

Cemented Tibial Tray Fixation

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Researchers discover a previously unknown phenomenon, principally by demonstrating that an observation cannot be explained by any known phenomena, and then explore its various effects and learn how to maximise and control them.

from "The Knowledge"
by Lewis Dartnell

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Kurzfassung

Die totale Kniearthroplastie ist ein erfolgreicher chirurgischer Eingriff, führte aber in 2013 in Deutschland zu etwa 25 000 Revisionseingriffen. Häufig ist die tibiale Komponente der Prothese betroffen. Die Vermeidung oder ein Hinauszögern des Revisionseingriffes ist im Hinblick auf das erhöhte Infektionsrisiko und den Knochenverlust bei der Implantatextraktion im Interesse des Patienten. Bis zu ein Drittel der Revisionen werden aufgrund einer aseptischen Lockerung der Prothesenkomponenten durchgeführt, die durch eine unzureichende Implantatfixation ausgelöst wird. Die Fixierung der Implantate wird vorwiegend mit Knochenzement durchgeführt, der einen Formschluss mit dem trabekulären Knochen bildet. Ein Indikator für die Festigkeit der Fixierung ist die Auszugsfestigkeit, für die eine Korrelation mit der Zement Eindringtiefe in den Knochen gezeigt wurde. Im Hinblick auf die Formschlussverbindung spielt vermutlich die Architektur des trabekulären Knochens eine Rolle für die Fixationsfestigkeit. Die trabekuläre Struktur ist patienten- und ortsabhängig, deshalb sind fallspezifische Analysen notwendig.

Das Ziel dieser Studie war die Verbesserung des Formschlusses zwischen Zement und Knochen, was durch die Analyse der Zementmantel-Morphologie in humanen Tibiae erreicht wurde. Der Einfluss von Zement Eindringtiefe, Zementierungstechnik, aber auch von Knochendichte und -porosität auf die Fixationsfestigkeit wurde mit Hilfe von Computer-Tomographie(CT)-Analyse, mechanischen Auszugsversuchen und statistischer Modellierung der Fixationsfestigkeit durch Regressionsanalysen ermittelt. Die untersuchten Zementierungstechniken waren Zementauftrag mittels Zementpistole oder manuell, Voll- oder Plateauzementierung, zweischichtiger Zementauftrag und Knochenreinigung mittels gepulster oder Spritzenspülung.

In dieser Arbeit wurde eine Prozedur entwickelt, die die 3D-Rekonstruktion des Zementmantels aus CT-Aufnahmen zementierter Implantate in humanen Tibiae ermöglicht. Die Auflösung klinischer CT-Bildgebung ist nicht ausreichend für die Darstellung der trabekulären Architektur. Daher wurde die trabekuläre Struktur anhand von Mikro-CT-Aufnahmen von Knochenproben charakterisiert, die aus dem trabekulären Knochen unter dem tibialen Plateau von nativen Tibiae gewonnen wurden. Die Ergebnisse wurden auf die Knochendichte, bestimmt aus klinischen CT-Aufnahmen, bezogen. Die Kontaktfläche zwischen Knochen und Zement im belasteten Formschluss wurde bestimmt und als entscheidend für die Fixationsfestigkeit identifiziert. Die Zement Eindringtiefe spiegelt die Fläche wider, die zur Übertragung der aufgebrachten Last vom Zement auf den Knochen zur Verfügung steht. Ist die Zement Eindringtiefe unter einem kritischen Wert so entstehen Spannungen und Verformung von Zement sowie porenbildenden Trabekeln, bis zur Überlastung der wenigen Trabekel, die sich im Formschluss befinden. Der Zement wird aus den Knochenporen gezogen. Ab einer kritischen Größe der Last-Übertragungsfläche sind Spannungen und Verformung so gering, dass die Last auf den unter dem Zementmantel liegenden Knochen übertragen werden kann. Die zur Verfügung stehende Last-Übertragungsfläche hängt von der Zement Eindringtiefe und der Porosität des trabekulären Knochens ab.

Die Ergebnisse dieser Arbeit zeigen, dass von den untersuchten Zementierungstechniken nur Zementauftrag mittels Zementpistole die Morphologie des

Zementmantels verbessern konnte und das auch nur, wenn die Knochenoberfläche vorher gründlich gereinigt wurde. Nach einer solchen gründlichen Reinigung wurde die notwendige Zementeindringtiefe jedoch immer erreicht.

Das statistische Model zur Abschätzung der Fixationsfestigkeit kann genutzt werden, um die Zementeindringtiefe zu ermitteln, die notwendig ist um die entscheidende Last-Übertragungsfläche bereitzustellen. Dieses Ergebnis sollte in der präoperativen Planung eingesetzt werden, um Extremfälle zu identifizieren und die Zementierung anzupassen, aber auch in der postoperativen Risikoabschätzung in Bezug auf eine aseptische Lockerung.

Abstract

Although a successful surgical intervention, total knee arthroplasty resulted in about 25 000 revision procedures in 2013 (Germany). The majority of cases concern the tibial component of the prosthesis. Avoidance or at least postponement of revision surgery is desirable in order to decrease infection risk and bone loss related to implant extraction. In up to one third of the cases the reason for revision is aseptic loosening, which is caused by poor implant fixation. Fixation is typically performed using bone cement that forms an interlock with the trabecular bone. An indicator for the fixation strength is pull-out strength, which has been shown to correlate to penetration depth of the cement into the bone. Considering the interlock connection, the architecture of trabecular bone may play a role in fixation strength. The trabecular architecture is patient- and location-dependent, requiring patient-specific analysis.

The aim of this thesis was to improve interlock between cement and bone. This goal was achieved by investigation of cement layer morphology in cadaveric specimens. The influence of cement penetration depth, cementation technique, as well as of bone density and porosity on fixation strength was analysed using computed tomography (CT) image analysis, mechanical pull-out testing and statistical modelling of fixation strength by regression. Investigated cementation techniques were gun and manual application, full and plateau-only cementation, two-layered cementation and bone cleansing using pulsatile or syringe lavage.

A procedure was developed that enabled 3D reconstruction of the cement layer from the CT images of cemented tibial implants within cadaveric specimens. Clinical CT imaging offers insufficient resolution for the accurate representation of trabecular architecture, limiting the analysis of the role of trabecular architecture in fixation strength. Micro-CT was used to characterise the trabecular architecture in samples obtained from below the tibial plateau of native tibias. The results were related to the bone density as determined in normal CT. The cement-bone contact area within the loaded interlock was determined and shown to be crucial for fixation strength. The cement penetration depth indicates the area available to transfer the applied load to the bulk bone of the tibial head. Cement penetration depth below a critical value leads to deformation of cement and pore-forming trabeculae close to the surface. The few existing interlocking trabeculae are overloaded and fail, so that the cement pulls out of the pores. Above the critical value, load acts on a larger contact area, stress and strain are lower and load can be transferred to the bone below the cement mantle. The available load-transfer area depends on the cement penetration depth and the porosity of the trabecular bone.

The results of this thesis show that from the investigated cementation techniques only cement application using a cement gun had an improving effect on the cement layer, but only, if the resection surface underwent pulsatile lavage cleansing preceding cement application. However, regardless of the cement application technique, the critical cement penetration depth was always exceeded after thorough cleansing.

The statistical model for estimating fixation strength allows patient-specific determination of the penetration depth that is necessary to obtain the critical load-transfer area. These findings should be applied in pre-operative planning to identify extreme cases and select cementation technique accordingly, as well as in postoperative risk assessment with regard to aseptic loosening.

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