be extended due to limited support by experts form Earth. Most likely all crewmembers will receive training equal to that of a crew medical officer. In addition, each crew member shall receive some level of dental training on basic dental procedures that may need to be performed while on a mission. Dental procedures also documented as video tutorials and associated dental specific instruments shall be available.

Not only the designated crew medical officer but all crewmembers should be familiar with potential dental tasks such as:

- Administering pain medication and oral antibiotics.
- Using an intraoral scanner for diagnostic and therapeutic purposes.
- Checking and cleaning (scaling) the teeth to prevent caries and periodontal diseases.
- Placing or replacing a long-term temporary crown, filling or dislodged restoration.
- Removing cement residue to avoid inflammantory periodontal disease.
- Checking and adjusting the dental occlusion ("bite") to avoid premature tooth contacts on the temporary restoration or occlusal appliance (Premature contacts can cause tooth fracture and pain) .
- Anesthetizing, trepanning and extracting teeth.

E. Medical onboard facilities and equipment

Future onboard medical facilities and equipment will be much more sophisticated than those available today. However, due to the many constraints of the space environment and mission design related decisions (e.g. mass and volume), there will be a sharp trade off between the ability to provide medical care and what facilities can be provided (cf. Clément 2011, p. 66). It is likely that technical progress will lead to a significant weight reduction of intraoral scanner, 3D printer and digital X-ray equipment for (dental) radiography.

In addition to the current dental kit, an assortment of temporary crowns individually prefabricated for each crewmember shall be included. Each crewmember should also be equipped with an occlusal splint that he or she should wear during phases of high G-forces (e.g. lift-off, reentry) and in phases of stress-induced bruxism for protecting the teeth and dental restorations against damage.

IV. Conclusion and Outlook

Dental emergencies during space missions have been rare, but are expected to increase on long-duration missions. During outbound flights to Mars or deep space, it is not possible to evacuate an injured astronaut and bring him back to Earth for medical treatment. In addition, communication delays will not allow personal communication with specialists on Earth. The crew will have to treat all medical incidences by themselves with the personnel, equipment and resources available. Potential risks to both mission and crewmembers will rise significantly with length and remoteness of future exploration mission to Moon, Mars and deep space. Dental emergencies are one of many important risks to be assessed in preparation for future long-term exploration missions.

In addition to intensive pre-flight examinations and evaluations, as well as strategies for in-flight-prevention, it will be necessary to introduce procedures for the treatment of dental emergencies. Astronauts have to be trained accordingly and equipment and procedures have to be developed and tested. Currently no procedure or technology is available to sustain and restore teeth for long-term missions.

The authors propose a workflow of a dental treatment with remote support that combines 3D technology with high-end dental manufacturing. This strategy incorporates available resources both on the desired destination and on Earth. The workflow has been tested under normal laboratory conditions and during an analog Mars simulation.

A simulation of selected sequences in microgravity, during a parabolic flight, is a logical next step to validate the procedure towards human space missions, refine the procedure and to attract industrial and scientific partners. After succeeding the parabolic flight testing, the procedures/techniques could receive demonstration in a dedicated space flight experiment.

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