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Clinical applicability of robot-guided contact-free laser osteotomy in cranio-maxillo-facial surgery: in-vitro simulation and in-vivo surgery in minipig mandibles

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Abstract

Laser was being used in medicine soon after its invention. However, it has been possible to excise hard tissue with lasers only recently, and the Er:YAG laser is now established in the treatment of damaged teeth. Recently experimental studies have investigated its use in bone surgery, where its major advantages are freedom of cutting geometry and precision. However, these advantages become apparent only when the system is used with robotic guidance. The main challenge is ergonomic integration of the laser and the robot, otherwise the surgeon's space in the operating theatre is obstructed during the procedure. Here we present our first experiences with an integrated, miniaturised laser system guided by a surgical robot. An Er:YAG laser source and the corresponding optical system were integrated into a composite casing that was mounted on a surgical robotic arm. The robot-guided laser system was connected to a computer-assisted preoperative planning and intraoperative navigation system, and the laser osteotome was used in an operating theatre to create defects of different shapes in the mandibles of 6 minipigs. Similar defects were created on the opposite side with a piezoelectric (PZE) osteotome and a conventional drill guided by a surgeon. The performance was analysed from the points of view of the workflow, ergonomics, ease of use, and safety features. The integrated robot-guided laser osteotome can be ergonomically used in the operating theatre. The computer-assisted and robot-guided laser osteotome is likely to be suitable for clinical use for ostectomies that require considerable accuracy and individual shape.

Keywords: Er:YAG laser; Bone; Laser osteotomy; Ergonomic; Computer assisted surgery; Robot guided surgery

Introduction

Laser-photoablation has been used in medicine since the development of laser in 1960, and its first medical use was reported in 1961 in ophthalmology.[1] Three years later, the effects of laser radiation on teeth, pulp, and oral mucosa

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were reported,[2] but because of the low water content of bone and teeth, it was difficult to photoablate them. However, the use of lasers in dentistry is now common, and Er:YAG lasers have been used to treat dental problems. The first lasers used to cut bone tissue were carbon dioxide (CO2) gas lasers, which cut well but initially bone healing was impaired by carbonisation.[3–5] This problem was solved with improvements in laser technology together with more effective cooling systems. The development of Q-switched CO2 lasers that could deliver sub-microsecond pulses finally achieved char-free cutting of bone.[6] However, it was with the advent of solid-state Er:YAG lasers that photoablation of bone improved considerably. Er:YAG lasers had a more efficient photoablation rate than conventional lasers, and left almost no charred layer under experimental conditions.[7–9] Despite all these advances, the use of lasers in osteotomy is still in the developmental stage. We know of only a few reports of experimental animal studies, and the clinical application is limited to oral surgery.[10–12]

Cutting, drilling, and healing of bone are fundamental issues in oral and craniomaxillofacial surgery, and many treatments are based on disuniting, repositioning, and refixing of bony structures in the facial skeleton. Because of the complex 3-dimensional anatomy and close proximity of vulnerable structures, the interventions demand precision and accuracy. The approach is challenging, as the oral cavity is one of the most common access routes in the specialty. To make laser osteotomy clinically applicable, considerable downsizing of the whole laser-robot system will be required.

Miniaturised, computer-assisted, and robot-guided laser osteotomy would be ideal in craniomaxillofacial surgery. The fact that laser osteotomy is contact-free minimises mechanical and thermal damage to the bone and preserves vulnerable tissues nearby. The most challenging aspect is to provide an appropriate operative system and to find a way to implement such an integrated system into the operating theatre. Various technologies have been introduced in medicine, but not all are used clinically. Even when the surgeon needs them, they often hinder his routine by obstructing both space and view, as is the case with the 3-dimensional navigation systems or laser osteotomy systems that are currently available.[13]

Here we have analysed our first experience with a new computer-assisted, robot-guided laser osteotome and illustrated its advantages for cutting bone, compared with a manually operated piezoelectric (PZE) osteotome and conventional drills.

An Er:YAG laser was erected in a miniaturised setting and mounted on a surgical lightweight robotic arm. Preoperative imaging enabled accurate surgical planning. Intraoperative navigation and robotic guidance ensured its correct execution. The system was initially erected in a dummy operating theatre to simulate a series of craniomaxillofacial operations. It was then used in an actual operating theatre for an in vivo study to create different shapes of defects in one side of the mandibles of 6 minipigs. Similar defects were created on the opposite side with a PZE osteotome and conventional drills, and performance was analysed in terms of workflow, ergonomics, and safety.

Material and Methods

Laser head

We used the prototype laser head. The laser source is an Er:YAG laser (wavelength 2940 nm) that is integrated with an optical system in a compact casing and mounted on a surgical robot. The Er:YAG laser provides a cutting width of 500 μm. The tissue being photoablated is permanently cooled and hydrated by a nozzle system to create a fine sterile aqueous vapour of sterile sodium chloride.

Surgical robot

A KUKA light-weight-robot (LWR4+, KUKA Robotics, Augsberg, Germany) was used to position the laser head. This robot features 7 degrees of freedom and provides a range of movement up to 170° or 120°. The robot is extremely sensitive because of its integrated sensors, which make it ideal for force-controlled tasks, and provide increased safety.

System control

The entire robot-guided laser system is integrated with a computer-assisted preoperative planning and intraoperative navigation system. A software package developed in house uses preoperative imaging to define sites and designs of osteotomies. The navigation system is a key safety feature: it monitors the position of the laser's casing with respect to the target, and converts the preoperative digital data into a real osteotomy by driving the robot. Referencing was done through fixed markers and anatomical landmarks with a passive marker system (Fig. 1).

In vitro dummy operating theatre

To test the ergonomics of the laser system before using it in vivo, we created a dummy operating theatre. The computer-assisted, robot-guided laser system was placed at the 3 o'clock position, at the level of the patient's shoulder. The instrument table was in its typical place, over the patient's chest. A tripod, which carried the infrared camera for the navigation system, was placed at different positions depending on the surgical site to ensure an unimpeded optical corridor. All procedures were recorded with photographs and video for subsequent analyses (Fig. 2).

In vivo operation

We used 6 fully grown female Göttingen minipigs (mean (SD) age 26 (5) months, mean (SD) weight 49 (3) kg).