Kirschner Wires: insertion techniques and bone related consequences

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Kirschner Wires: insertion techniques and bone related consequences

Kirschner draden: insertie technieken en bot gerelateerde consequenties
(met een samenvatting in het Nederlands)

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Aan mijn ouders
Voor Marjorie

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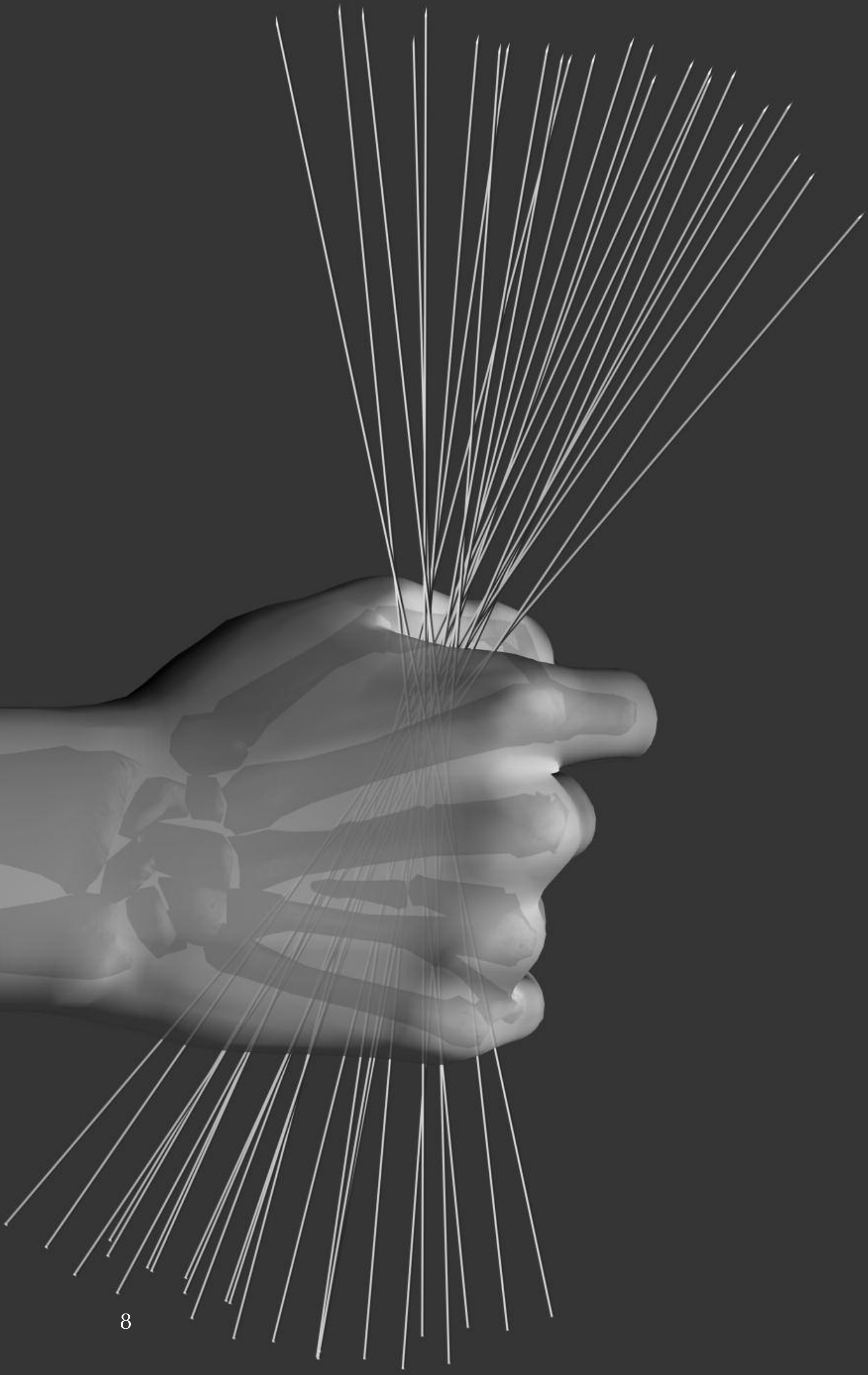

CHAPTER 1

General introduction

INTRODUCTION

Fractures of the hand and forearm occur with greater frequency than anywhere else in the body[1]. Hand fractures account for up to 20% of all fractures, with phalangeal being the most common location, followed by the metacarpals[2-4]. Some hand fractures may be treated conservatively, but there are definite indications for surgery. Unstable fractures, or those which are angulated, rotated or shortened require surgical fixation. The operative goals in hand surgery are to achieve adequate reduction and rigid fixation, allowing early digital mobilization in an attempt to reduce morbidity due to stiffness[5]. Fractures can be approached either by an open (lag screws, plates, interosseous wires) or percutaneous method (K-wires)[6].

The use of Kirschner wire (K-wires) is often promoted as a simple technique because of its easy placement, cost-effectiveness and safety[7,8]. The most important advantage of K-wires is the ability for percutaneous placement with reduced soft tissue dissection and concomitant prevention of swelling by preserving the dermal plexus and reducing soft tissue trauma. The use of K-wires is especially prevalent in hand surgery as the bones of the hand have suitable access for wire placement. The use of percutaneous technique is therefore indicated when adequate closed reduction can be achieved and in injuries with significant soft tissue damage[9,10]. Some research studies show the advantage of K-wires over open reduction and internal fixation of hand fractures even when used in the emergency room[11-13].

KIRSCHNER WIRE

The Kirschner wire was first introduced in 1909 by Martin Kirschner[14]. This is a thin unthreaded wire of surgical steel with a diameter of up to three millimeters and a selection of different tips. Previous research has shown that the trocar tip has the greatest holding power but the highest temperature elevation during drilling[15-17]. Other studies have shown that thinner wires generate more heat than thicker ones regardless of the type of tip[18]. The K-wire, in contradistinction to a surgical drill, does not have sharp angled cutting facets and flutes which usually clear the debris produced during drilling[19,20].

K-wires are widely used in surgery. One of the most common areas they are used is in hand surgery. K-wires are often used for proximal and distal phalanx fractures[21-25], unstable mallet fingers[26,27], metacarpophalangeal joint arthrodesis[28], metacarpal fractures[8,29-33] and carpal fractures[34,35].

The wires are also used for fractures of the distal radius[36,37] and olecranon[38]. The use of K-wires has also been described for the fixation of long bone fractures such as paediatric supracondylar humeral fractures[39-42], displaced midshaft or diaphyseal forearm fractures[43-46], epicondylar fractures[47] and distal tibial fractures[48]. The use of K-wires has even been described in the sacrum[49]. The widespread use of K-wires extends to reconstructive surgery such as fixating vascularized free fibular grafts[50] or premaxillary fixation in bilateral cleft lip surgery[51]. In the face K-wires are used to stabilize zygomatic arch fractures[52,53], nasal septal fixation in the case of a saddle nose[54,55] and mandible reconstruction[56].

K-wires are also commonly used for foot and ankle surgery, namely : metatarsal fractures[57], mallet toes of the hallux[58] and calcaneum fractures[59]. Less common uses include sternoclavicular joint fixation[60] and midshaft clavicular fractures[61].

Drilling

As mentioned before the K-wire does not have sharp angled cutting facets and flutes like surgical drills, so the debris produced during drilling is not cleared from the point[19,20]. As a result, the debris is compressed between the hole and the K-wire, resulting in increased friction and a significantly higher temperature elevation of the bone compared to surgical drill usage. Due to the low thermal conductivity of bone, there will be prolongation of the generated heat, resulting in thermal necrosis[62-64]. The temperature rise ultimately results in acute vascular insufficiency and reduction of osteocytes in cortical bone[63,65].

The total heat generated is a product of temperature elevation and the insertion time. Research has shown that osteonecrosis occurs when the temperature exceeds 47 degrees Celsius for >1 minute[64]. Further research has shown that temperatures higher than 50 degrees Celsius results in irreversible change in the bone structure[66-69]. Since thermal related necrosis has a negative impact on the fixation[62], bone temperature must be kept below the temperature which will result in necrosis. Drill speeds of less than 2000 rpm are recommended in contemporary orthopaedic surgery[62,63,70,71].

Irrigation

Reduction of the temperature rise during drilling is a crucial method of reducing thermal damage. Irrigation has been used for this purpose for centuries. Circa 500BC, Hippocrates advised that cooling should be applied to the trepanning tool[72]. Contemporary studies have shown that a direct stream of irrigation fluid to the point of cortex penetration is effective in diminishing cortical temperature elevation[71,73,74]. This is difficult to maintain in practice. The most effective way of cooling would be internally through the shaft, which is not possible with K-wires[73]. Irrigation is also difficult when penetrating the contralateral cortex or during percutaneous K-wire insertion[75].

Complications

Most morbidity due to the complications of K-wire insertion is caused by pin-tract infections, non-union, mal-union, local soft tissue reaction, nerve injury, wire migration and the need for repeat procedures or K-wire removal[76-78].

Thermal related damage due to drilling is thought to increase the incidence of pin tract infections[70]. Egol found in a study of 118 patients, that 19% of all complications were related to the pin tract and concluded that the prevalence of these complications was unaffected by the use of hydrogen peroxide wound care or chlorhexidine-impregnated dressings[79]. Pin tract infections are often effectively treated with oral antibiotics or early K-wire removal[80]. If the infection is not treated expediently, it can lead to serious complications such as osteomyelitis, septic arthritis and toxic shock syndrome[80,81].

Botte described an overall complication rate of 18% in 137 patients with 422 K-wires following hand or wrist surgery. Forty five (11%) of the K-wires were involved[76]. Stahl described a 15.2% complication rate from 590 K-wires in 236 patients[77]. Pin tract infections make up to 33% of the total complication rate, and up to 5% of the time will result in pin loosening, migration or non-union [76,77,80]. The infection rate can be diminished when the wires are buried[80,82] and it is recommended to bury K-wires if they are to be in situ for more than four weeks[82,83].

In a study concerning 202 children with fractures treated with K-wires the overall infection rate was 7.9%[84]. It is of note that K-wire placement in supracondylar fractures may result in nerve lesions[40,85].

Migration of K-wires has been described in the literature, for example: migration from the hip to the heart[86] or liver[87,88]; from the greater trochanter to the popliteal fossa[89], from the shoulder or even hand to the heart[90,91] or spleen[92]. When K-wire migration is diagnosed it is advised to remove the wires immediately, due to the vastly increased risk of serious and sometimes life threatening complications[93]. To prevent migration, K-wires must be sufficiently bent at the protruding end[94,95].

During K-wire insertion, it is important to avoid interposition of local soft tissues such as like vessels, nerves and tendons around the rotating K-wire[77,96]. This may be effectively prevented by using a K-wire guiding system[97]. The complications are summarized in *table 1*.

Author	Number of Patients	Number of K-wires	Patients with complication	Involved K-wires	Complication on rate: PR=PC/NP*	Complication on rate: KR=IK/NK**	Year
Burton[78]	134	-	5	-	3.7%	-	1986
Botte[76]	137	422	24	45	17.5%	10.7%	1992
Hochwald[96]	44	88	-	22	-	25.0%	1997
Stahl[77]	236	590	36	-	15.2%	-	2001
Hargraeves[80]	56	99	-	12	-	12.1%	2004
De las Heras[40]	77	158	5	-	6.5%	-	2005
Karakurt[85]	13	29	7	-	53.8%	-	2005
Rafique[82]	60	100	-	12	-	12.0%	2006
Battle[84]	202	-	16	-	7.9%	-	2007

Table 1. Kirschner wire related complication rates.
This table presents Kirschner wire related complication rates. Case reports are excluded. *PR=PC/NP; patient complication rate = patients with complications / total number of patients. **KR=IK/NK; K-wire complication rate = involved K-wires / total number of K-wires.

AIMS OF THIS THESIS

The hand is a precise and dynamic system which is crucial for a patient's livelihood, hobbies and caring for the family. Optimal hand function is the primary goal of all corrective surgery. As K-wires are commonly used for bone fixation, we must search for optimal surgical outcomes and reduce the complication rate. Martin Kirschner himself pondered whether a hammer device for K-wire insertion would be preferable to drilling and devised such a system[98]. In 1993 Zegunis hammered K-wires into place. His results were promising because the temperature rise was significantly less when hammering was compared to drilling[99].

We wondered if a pneumatic hammer would be an appropriate insertion device for K-wires. To investigate this hypothesis we performed *in vivo* and *in vitro* studies leading to this thesis. We analyzed the insertion time, temperature elevation, bony fixation, the effect on osteocytes and the mechanical damage of the bone during wire insertion. We compared these parameters between hammering and drilling as insertion techniques for K-wires.

OUTLINE OF THE THESIS

In Chapter 2 we describe the development of the K-wire, the surgical indications for K-wire use and its insertion techniques during the last century. In Chapter 3 and Chapter 4 the histological effect of drilling and hammering K-wires is investigated. Drilling time, which is an important aspect in the survival of osteocytes surrounding the drill tract, is described in Chapter 3. In Chapter 4 the difference in osteocyte survival between hammering and drilling k-wires is described. Chapter 5 to 8 further describe the non-histological differences between hammering and drilling K-wires. Chapter 5 describes an in vitro study where the fixation of hammered and drilled K-wires in pig ribs are tested. In chapter 6 an *in vivo* study is described in which hammered and drilled K-wires are placed in the femurs and tibias of rabbits. The insertion time is measured during K-wire placement and fixation is measured at two time intervals (immediate and 4 weeks after insertion). Chapter 7 describes an *in vitro* study with fresh human metacarpals in which the effect of irrigation on temperature elevation, insertion time and extraction force during drilling is compared to hammering K-wires. Chapter 8 focuses on characteristics of the K-wire and its impact on temperature development and the strength of fixation using fresh frozen metacarpals and both insertion techniques. Chapter 9 includes a summary, conclusions and future perspectives.

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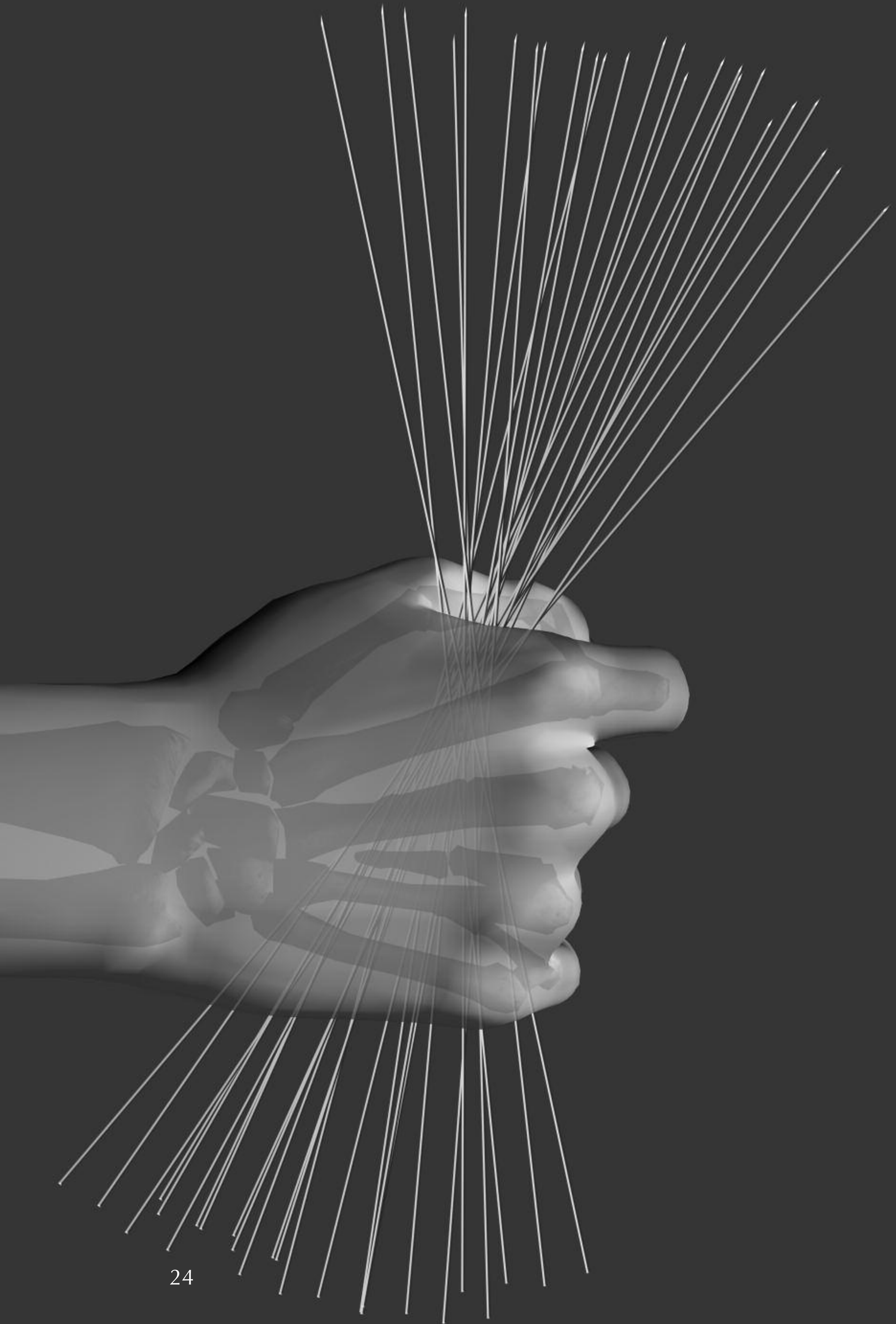

CHAPTER 2

Historical review: One century of Kirschner wires and Kirschner wire insertion techniques

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ABSTRACT

Almost a century ago, in 1909, Martin Kirschner (1879 – 1942) introduced a smooth pin presently known as the Kirschner wire (K-wire). The K-wire was initially used for skeletal traction and is currently used for many different goals. The development of the K-wire and its insertion devices were mainly influenced by change of operative goals and the introduction of antibiotics. The first versions of the K-wire were hammered through a predrilled hole in the bone; where after drilling became the standard technique of insertion. Drilling is considered a simple K-wire insertion technique with many advantages, like percutaneous and atraumatic placement. However, this technique also has its disadvantages like temperature rises resulting in osteonecrosis and temperature-related complications. Despite these complications the K-wire is a standard method for the treatment of hand fractures worldwide.

MARTIN KIRSCHNER

Martin Kirschner (*Figure 1*) was born on the 28th of October 1879, in Breslau, Germany today known as Wroclaw, Poland. He studied medicine in Freiburg, Zurich and Munich and received his MD degree from the University of Strasbourg in 1904[1-3]. In 1909 Martin Kirschner introduced one of his most important contributions to emergency medicine; thick, smooth pins which evolved over the years into thin, smooth, stainless steel wires with different tips[4,5]. The latter we know today as Kirschner wires (K-wires). It took quite some years before the K-wire became what it is now. The development was influenced by different factors like wound infection, refinement of the insertion method and by changing of its goals e.g. they became very useful for small fragile bones instead of thick long bones. During his life Martin Kirschner was promoted to professor of surgery at the University of Königsberg, the University of Tuebingen and the University of Heidelberg in 1916, 1927 and 1934 respectively. He remained at Heidelberg until his death due to an inoperable carcinoma of the stomach on the 30th of August 1942[1-3].

Figure 1. Martin Kirschner. This figure is published with kind permission of Heidelberg University Hospital.

KIRSCHNER WIRE AND THE INSERTION DEVICES

Steinmann versus Kirschner

At first, the K-wire was not a wire but a pin which Martin Kirschner used for "Nagelextension", e.g. skeletal traction of fractures in long bones by using a nail. The principle of the pin was based on the Steinmann nail which was introduced by Fritz Steinmann in 1907[6]. Steinmann placed two nails at the distal fragment of a broken bone, lateral and medial, where-after traction was applied to the protruding ends of the nails, keeping the fragments in proper alignment. In contrast to Steinmann, Kirschner placed only one pin through a predrilled hole in the distal end of the fracture. The pins Martin Kirschner used at that moment had a diamond shaped tip and diameters varying from 3.5 to 6.0 mm and today they are surprisingly known as Steinmann pins[4,7].

Throughout the years it became more obvious that the Steinmann pins often resulted in infections[6,8]. According to both Fritz Steinmann and Martin Kirschner these infections were caused due to the thickness of the pins and the necessity of predrilling which resulted in the lateral slipping of the pin[9]. Therefore Martin Kirschner refined and improved an insertion apparatus which made it possible to insert small diameter wires instead of pins, which resulted in a diminished rate of trauma due to wire insertion. It was in 1927 that he showed an external accordion-like guide (*figure 2 and 3*) which made it possible to insert small chromo plated steel piano wires varying in diameter from 0.7 till 1.5 mm without the need of predrilling[8,10].

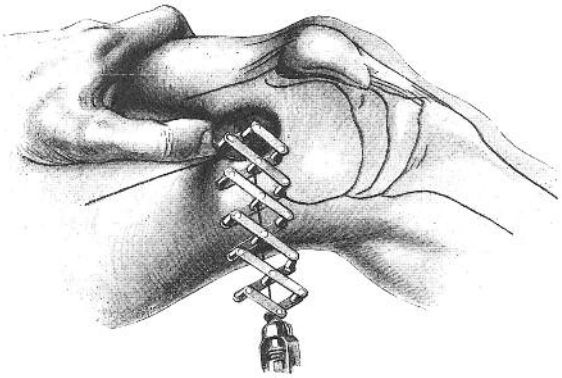

Figure 2. External accordion-like guide. This figure is published with kind permission of Springer Science+Business Media. Kirschner M. Verbesserungen der drahtextension. Arch Klin Chir 1927;148:651-658.

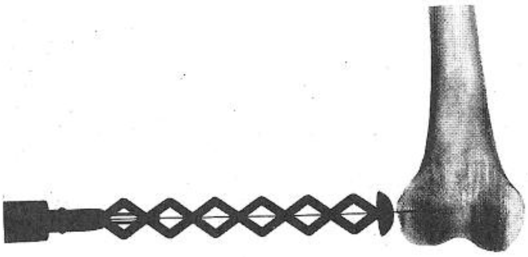

Figure 3. External accordion-like guide. This figure is published with kind permission of Springer Science+Business Media.
Kirschner M. Verbesserungen der drahtextension. Arch Klin Chir 1927;148:651-658.

With this K-wire insertion apparatus, designed by Martin Kirschner, chromo plated steel piano wires could be driven through skin, soft tissue and bone, making percutaneous placement of K-wires possible from that moment on.

Because predrilling was no longer necessary, there was a rigid fixation between wire and bone preventing lateral slipping and resulting in less trauma to the soft tissues[8]. Martin Kirschner called the procedure "Drahtextension" instead of "Nagelextension". The external accordion-like wire guide could be used for hand or electric-driven K-wires. It was, however, difficult to handle. This resulted in the development of improved and simpler K-wire drills which appeared in 1931 (*figure 4*)[11].

In 1934 the first spiral Key-way drive (figure 5) was described, where only a small piece of the K-wire protruded to prevent side bending. This particular Key-way drive could also be connected to a motor for automatic drilling (*figure 6*)[12].

Since 1935 other indications for the K-wires were described, like maintaining, in a different manner, reduction of fracture dislocations of the ankle joint, femur head and elbow[13-15]. In 1937 it was described that the K-wires could be used for hand fractures, which is the main area they are used for today. This was because Meekinson presented an even simpler hand device for K-wire insertion[16]. In the same year Gerster stated "that Kirschner wires, compared to nails, have proven to be less irritating to both soft tissue and bone[17]."

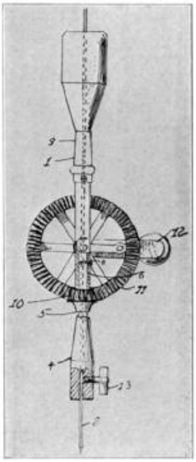

Figure 4. Wire insertion apparatus by SS Mathews 1931. This figure is reprinted with kind permission from The Journal of Bone and Joint Surgery, Inc. Mathews SS. A simple wire pin skeletal traction apparatus.
J Bone Joint Surg [Am] 1931;13:595-597.

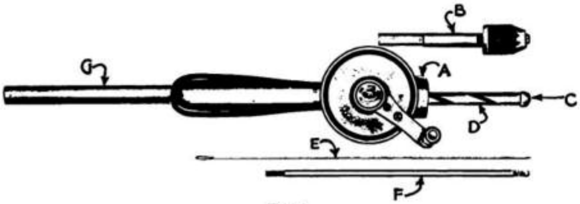

Figure 5. Spiral key-way drive, for K-wire penetration by RE Niedringhaus, 1934. This figure is reprinted with kind permission from The Journal of Bone and Joint Surgery, Inc. Niedringhaus RE. Improved methods in applying the Kirschner pin by hand or electric power. J Bone Joint Surg [Am] 1934;16:972-973.

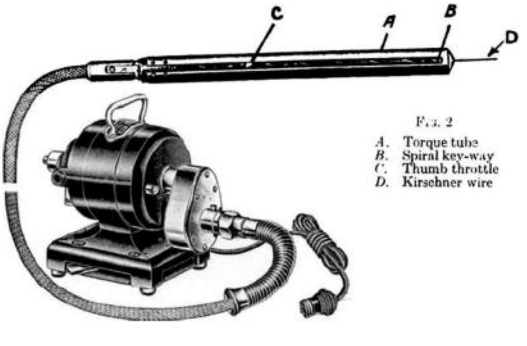

Figure 6. Drill attachment with an automatic feed for the K-wire which is driven by motor. This figure is reprinted with kind permission from The Journal of Bone and Joint Surgery, Inc. Niedringhaus RE. Improved methods in applying the Kirschner pin by hand or electric power. J Bone Joint Surg [Am] 1934;16:972-973.

Second World War

In the Second World War surgeons became progressively more innovative in the use of Kirschner wires because of the introduction of antibiotics and corrosion-resistant metals. K-wires with a diameter of 1.5 mm were generally used in World War II, and smaller ones (0.7 – 1.0mm) for the fingers. In 1940 Murray started to place K-wires in a relative new manner, longitudinally through the lumen of the clavicle[18].

Because he was quite enthusiastic about the principle of placing wires longitudinally through the lumen of bones, he advised the use of this technique for the radius, ulna and fibula too. In 1943 the first published study of metacarpal fractures by Captain Berkman from the Medical Corps, United States Army, described internal fixation using K-wires. This treatment was very useful in the army where patients were assigned to light duty immediately after surgery[19]. Today the K-wire is used besides in hand fractures for many other operative goals like sacral fractures[20], in the treatment of Buerger's disease[21], and even rarely in phalloplasty during female to male transsexual surgery[22].

K-wire characteristics

Apart from the changes in K-wire insertion devices, the K-wire itself has changed over the years. In 1909 the original Kirschner nails had a diamond shaped tip[5]. During the past three decades research has been done regarding K-wire characteristics like tip and diameter. This was done for the first time by Namba[5] in 1987. The most frequent analyzed K-wire tips were the diamond and trocar ones[5,23-26]. The trocar tip needs the highest insertion force resulting in a significantly higher temperature development compared to the diamond tip but it results in a significantly better fixation, especially immediately after fixation[25]. In 1999, a new design K-wire tip, which had two steep flutes for removal of bone fragments during drilling, was evaluated. This tip had the lowest temperatures during insertion compared to the trocar and diamond tip[27,28].

Another important K-wire characteristic is the diameter. K-wires with diameters smaller than 1.1mm generate more heat compared to thicker K-wires, regardless of point configuration.

As well as smooth K-wires regularly used in hand surgery, there are fine-threaded K-wires for foot and ankle surgery[27]. These threaded K-wires need significantly more extraction force compared to smooth K-wires.

Drilling versus hammering

On November 15th 1942, shortly after his death, Martin Kirschner's final publication appeared[29]. In this publication he made some very interesting

remarks. As he discussed the disadvantages of drilling K-wires, like wire migration and pin tract infection, he wondered how to prevent these disadvantages and finally mentioned the insertion of K-wires by hammering instead of drilling. He even described and produced a hammer device which he called the "Drahtnagler" and wrote "Die Kraft des einfachen Hammers versagt nie". He mentioned that hammering prevented heat development and that this technique resulted in a longer and better fixation.
For this device K-wires with a diameter of 1.5 mm were used.

So, initially in 1909, Kirschner nails were hammered through a predrilled hole[4], where after in 1927 the Kirschner nail changed in a Kirschner wire which was inserted by drill without predrilling[8] and finally, in 1942, the Kirschner wire was hammered into bone[29]. Despite Martin Kirschners' last publication K-wires are still inserted by using a drill. However, in 1993, Zegunis introduced a pneumatic hammer K-wire insertion technique[30]. His results showed that hammering resulted in lower temperatures. Based on these results Zegunis suggested that hammering may reduce the risk of thermal related injury. After this publication no other papers were published concerning hammering K-wires, until 2006, when Wassenaar presented his results concerning hammering K-wires. He showed that hammering resulted in a shorter insertion time and better fixation[31]. Our research further shows that hammering resulted in significant less death of osteocytes, which indicates less or even no thermal related damage to the bone[32].

Advantages

The advantage of K-wires is the relative ease of insertion with minimal trauma to the soft tissue and the tendons[33]. But the biggest advantage is the possibility of atraumatic percutaneous placement[34]. This technique is easier than open reduction and internal fixation, has less associated risks, minimizes swelling and stiffness and is still preferred today[35,36]. Percutaneous K-wire fixation achieves rigid fixation after adequate reduction and will allow early mobilization to prevent permanent deformity and stiffness.

Percutaneous transverse K-wire fixation diminishes and even avoids complications which occur after open reduction and internal fixation, including infection, difficulties in fracture healing, stiffness due to extensive soft tissue dissection, fibrosis, extensor tendon adhesion, plate loosening or breakage and complex regional pain syndrome[37]. Intramedullary metacarpal K-wire fixation is even more simple and puts the least strain on the sliding tissue[36].

Disadvantages

Apart from advantages, the use of K-wires has its drawbacks. From 1939 the first publications appeared in which the use of K-wires was discouraged. The first cases of migration of K-wires and lack of rigidity and strength when K-wires were used in femoral-neck fractures[38] were described. In 1943, the first cases of K-wire migration from the clavicle to the lungs were reported[39].

K-wire migration still occurs today and is a serious problem because it can result in serious non-fatal to devastating complications like death[39,40].

In most of the reported cases the K-wires migrated from the shoulder girdle to the aorta[41], heart[40], lung[39,42], trachea[43], mediastinum[44], neck[45], spleen[46] and spinal canal[47]. There are also reports of migration from other anatomical sites like migration from the hip to the heart[48], liver[49] or popliteal fossa[50] and, even more rare, from the left hand into the heart[51]. The explanation of the K-wire migration remains obscure but in most cases migration can be prevented by bending the distal end of the K-wire[52]. Nevertheless there are still case reports in which bent wires migrated after breakage, so follow-up radiographs should be made until the K-wires are removed[42,53].

Since the introduction of the K-wire, pin track infections have occurred[29]. This complication was one of the factors which resulted in the development of thinner K-wires. But even with smaller diameter K-wires, pin track infections still occur. Therefore, in 1954, Stone described a device of sterile dressings covered with foam rubber anchors which were placed where the K-wire penetrates the skin, to prevent skin necrosis and infection[54]. The incidence of pin track infections must not be underestimated. Presently, the use of K-wires results in pin track infections varying from 2.2% to 21%[36,55-58]. This complication may result in earlier pin removal and can result in non-union[59]. Early treatment of pin track infections, by immoblization, antibiotics and removal of loose pins, is important.

Some other complications described through the years are damage of peripheral structures[36,57,58,60-63], traumatic subarachnoid-pleural fistula[64] and toxic shock syndrome[65].

Future perspectives

Due to the increasing use of Kirschner wires in hand surgery during the last decades it has an excellent future perspective. In the last century the K-wire itself and the K-wire insertion apparatus underwent refinements resulting in less complications but they still occur. Therefore the most important goal is to minimize these complications further, for example by hammering K-wires, which might lead to a drop in the number of complications.

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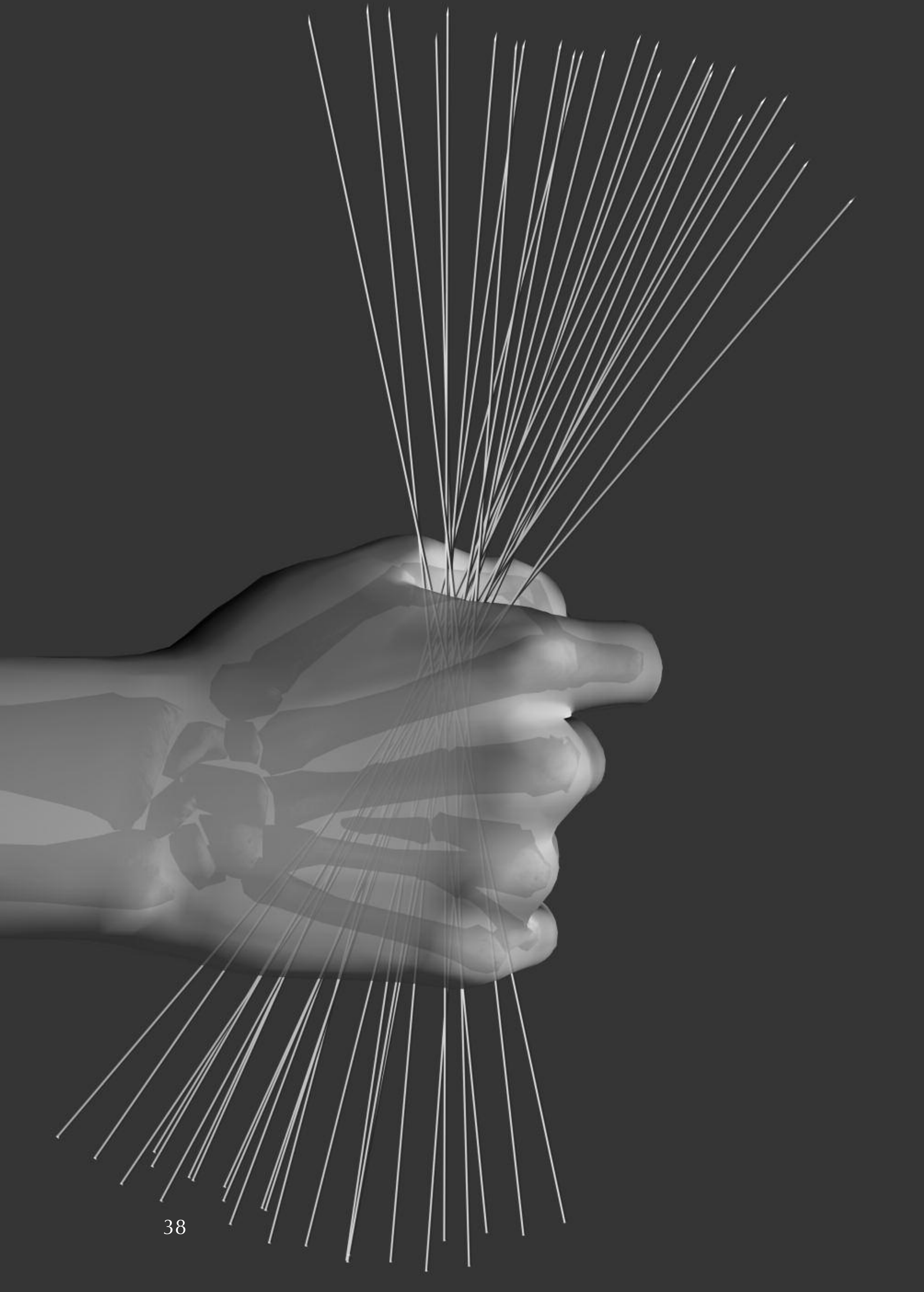

CHAPTER 3

Drilling K-wires, what about the osteocytes?

An experimental study in rabbits

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ABSTRACT

Introduction

The function of osteocytes regarding osteonecrosis has been underestimated for a long time. Recently it has been suggested that apoptosis of osteocytes results in strong osteoclastic bone resorption. Death of osteocytes due to drilling may therefore increase the risk of K-wire loosening. The purposes of our in vivo study were to assess the minimal drill time needed to notice disappearance of osteocytes and to measure the distance of the empty osteocyte lacunae surrounding the drill tract in relation with the insertion time, directly and four weeks after drilling Kirschner (K-) wires into the femur and tibia of rabbits.

Materials and Methods

Trocar tipped K-wires (70 mm length and 0.6 mm thickness) were drilled into the femur and tibia of 14 New Zealand white rabbits [mean body weight 2.81 kg (2.66 - 3.09 kg)]. Six rabbits were terminated following surgery ($t = 0$) and eight rabbits were terminated four weeks ($t = 4$) after surgery. Following termination, hematoxylin and eosin stained sections were cut from femur and tibia until the drill hole was visible. The sections were evaluated under a light microscope for the presence or absence of osteocytes in osteocyte lacunae surrounding the drill holes.

Results

All osteocyte lacunae were empty around the K-wires in 50% and 87% of the cases, directly and four weeks after surgery, respectively. The osteocytes disappeared especially beyond a drilling time of 37 s ($p = 0.011$) and 27 s ($p = 0.008$) at $t = 0$ and $t = 4$, respectively. Furthermore, a significantly positive correlation was seen between the distances of the empty osteocyte lacunae surrounding the drill holes in relation with time at $t = 0$ ($p = 0.008$) and $t = 4$ ($p = 0.000$).

Conclusion

Although only drilling without cooling was studied, short drilling times may prevent the disappearance of osteocytes in case cooling is not used in clinical practice as is the case in percutaneous K-wire insertion.

INTRODUCTION

Experiments concerning thermal damage to bone tissue due to drilling Kirschner Wires (K-wires) show several variables interfering with heat generation[1-8]. These variables can be categorized into three subgroups: drilling technique, K-wire characteristics and external factors. The drilling technique is a subtle balance between drilling speed, insertion time and pressure[9-14]. The characteristics of K-wires differ in diameter and K-wire tip[15-17]. The main external factor is irrigation with a water spray during drilling[18-21].

It is believed that critical temperature for bone injury is around 56°C because alkaline phosphatase denaturates at this temperature. Osteocytes however, may even be more sensitive to heat[17,18]. Eriksson observed that a temperature of 47°C for only one minute results in bone resorption[1,2,4]. Bone is capable of remodelling by bone resorbing osteoclasts, bone forming osteoblasts and osteocytes[22-25]. The latter differentiate out of osteoblasts which have ceased bone production and become embedded in the bone matrix, in vacuoles cushioned by fluid and large molecules, forming a network[22-24,26,27]. Despite the fact that the osteocytes are the major constituents of bone, their role in bone resorption regulation has remained controversial for a long time[22,28-31]. In the past decade however, understanding of osteocyte physiology has increased dramatically and it has become clear that osteocytes play an important role in bone remodelling[23,25,26,32-34]. Now we know that micro damage to bone, by e.g. drilling, is associated with an increase in osteocyte death by apoptosis[26]. This process triggers local bone resorption resulting in K-wire loosening, because death of osteocytes turns off the inhibition of osteoclasts[22,23,26,31,32,34].

The status of osteocytes after drilling into bone has been investigated before. Thompson describes the absence of osteocytes as an acute cellular reaction, which increases in severity with increase of drilling speed[35]. Pallan et al.[36] continued Thompson's[35] work and describes the delayed cellular changes in bone after pin insertion which were left in situ for maximum 10 weeks. He also concluded that higher speeds produce relatively higher temperatures and increased tissue response after a long time period[36].

It is well known that in clinical daily practice K-wires are often drilled without proper cooling because most drilling devices do not have an incorporated cooling system and therefore cooling has to be done manually. In case percutaneous drilling is performed, the cooling effect on bone is minimal because of the surrounding soft tissues. An *in vivo* study was therefore designed which simulated daily practice concerning K-wire drilling to analyze the absence of osteocytes directly ($t = 0$) and four weeks ($t = 4$) after insertion.

Our first aim was to measure the minimal drill time needed to notice disappearance of osteocytes. The second aim was to measure the distance of the disappeared osteocytes around the periphery of the drill holes in relation to drilling time.

MATERIALS AND METHODS

Animals and Anaesthesia

A total of 14 healthy, New Zealand white rabbits of female sex weighing a mean of 2.81 kg (2.66 – 3.09 kg) were used in this investigation. The rabbits were solely housed on a 12 h/12 h (light/dark) cycle and provided with standard diet food and water ad libitum. All animals were housed in the Central Animal Laboratory, Utrecht University, Utrecht, The Netherlands and received care in compliance with the European Convention Guidelines.

The animals were pre-anesthetized with a combination of methadone (10 mg/ml at a dose of 2.5-5.0 mg i.m.), ventraquil (10 mg/ml at a dose of 2.5-5.0 mg i.m.) and etomidaat (2 mg/ml at a dose of 2.0-8.0 mg i.v.).

After introduction of anaesthesia the rabbits were cuffed and mechanically ventilated with O_2:N_2O, proportion 1:1, and 2% isoflurane. During the surgical procedure methadone (2.0-5.0 mg i.v.) was given. At the end of the operation nalbuphine (10 mg/ml at a dose of 1.0-2.0 mg/kg i.v.) was administered. After surgery the rabbits were housed at the intensive care for the rest of the day and night. At the end of the study the rabbits were euthanized by an i.v. overdose of pentobarbital.

Surgical technique

An operation device was created by the first author (*Figure 1*). The operation device consists of a base plate. On this base plate, a dynamic plate was fixed which could be moved up or down. In front of the entire length of this dynamic plate a sideways moving slide was fixed on the base plate. On this sideways moving slide another back-forward slide including the drill was fixed. Forward movement of the drill was initiated by using a 1.5 kg weight.

During surgery the rabbit was fixed on the dynamic plate. This plate made it possible that the femur or tibia were on the same height as the K-wire. The sideways moving slide was responsible for the exact position of the K-wire in front of the femur or tibia.

After the rabbits were preanesthetized, X-rays were made to exclude deformities. Thereafter the animal's hind limb was carefully shaved and prepared with a povidone-iodine solution. After this procedure, the hind limb was fixed in the testing machine. With the animal surgically draped, a straight-line skin incision was made on the lateral aspect of the femur extending from just below the anterior inferior spine to the distal femur, followed by a straight-line skin incision on the lateral aspect of the tibia extending from just below the joint line proximally to about the joint line distally.

Dissection was carried out down to the periostium. Synthes Trocar tipped K-wires of 70 mm length and 0.6 mm thickness were drilled through the diaphysis. One K-wire was drilled into the femur and one into the tibia. Drilling was performed by a rotary engine fixed at 1,200 rpm. This is the maximum drilling speed used in our daily practice. Cooling was not performed. After insertion, the K-wires were cut short and the K-wire ends were bent to the cortex. After the wounds were closed in layers, X-rays were made to check the position of the K-wires and the condition of the bone. Insertion time could be measured very accurately by analysing the operations recorded on video camera. All the experiments were performed by the same investigator.

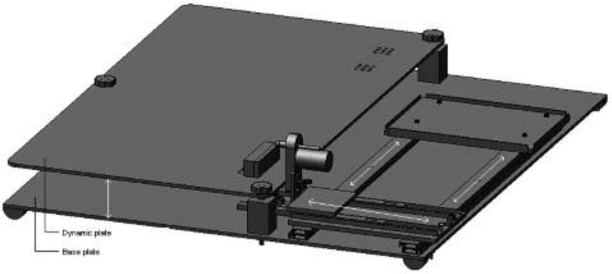

Figure 1. Operation device consisting of a base plate with a slide for sideways movement on top of this. On this slide another back-forward slide with a drill was fixed. The forward movement was initiated by a weight of 1.5 kg. Another dynamic plate was fixed on the base of the plate to move up and down. During surgery, the rabbit was fixed on this dynamic plate.

Histological technique

After termination, the femur and tibia were removed from the hind limb and fixed in 4% formaldehyde solution. They were then decalcified, cut transversely next to the K-wire hole where after the K-wire was removed gently by a pair of tweezers, and embedded in paraffin according to standard procedures. Four micrometer thick serial sections were cut until the drill hole was visible, stained with hematoxylin and eosin and evaluated under a light microscope at 400× magnification for the presence or absence of osteocytes in the osteocyte lacunae surrounding the drill holes by a single investigator.

The best section was used for evaluation. The distance over which the osteocytes had disappeared perpendicular to the drill holes was measured with an interactive morphometry device (Q-PRODIT, Leica, Cambridge, UK). In each section, four distances from the drill hole to the first osteocyte bearing lacuna were measured and averaged.

Statistics

Pearson's Chi-Square test was used to determine the drilling time needed for osteocytes to disappear. Pearson correlation was used to highlight any significant correlation between drilling time and the distance of the disappeared osteocytes surrounding the drill holes. A p-value <0.05 was considered statistically significant. The data were analyzed using SPSS 12.0.1 for windows.

RESULTS

After surgery ($t = 0$) six rabbits were terminated. Both hind limbs were used resulting in 24 assessments. From the remaining eight rabbits only one hind limb was operated. Four weeks later at termination this resulted in 16 assessments ($t = 4$). Two $t = 0$ and one $t = 4$ assessments were lost because no sections could be produced showing the drill hole, leaving 22 $t = 0$ and 15 $t = 4$ assessments.

Histological response to drilling was seen in most sections next to the drill hole (*Figure 2*). At $t = 0$ and $t = 4$, all osteocyte lacunae next to the drill holes were empty in 11/22 (50.0%) and 13/15 (86.7%) of bones, respectively.

At $t = 4$, a drilling time longer than 27 s resulted in a significant loss of osteocytes surrounding the drill holes ($p = 0.008$). At $t = 0$, a drilling time longer than 37 s resulted in a significant loss of osteocytes surrounding the drill holes ($p = 0.011$).

A statistically significant positive correlation was seen between the distance of the empty osteocyte lacunae surrounding the drill hole in relation with drilling time, directly ($p = 0.008$, *Figure 3a*) and four weeks after K-wire insertion ($p < 0.000$, *Figure 3b*).

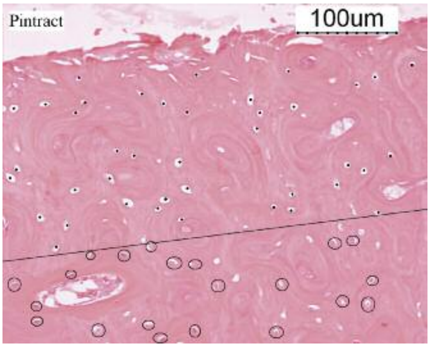

Figure 2. Status of osteocytes due to K-wire drilling at 1200 RPM. Disappeared osteocytes due to drilling are marked by a *dot* (·). The osteocytes are *encircled*. The *dotted line* indicates the border between the present and disappeared osteocytes (hematoxylin and eosin).

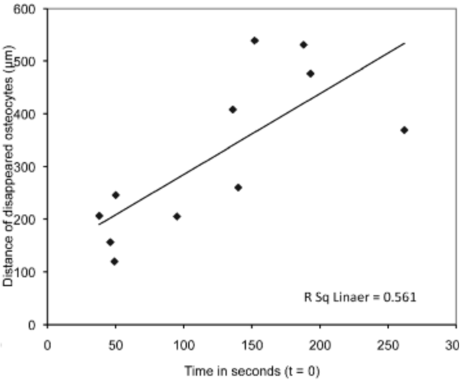

Figure 3a. Distance of empty osteocyte lacunae, in micrometers, surrounding the drill hole in correlation with drilling time, in seconds, at *t* = 0.

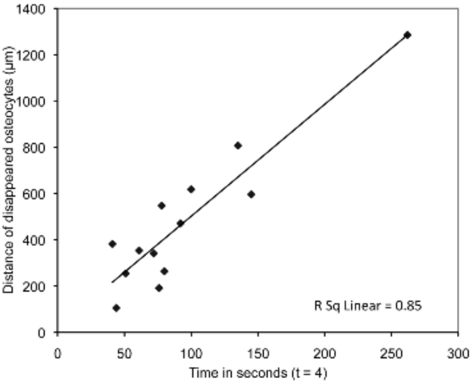

Figure 3b. Distance of empty osteocyte lacunae, in micrometers, surrounding the drill hole in correlation with drilling time, in seconds at *t* = 4.

Discussion

The two most important findings of this experiment are that (1) osteocytes disappear especially beyond a drilling time of 27 seconds and (2) that there is a positive correlation between the distance of the empty osteocyte lacunae in relation with drilling time.

As far as we know there are no experiments studying the presence / absence of osteocytes while using drilling time as a variable. Therefore it is interesting to notice that our results, representing daily practice by using a drilling speed of 1,200 rpm, clearly indicate that osteocytes disappear after a drilling time above 27 s in this animal model, when no cooling is used. Pallan[36] and Thompson[35] however, noticed absence of osteocytes already after a drilling time varying from 5 to 12 s. The limitation of their experiments is that the insertion force was not standardized. That could be a possible factor explaining the difference in insertion time with matching histological changes.

The effect on osteocytes in our study was more pronounced four weeks after insertion compared to the effect on osteocytes directly after surgery. This confirms the results from Thompson[35] where the effect on osteocytes was more pronounced 72 h after the operation than at either 24 or 48 h. Apparently, not all damage to osteocytes is acute and microscopically visible, directly after K-wire insertion. This can be explained by the study of Eriksson et al.[5]. They compared histology and histochemistry for detection of bone viability directly after surgery. The histological sections revealed a 200 μm wide zone of empty osteocyte lacunae around the periphery of the drill hole while histochemistry of the same bone specimens showed a zone of 500 μm lacking diaphorase enzyme activity. This indicates that the empty osteocyte lacunae directly after surgery underestimates the extent of the drilling trauma and becomes clear as time passes. Neovascularisation is probably a reason for the increase of osteocytes disappearance in time. During heating, due to drilling, blood flow will stop in minor vessels preventing the clearance of the osteocyte lacunae[2,5]. After neovascularisation the osteocyte lacunae can be cleared finally.

Our study also showed an interesting positive correlation between the distance of the empty osteocyte lacunae in relation with time. The zones of disappeared osteocytes varied from 106 to 1,285 μm and the drilling times from 41 to 262 s. A correlation between drill time and distance was not shown before. What we do know is that Eriksson et al. showed a 200 μm wide zone of empty osteocyte lacunae around the periphery of the hole after drilling into femurs of New Zealand white rabbits while conventional irrigation was administered5. These results are difficult to compare because Eriksson et al. did not measure time, irrigated with saline, did not standardize the insertion force and drilled with a running speed of 20,000 rpm. Furthermore, Pallan[36] showed that the histological changes, including absence of osteocytes, were never apparent more than 250 to 500 µm from the pins[36]. Like Eriksson they did not standardize insertion force and drilling time varied from 5 to 12 s.

No osteoclastic activity was noticed in the already existing cortex. This was expected as Pallan[36] hardly noticed osteoclastic activity after six weeks, and only slight osteoclastic activity after eight and ten weeks and our experiments covered a time span of only four weeks.

We are convinced that delayed tissue response corresponds with late K-wire loosening seen in daily practice. Although we did not compare drilling, with and without cooling, this study demonstrates the need for a short drill time, less than 27 to prevent the disappearance of osteocytes and to limit the bone resorption cascade.

ACKNOWLEDGEMENTS

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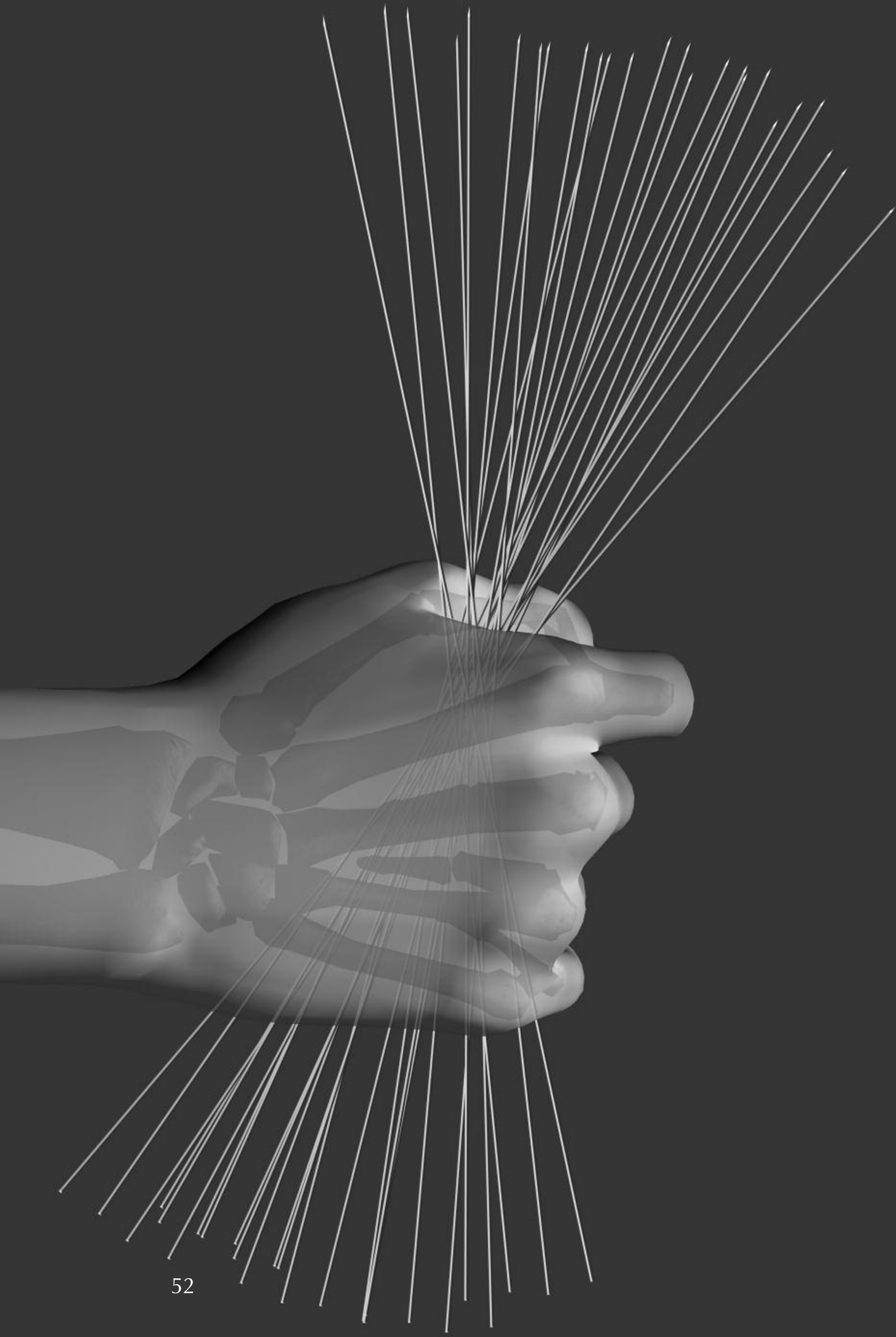

CHAPTER 4

Keeping osteocytes alive: a comparison of drilling and hammering K-wires into bone

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ABSTRACT

Background

In this study, the insertion time and histological effects of drilling and hammering K-wires into bone are described.

Materials and Methods

The insertion time was measured while drilling or hammering K-wires into the femurs and tibias of ten rabbits. Four K-wires, inserted in one hind limb, were used for histological examination directly after insertion and four K-wires inserted in the contra lateral hind limb were used for the same measurements four weeks later. The specimens were scored for presence, or absence, of osteocytes, fragmentation of the bone edges, haemorrhage, microfractures, cortical reaction and callus formation around the pin track.

Results

The insertion time needed for drilling in K-wires was significantly longer than that of hammering. Drilling also resulted in the disappearance of the osteocytes in almost all sections while hammering did not have this effect but did result in more microfractures.

Conclusion

Hammering K-wires may be a superior technique because it prevents osteonecrosis and requires a shorter insertion time.

INTRODUCTION

Since the introduction of Kirschner-wires by Martin Kirschner, the drilling technique has been used to insert them into bone[1]. However, drilling generates frictional heat because the debris produced during drilling is not cleared from the drilling track. The heat will largely remain around the drill hole because of the low thermal conductivity of bone. This can lead to local aseptic thermal necrosis. Degenerated osteocytes due to thermal damage is an early sign of necrosis[2-4]. This suggests that the absence, or presence, of osteocytes is a good means to evaluate the presence of thermal damage. Even minimal loss of bone at the implantation site due to necrosis may cause K-wires to loosen post-operatively[2,3,5-17]. The extent of necrosis depends on the temperature reached during drilling[14,17,18].

Many aspects of drilling K-wires have been investigated. Diminishing heat related complications has been the main goal of this research. We now know that adequate cooling is reasonably successful in preventing necrosis[19]. There are, however, fewer studies of the effectiveness of using other insertion techniques, such as an oscillating K-wire driver[20] and a hammering device[13,21], in reducing heat related complications. Hammering in K-wires has been shown to result in lower temperatures, equal, or more, firm fixation of the wires and also to be quicker[13,21]. This technique also protects against the problem of rotating K-wires catching and wrapping adjacent soft tissue around the wire[22,23]. These few papers suggest that hammering in K-wires may be a better method of K-wire insertion than drilling them in. To our knowledge, there are no reports of the histological effects of hammering K-wires into bone *in vivo*.

In this study, we compared the histological effects and the insertion time of drilling and hammering K-wires into femurs and tibias of rabbits.

MATERIALS AND METHODS

Ten female New Zealand white rabbits were studied. Their mean weight was 2.8 (range 2.7 - 3.1) kg. They were treated by placement of four K-wires in the bones of one hind limb with a follow-up period of four weeks. At four weeks, another four K-wires were inserted into the contralateral hind limb and the animals were euthanised.

The rabbits were individually housed in the Central Animal Laboratory, Utrecht University, Utrecht, The Netherlands, on a 12 h/12 h (light/dark) cycle and provided standard diet food and water ad libitum. They received care in compliance with the European Convention Guidelines.

Full approval from the Utrecht University Committee for Experiments on Animals was obtained and was in accordance with Dutch laws on experimental animals.

Pre-operative X-rays were taken to exclude deformities. The animals were then pre-anesthetised with a combination of 2.5 to 5.0 mg im of 10 mg/ml Methadone (Eurovet Animal Health, Bladel, the Netherlands), 2.5 to 5.0 mg im of 10 mg/ml Acepromazine (Ventraquil, Ceva Santé Animale B.V., Naaldwijk, the Netherlands) and 2.0 to 8.0 mg iv of 2 mg/ml Etomidaat-Lipuro (B Braun, Melsungen AG, Germany). The rabbits were cuffed and mechanically ventilated with a 1:1 mixture of O_2 and N_2O and 2% Isoflurane (Abbott laboratories Ltd, Berkshire, England).

During surgery, the rabbit was fixed to an operation device enabling positioning of the pneumatic hammer or drill fitted with a K-wire in front of the femur or the tibia.

The drill

Drilling was performed with a rotary engine set at 1.200 rpm[24]. This corresponds to the maximum drilling speed of the standard K-wire insertion machine we use in the theatre. The insertion force was standardised using a 1.5 kg weight for drilling.

The hammer

Hammering was performed with a Lithoclast hammering device[21] (EMS Medical GmbH, Konstanz, Germany). This handheld device was originally used for intracorporeal disintegration of urinary calculi. The K-wire is inserted into the top of the device such that 42 mm of the K-wire are within the device and 28 mm are protruding. The device is connected to a unit in which a hammer pressure of 1.0 Bar is generated. On touching a foot pedal, the pneumatic hammer mechanism is activated, resulting in one tap on the K-wire to drive it forward. The insertion force was standardised using a 1.0 kg weight for hammering.

Surgical technique

A straight-line skin incision was made on the lateral aspect of the femur extending from just below the anterior inferior iliac spine to the distal femur. Then, a straight-line skin incision was made on the lateral aspect of the tibia extending from just distal to the knee joint to just proximal of the ankle joint. Dissection was carried out down to the periostium. 0.6 × 70 mm Trocar tipped K-wires (Synthes, Zeist, the Netherlands) were inserted parallel to each other through the diaphysis of the bone. Two K-wires were inserted into the femur of one hind limb of each rabbit, one by drilling and one by hammering, and two K-wires were inserted into the tibia of the same hind limb, one by drilling and one by hammering. After penetration of the first cortex, drilling or hammering was stopped as soon as the resistance of the second cortex was noted. The K-wires were cut and the ends were bent towards the first cortex before closure of the wound. X-rays were taken to assess K-wire position and the condition of the bone. At the end of the procedure, the rabbits received a dose of 1.0 to 2.0 mg/kg iv of 10mg/ml Nalbuphine (Nubain, Du Pont Pharma GmbH, Bad Homburg, Germany) for pain relief and were housed in the Intensive Care for the rest of the day and night.

The surgery was recorded on video. This allowed us to measure the duration of drilling or hammering of each K-wire.

The same surgical procedure was repeated in the second hind limb of all ten rabbits, 28 days later.

Immediately after the second procedure, t = 0 measurements were performed on the second limb and t = 4 measurements were performed on the first. The rabbits were then euthanized by an intravenous overdose of Pentobarbital (Sanofi Santé Animale, Libourne, France). The femur and tibia were removed from the hind limbs, sawn into pieces and fixed in 4% formaldehyde solution. They were then decalcified, cut transversely next to each K-wire track and embedded in paraffin, according to standard procedures. Four µm thick serial sections were cut until the K-wire tracks were visible. The sections were stained with Hematoxylin and Eosin and evaluated under a light microscope at 400 × magnification by a single investigator. Only the most representative section of each K-wire track was used.

Histological evaluation

The histological sections were evaluated for the absence of osteocytes in the osteocyte lacunae next to each K-wire track as a measure of bone necrosis.
Fragmentation of the bone edges, haemorrhage and microfractures were defined as a measure of mechanical damage. In respect of the fragmentation of the bone edges we measured the number and size of bone splinters. The results were graded semi-quantitatively as none, moderate or severe. Judgement of these three grades was made on the basis of the changes seen in all the slides and relative to each other.

Haemorrhage evaluation was based on the percentage of involved bone marrow. The results were graded semi-quantitatively as none, moderate or severe. Judgement of these three grades was made on the basis of the changes seen in all the slides and relative to each other.

Microfractures were evaluated as present or absent.

Reaction in the already existing cortex next to the pin track and callus formation at the outer cortex surrounding the K-wire were typical late cortical reactions.

Reaction in the cortex next to the pin track was compared to the unaffected cortex in the same section and was evaluated for signs of reactive cortical osteoblastic reaction.

Callus formation arising from the outer cortex surrounding the K-wire was evaluated as present or absent.

Insertion time is presented as the mean followed by standard error of mean (SEM).

Statistics

All of the results were processed with SPSS 12.0.1 for Windows. Between-group differences with respect to the absence of osteocytes and mechanical damage measurements were analysed by the Pearson Chi-Square Test or Fisher's Exact Test. Between-group differences in fragmentation and haemorrhage measurements were analysed by the Pearson Chi-Square Test. Statistical significance was set at $p < 0.05$.

RESULTS

Four K-wires were inserted into each of 20 hind limbs. Within 24 hours of the first surgery, two rabbits developed a fractured hind limb during recovery in the intensive care. After the diagnosis was made and before termination the contralateral hind limb underwent the same insertion procedure, resulting in four hind limbs which were used for $t = 0$ measurements. This resulted in 48 $t = 0$ and 32 $t = 4$ measurements. Four measurements had to be excluded because no sections could be produced showing the K-wire tracks, leaving 45 $t = 0$ and 31 $t = 4$ assessments.

The X-rays showed no fractures, either before or directly after, surgery.

The histological data are summarised in *Table 1*.

Histological measurements

The drill-inserted sections showed significantly more sections with empty osteocyte lacunae around the K-wire tracks than the hammer-inserted sections, in which, in all the cases except for one, the osteocytes were still present in their lacunae, directly ($p < 0.001$) and four weeks ($p < 0.001$) after insertion.

At $t = 0$, fragmentation of the bone edges was significantly more evident in the hammer-inserted section (*Figure 1*) than in the drill-inserted sections

($p < 0.001$) (*Figure 2*). At $t = 4$ no significant difference was seen between the two techniques with respect to bone edge fragmentation ($p = 0.678$). Haemorrhage was significantly more severe after hammered insertion at $t = 0$ ($p = 0.001$) and at $t = 4$ ($p = 0.006$) (*Figure 3*).

			T = 0			T = 4	
		Drilling	Hammering	p-value	Drilling	Hammering	p-value
Osteocytes	Present	11	23	<0.001*	2	15	<0.001*
	Vanished	11	0		13	1	
Fragmentation of bone edges	None	3	0	<0.001*	7	5	0.678*
	Moderate	16	4		5	7	
	Severe	3	19		3	4	
Haemorrhage	None	9	0	0.001*	2	1	0.006*
	Moderate	12	16		13	7	
	Severe	1	7		0	8	
Micro fractures	None	22	12	<0.001*	15	16	
	Present	0	11		0	0	
Cortical Reaction	None	22	23		0	0	
	Present	0	0		15	16	
Callus Formation	None	22	23		3	2	0.654**
	Present	0	0		12	14	

* Pearson Chi-Square Test

** Fischer's Exact Test

Table 1. Histological response to drilling versus hammering K-wires into rabbit bone directly ($t = 0$) and after 4 weeks ($t = 4$).

Significantly more micro fractures were seen after hammered insertion but only at $t = 0$ ($p < 0.001$)(*Figure 4*). At $t = 4$, no microfractures were visible after either method of insertion.

At $t = 0$ cortical reaction and callus formation were not seen after either method of K-wire insertion. At $t = 4$, however, all the specimens examined showed cortical reactions, whether due to drill or hammer insertion and in 26 of the 31 sections, callus formation around the K-wire track was seen; the difference was not significant (*Figure 5*).

Insertion time showed a more than four times difference and was significantly longer for drilling compared to hammering, respectively, 88.4 (10.6 SEM) s versus 17.7 (2.9 SEM) s ($p < 0.001$).

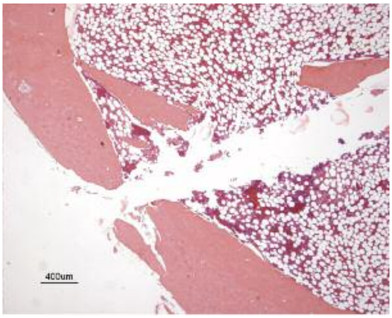

Figure 1. Severe fragmentation of the bone edges directly after hammering a K-wire into rabbit bone.

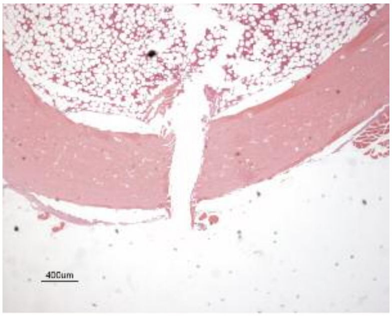

Figure 2. Moderate fragmentation of the bone edges directly after drilling a K-wire into rabbit bone.

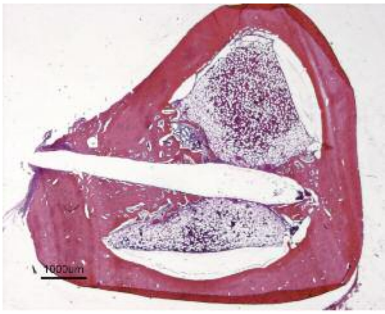

Figure 3. Haemorrhage four weeks after hammering a K-wire into rabbit bone.

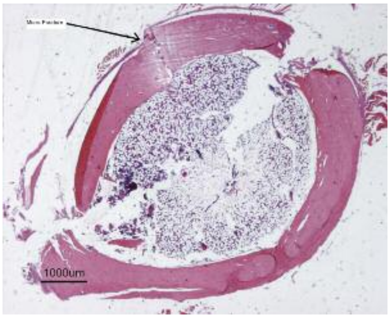

Figure 4. Micro fracture in rabbit bone directly after hammering a K-wire

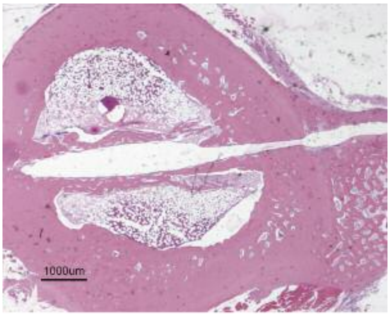

Figure 5. Cortical reaction and callus formation around the pin track four weeks after drilling a K-wire into rabbit bone.

DISCUSSION

The most important findings of this study were that osteocytes do not disappear from their lacunae after insertion of K-wires by hammering and a significantly shorter insertion time is needed for this technique. However, hammering results in an increased occurrence of microfractures, more severe fragmentation and more severe haemorrhage.

After drill insertion of K-wires, osteocytes disappeared from their lacunae next to the K-wire track in 11 of the 22 sections examined immediately and in 13 of the 15 sections examined at 4 weeks after surgery, indicating the fact that the effect of thermal necrosis increases over the four weeks after K-wire insertion. In contrast, the histological sections after insertion of the K-wires by hammering showed, with the exception of one specimen, that the osteocytes were still present in their lacunae around the K-wire track, i.e. there is no osteonecrosis at all. Most probably, this is due to the short duration of the insertion time and the lack of heat generated during hammer insertion, as reported in previous *in vitro* studies[13,21]. These results would suggest that K-wire loosening is less likely after hammer insertion, especially during long term fixation, because of the absence of osteocyte loss after this method of insertion.

Microfractures, however, were seen only after hammer insertion. There may be several explanations for this phenomenon. First, we used a foot pedal to insert the K-wire and at each tap the K-wire received a maximal insertion force. It might have been better to insert the K-wire by means of a fast repeating movement. Second, the pressure applied by the hammer device to the K-wire was standardised at one bar, which might be too much for these fragile bones. Zegunis et al. advocated use of a lower pressure when using fragile and small bones[13]. After four weeks, no microfractures were seen at all. This may suggest that microfractures, arising as a result of hammer insertion of K-wires, do not influence long term loosening because the microfractures will heal in four weeks.

Our sections also showed that hammer insertion of K-wires results in more severe fragmentation of the bone edges. The difference in severity of fragmentation between the two methods of wire insertion had, however, completely disappeared four weeks later. These results, again, suggest that this factor is unlikely to influence K-wire fixation after four weeks.

The difference in haemorrhage observed between the insertion techniques may be explained by the temperature rise during drilling: this stops the blood flow in minor vessels[15,16,25]. Hammer insertion does not cause high temperatures to occur for such a long insertion time[13,21].

Furthermore, more severe fragmentation of bone during hammer insertion of K-wires is probably also responsible for an increase in haemorrhage.

Although, in hand surgery, K-wires with a diameter of about 1.0 mm are commonly used, we used K-wires with a diameter of 0.6 mm in our study because a pilot study showed that this K-wire diameter was the best size suitable for the bone diameter in a rabbit model and, therefore, resulted in an optimal experimental set-up. During K-wire insertion, the K-wires did not bend or deform, probably because only 28 mm of the wire stuck out of the pneumatic hammer handheld device.

Because this study suggests that hammer insertion may be a superior technique of K-wire insertion to drilling the wires into small bones, our present research is focussed on 1.0 mm K-wire insertion into fresh-frozen human metacarpals using an adapted oscillating device used in clinical practice (MicroAire 2500).

ACKNOWLEDGEMENTS

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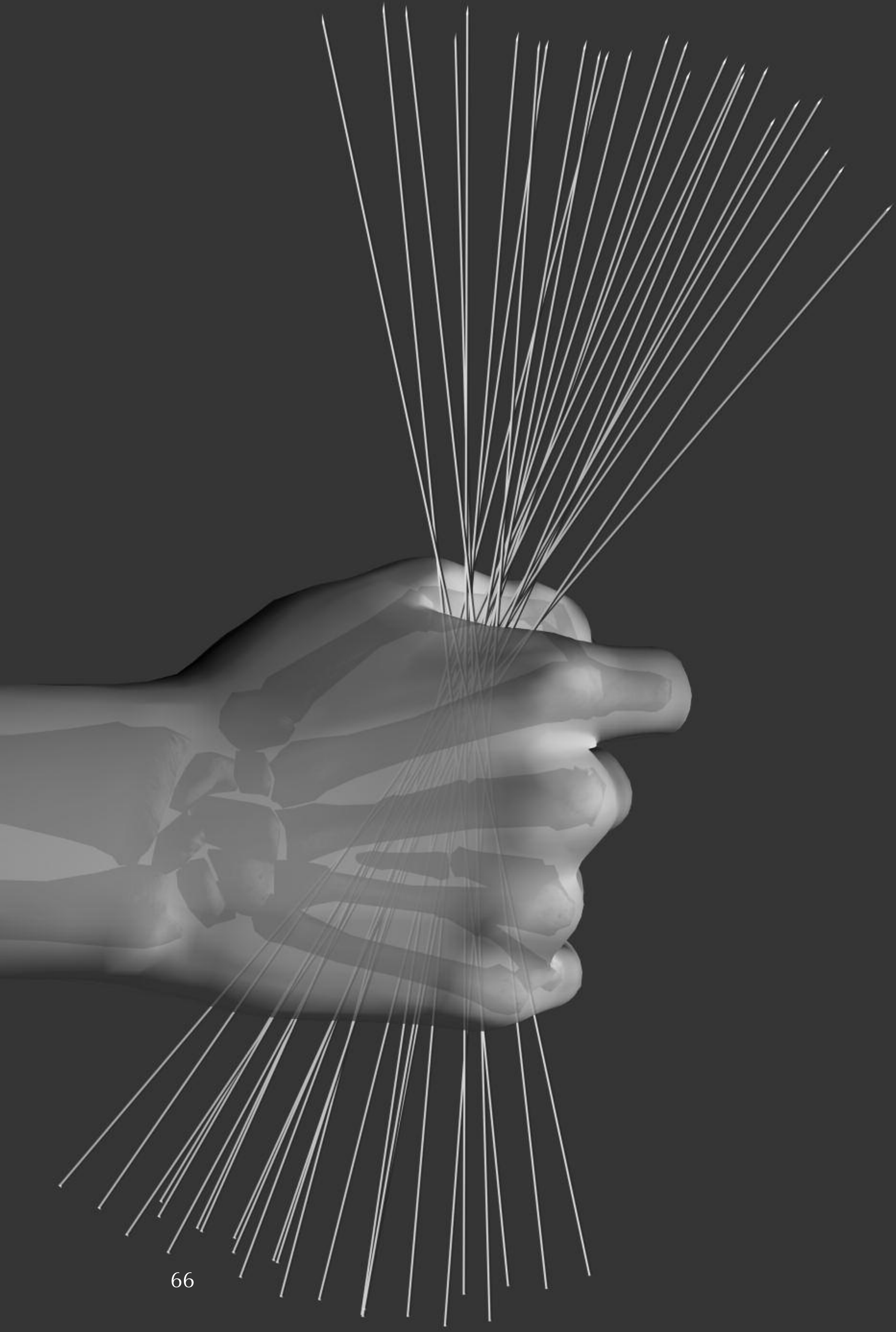

CHAPTER 5

Fixation of Kirschner wires: A comparison between hammering and drilling K-wires into ribs of pigs

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ABSTRACT

Background

Kirschner wire (K-wire) fixation is a well-accepted method for stabilization of fractures. However, the rotary drill traditionally used for insertion leads to a considerable amount of complications (33%). Another method for insertion was tested which might possibly reduce these complications – hammering.

Material and Methods

Forty-four K-wires were inserted into fresh frozen ribs of pigs using a drilling and a hammering technique. Peak extraction force, peak torque, and insertion time were measured.

Results

The mean peak extraction forces for drilling and hammering were 57.4 and 129.0 N, respectively. The mean peak torque for drilling and hammering were 2.4E-02 and 5.7E-02 Nm, respectively. Using the drilling technique, it took 73.6 s to insert the K-wire compared with 18.4 s for hammering. At the exit site, there were splinters of bone in 18 of the 22 hammered K-wires and in 2 of the 22 drilled K-wires.

Conclusion

This study showed that hammering K-wires in ribs of pigs gives better initial fixation and results in a shorter insertion time.

INTRODUCTION

Kirschner wire (K-wire) fixation is a well-accepted method for stabilization of fractures and dislocations. This method is primarily used in orthopaedic, trauma, and hand surgery. K-wire fixation using a rotary drill is still an indispensable method because it is simple yet efficacious. However, this traditional insertion technique lead to complications in up to 33% of the cases in which a K-wire was used. These complications include infections, K-wire loosening without infection, K-wire migration, and, in rare cases, artery and nerve injury. K-wire migration can result in a devastating outcome[1-13]. These complications may be due to either osteonecrosis from thermal damage, inferior pin fixation caused by the rotary insertion technique, or both.

Different methods of inserting K-wires have been studied to decrease complication rates: using an oscillating K-wire driver[14], changing the K-wire tip, or changing the insertion speed[9,15-18]. Another technique which might overcome the disadvantage of drilling K-wires into bone is to use a hammering device. Theoretically, hammering K-wires into bone has several advantages. It generates less energy at the K-wire tip and therefore produces less heat than drilling[19]. The fixation of the wire may also be superior because the bone is pushed aside instead of being fragmented by the rotating K-wire point. These advantages may lead to a better fixation in the long term and this can help to decrease the percentage of complications. The aim of this study is to measure and compare the initial strength of fixation of K-wires to bone using two different insertion techniques: drilling and hammering.

MATERIALS AND METHODS

Bones and K-wires

One-size trochar-tipped K-wires (1.25 × 150 mm) were used. They were checked to be of equal tip configuration using a profile projector: the tip had three equal planes, with the tip exactly in the center. The length of the ellipse was 2.4 ± 0.05 mm. The angle of the plane to the axis was 14.5°.

Ribs of three-year-old pigs were obtained from the abattoir, the surrounding soft tissue was removed, and the ribs were stored in a freezer (-20°C). Before testing, the ribs were allowed to defrost and acquire room temperature (20°C). The ribs were chosen to be comparable to each other in size and thickness.

Drilling and hammering

The ribs were fixed in a clamp device with the portion receiving the pin not between the clamp. The diaphyseal entry sites for drilling and hammering were chosen to be comparable in each pair. A pair of K-wires (drilling and hammering) was always tested on the same rib. A maximum of five pairs of K-wires were tested on each rib to ensure comparable insertion sites between the pairs.

Measurements

The clamp device was placed on a rail on a tilting platform to allow for constant insertion force (axial load). The force was increased during testing until the pin entered the bone: 16.4 ± 4.9 N for drilling, 7 N for hammering (*figure 1*). The hammering device used is based on the Swiss LithoClast (EMS Medical GmbH, Konstanz, Germany), an instrument for the intracorporeal disintegration of urinary calculi. It uses shock waves, normally used to disintegrate calculi, for hammering the K-wire into bone. The hand piece holds K-wires from 0.6 to 2.0 mm in diameter. The drilling (rotary engine) or hammering device was bolted on a tilting platform. The drill speed was set at 600 rpm. The hammering pressure was $1.86\times10^5 \pm 0.35\times10^5$ Pa (1.86 ± 0.35 bar). The K-wire entered the rib perpendicular to the diaphyseal surface 50 mm from the clamp. Time from start of insertion to exiting of the second cortex was measured with a handheld stopwatch.

After insertion through the bone, the K-wires were evaluated for holding strength in the bone by peak pullout force and peak torque force.

To measure the peak torque, a bar (50 mm) was fixed at a right angle to the K-wire. The measuring device (9500 series CPU digital force gauge, AiKOH Engineering Co., Ltd.) was connected to this bar and pulled at until the K-wire started turning. The device kept the maximum torque in memory. To measure the peak pullout force, the measuring device was held in line with the K-wire attached to the bar. By gradually increasing force, the K-wire was pulled out. The maximum force was then read from the readout.

Statistical evaluation

The computer program SPSS 9.0 for Windows was used to calculate the results from this experiment. In this program, the paired-samples t-test was used to evaluate the differences in mean peak pullout force and mean peak torque for each of the two techniques. The Kolmogorov-Smirnov test of normality was used to evaluate the range.Finally, the Wilcoxon signed ranks test was used to evaluate differences in insertion time between the two techniques.

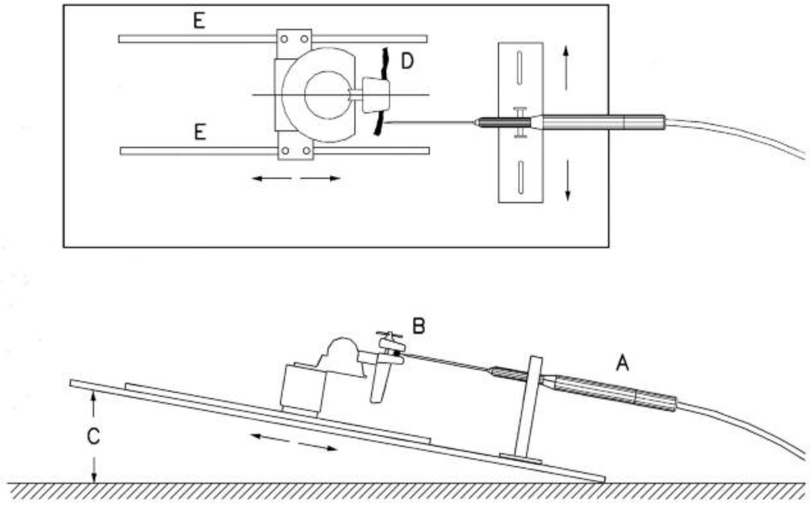

Figure 1. Side-view of experiment: A = hammering device; B = clamp device on tilting platform; C = variable height of platform. Top-view of experiment: D = rib in clamp device; E = rail on which clamp device slides.

Results

Forty-four K-wires were inserted on five ribs. Twenty-two K-wires were drilled, and 22 K-wires were hammered.

Insertion time

The time necessary to drill the K-wire into bone is significantly longer (Wilcoxon signed rank test, *p* = 0.001; *Table 1*) than the time necessary to insert a K-wire using the hammering technique: 73.6 s (range 10 – 267 s) compared to 18.4 s (1.5 -152 s; *figure 2*).

Wilcoxon test	Mean	SD	z	p
Insertion time (s)				
Drilling	73.6	75.8		
Hammering	18.4	33		
Difference	55.2	78.9	-3.44	0.001

Table 1. Results from the Wilcoxon signed rank test for insertion time. SD = standard deviation.

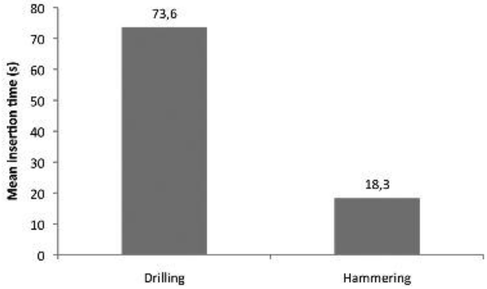

Figure 2. Mean insertion time. Drilling versus hammering in pig ribs.

Peak torque

The mean peak torque using the hammering technique was 5.7E-02 Nm (range, 3.0 - 7.5E-02 Nm) versus 2.4E-02 Nm (range, 1.0 - 5.0E-02 Nm) when using the drilling technique, this is significantly higher ($p < 0.001$; *table 1, figure 3*). The 44 K-wires are normally distributed as tested by the Kolmogorov-Smirnov test.

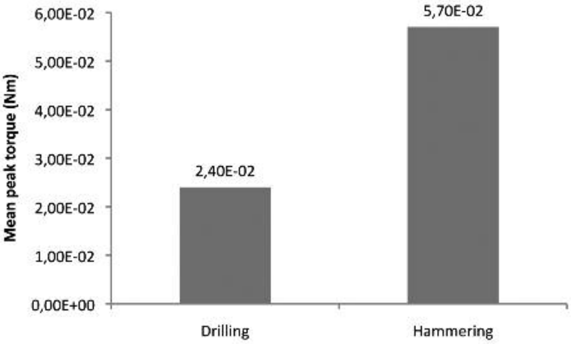

Figure 3. Mean peak torque. Drilling versus hammering in pig ribs.

Kolmogorov test	mean	SD	t	p
Pullout force (N)				
Drilling	57.4	25		
Hammering	129	43.5		
Difference	-71.6	43.2	-7.78	<0.001
Torque (Nm)				
Drilling	2.4E-02	1.1E-02		
Hammering	5.7E-02	1.2E-02		
Difference	-3.3E-02	-1.5E-02	-10.1	<0.001

Table 2. Results from the Kolmogorov-Smirnov test for peak pullout force and peak torque.

Peak pullout force

None of the samples demonstrated a higher peak pullout force using the drilling technique (*figure 4*). The peak pullout force after using the hammering technique to insert the K-wire was 129.0 N (range, 57.2 - 201.5 N) versus 57.4 N (range, 21.6 - 108.5N) for the drilling technique. This is significantly higher ($p < 0.001$; *table 1*, *figure 5*).

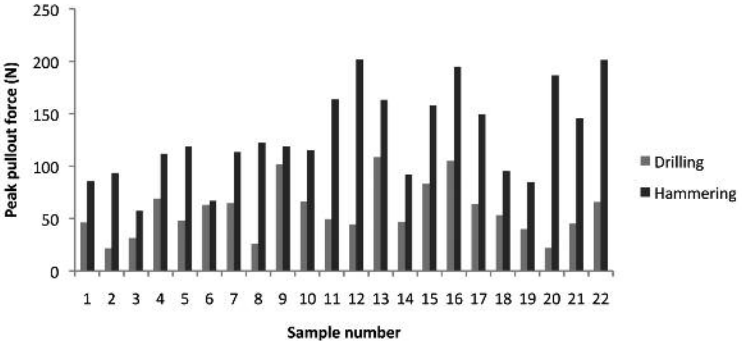

Figure 4. Peak pullout force in each separate pair. Drilling versus hammering in pig ribs.

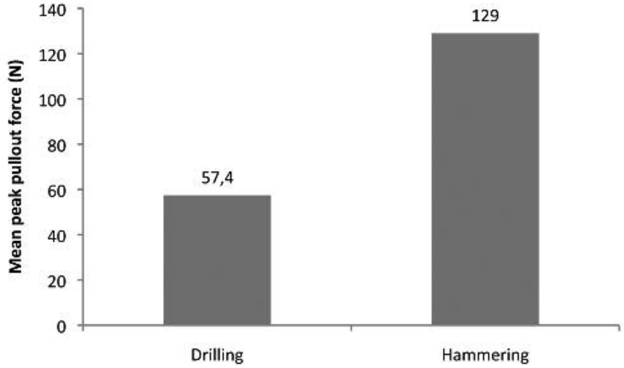

Figure 5. Mean peak pullout force. Drilling versus hammering in pig ribs.

Splintering of bone

In 81% of the hammered K-wires, there was splintering of bone at the exit site. This splintering was only found in 9% when drilling the K-wire into bone.

DISCUSSION

Zegunis et al.[19] used ox, sheep, and pig bone to study heat generation during K-wire insertion using both hammering and drilling techniques. In our study, we used pig ribs. They were readily available, easy to use, and comparable in size to each other. However, it should be noted that porcine ribs consist of membranous bone, which has different properties from trabecular and cortical bone, into which most K-wires are drilled in humans.

The results of our study showed overall significantly better initial fixation for peak pullout and peak torque with the hammering technique compared with the drilling technique. Zegunis et al.[19] also showed that inserting K-wires using a hammer produces superior initial fixation and generates less heat. High temperatures during insertion are thought to be the main cause of osteonecrosis; in drilling, this situation leads to loosening and pin migration due to bone resorption as a result of the osteonecrosis[1,4-6,11,15,16,20-22].

Wrapping of tissues (tendon, nerves, and blood vessels) around the K-wire during drilling[3,12,14] is much less likely to happen using the hammering technique.

To insert the K-wire into ribs, different insertion forces were necessary using the drilling technique. During hammering the same force was sufficient every time a K-wire was inserted.

A possible disadvantage of the hammering technique is the splintering of bone that arises especially at the exit site of the second cortex. Because the surrounding tissue was removed from the ribs, the periostium might be damaged. On the other hand, the contribution of periostium in preventing splintering also needs further investigation.

Several mechanisms have been investigated to improve the fixation strength of K-wires. These include predrilling and different drilling speeds[15,17]. Changing the tip might also be a way to improve the K-wires' drilling qualities[9,15,17,18,23].

Proving that hammering K-wires into bone produces superior initial fixation than the traditional drilling technique is an important step toward the development of better K-wire insertion.

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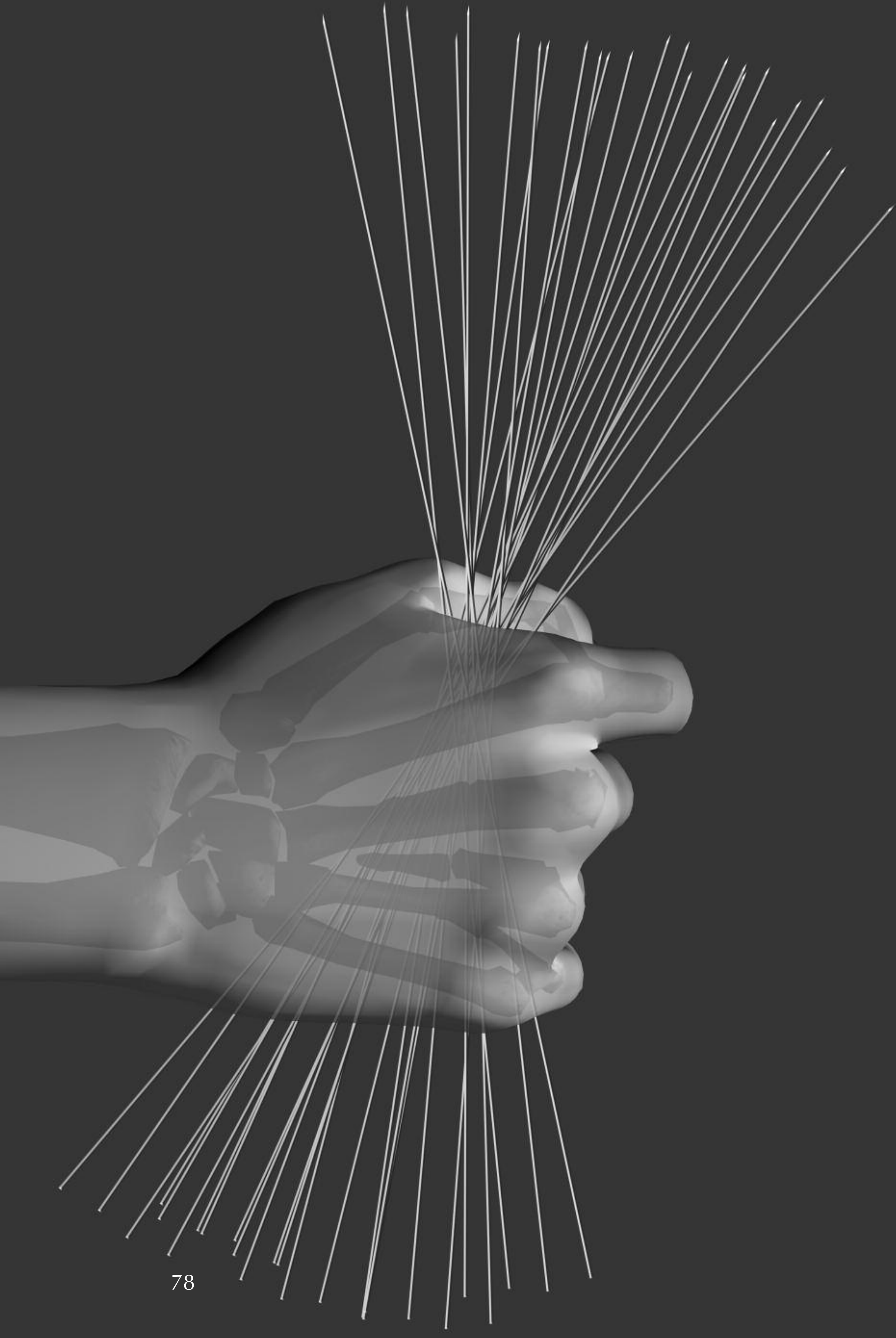

CHAPTER 6

In vivo biomechanical comparison of hammering versus drilling of Kirschner wires; a pilot study in rabbits

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M Kon

Eur. J. Plast. Surg. 2007; 30: 29-33

ABSTRACT

Background

Heat generation due to drilling Kirschner wires (K-wires) into bone can lead to serious complications. Hammering K-wires could be an alternative insertion method because it generates less heat and results in better fixation and a shorter insertion time. There is, however, no *in vivo* information about insertion time and biomechanics of hammered K-wires

Animals and methods

Insertion time was measured when drilling or hammering K-wires into femurs and tibias of 16 New Zealand White Rabbits. Four K-wires inserted in one hind limb were used to measure extraction and torque forces directly after insertion (t = 0) and four K-wires inserted in the controlateral hind limb were used for the same measurements four weeks after insertion (t = 4).

Results

The insertion time needed for hammering was significantly shorter compared to drilling. Extraction and torque properties measured at t = 0 and t = 4 were equal for both techniques. Hammering, however, resulted in more cracks.

Conclusion

Based on these results neither of these methods can be identified as a superior technique to insert K-wires in fragile bones.

INTRODUCTION

Hand fractures are the second most common fractures after forearm fractures. They account for up to 20% all fractures[1,2]. K-wire fixation, especially, is treatment of choice if the forces of the intrinsic and extrinsic tendons prevent adequate splint or cast immobilization[3]. A high-speed drill is the standard tool used to insert K-wires into bone[4]. This percutaneous technique is considered as a simple and quick method that reduces post surgical swelling and stiffness compared to open reduction and internal fixation[5]. The currently used drill technique, however, can cause human phalanges to reach temperatures up to 141°C, which can result in serious heat-related complications[6-9]. If temperature exceeds 47° C for 1 minute, osteonecrosis occurs[10-12]. This may cause infection and loosening of pins[6-8]. Pin-track infections require early removal of the pins, even before consolidation is reached[13]. Pin-track infections occur in up to 18% of the cases, 42% of which finally result in nonunions and even cases of osteomyelitis[3,14-17].

Hammering can be an alternative insertion method of K-wires. Hammering has some advantages compared to drilling *in vitro*, including lower temperatures, better initial fixation, and shorter insertion time[9,18]. However, to our knowledge, there are no reports of biomechanical aspects of hammered K-wires *in vivo*. Therefore, in the present study, we compared biomechanics and insertion time of drilled and hammered K-wires.

K-wires were inserted into femurs and tibias of rabbits by drill or pneumatic hammer. Besides insertion time, we measured extraction forces to remove the K-wires and torque forces necessary to turn loose the K-wires, directly ($t = 0$) and 4 weeks after surgery ($t = 4$).

MATERIALS AND METHODS

Sixteen female New Zealand white rabbits (2.94 ± 1.48 kg) were used. They were individually housed on a 12 h/12 h (light/dark) cycle and provided with standard diet food and water ad libitum. All animals were housed in the Central Animal Laboratory, Utrecht University, Utrecht, the Netherlands and received care in compliance with the European Convention Guidelines. Full approval from the Utrecht University Committee for Experiments on Animals was obtained and was in accordance with Dutch laws on experimental animals.

The animals were pre-anesthetized with a combination of methadone (10 mg/ml at a dose of 2.5-5.0 mg i.m.), ventraquil (10 mg/ml at a dose of 2.5-5.0 mg i.m.) and etomidaat (2 mg/ml at a dose of 2.0-8.0 mg i.v.).

Pre-operative X-rays were made to exclude deformities. The rabbits were cuffed and mechanically ventilated with O^2:N^2O (proportion 1:1) and 1% halothane.

During surgery, the rabbit was fixed on an operation device (*figure 1*) enable positioning of the pneumatic hammer or drill including K-wire in front of the femur or tibia. The insertion force was standardized using a 1.5 kg or a 1.0 kg weight for drilling and hammering, respectively.

Hammering was performed with a Lithoclast hammering device[18] (EMS Medical GmbH, Konstanz, Germany). The pressure was standardized at 1.0 Bar. Drilling was performed with a rotary engine set at 1,200 RPM[19].

Methadone was administered (2.0-5.0 mg i.v.) during surgery. A straight-line skin incision was made on the lateral aspect of the femur extending from just below the anterior inferior spine to the distal femur. Then, a straight-line skin incision was made on the lateral aspect of the tibia extending from just below the joint line proximal to the joint line distally. Dissection was carried out down to the periostium. Trocar tipped K-wires (0.6 × 70 mm, Synthes, Zeist, the Netherlands) were inserted parallel to each other through the diaphysis of the bone. Four K-wires were inserted using hammering and drilling in one hind limb of each rabbit; two K-wires in the femur and two in the tibia. After penetration of the first cortex, drilling or hammering was stopped as soon as resistance of the second cortex was noticed. K-wires were cut and ends were bent towards the cortex before closure of the wound. X-rays were made to assess K-wire position and condition of the bone. At the end of the procedure, the rabbits received Nalbuphine (10 mg/ml at a dose of 1.0-2.0 mg/kg i.v.) and were housed at the Intensive Care Unit for the rest of the day and night. Surgery was taped on video; after the procedure, we could exactly measure duration of drilling and hammering.

The same surgical procedure was repeated in the second hind limb, 28 days later. Immediately after the second procedure $t = 0$ measurements were performed on the second limb, and $t = 4$ measurements were performed on the first. The rabbits were euthanized by an i.v. overdose of pentobarbital. With the K-wires in situ, femur and tibia were inspected for fractures. One K-wire was used either for torque or for extraction measurements. The femur and tibia were placed in a bench device, after which the K-wire was extracted with an advanced force Gauge (MECMESIN AFG 1000N). Torque force was measured with a torque apparatus developed by the department of Oral and Maxillofacial Surgery, Prosthodontics and Special Dental Care, Utrecht Medical Center Utrecht, the Netherlands.

Within-group or between-group differences in the extraction and torque measurements were analyzed by the Bonferroni Multiple Comparisons and Independent *t*-test respectively. Between-group differences in excluded measurements were analyzed with Fisher's Exact Test. Statistical significance was determined based on $p<0.05$. Data were analyzed using SPSS 12.0.1 for windows.

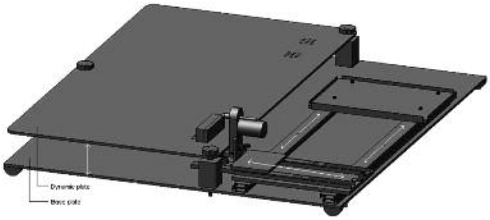

Figure 1. The operation device used in this study

RESULTS

X-rays showed no fractures either before or directly after surgery. Eighty-three K-wires were used for measurements. Five rabbits were excluded for further analysis due to femur or tibia fractures within 24 h after surgery. This resulted in the exclusion of 8 directly and 21 indirectly fracture-related measurements (*figure 2*). Additionally, 16 were excluded due to insufficient penetration of K-wires (n=3) and loose K-wires due to a crack (n=13) (*figure 3*). Hammering resulted in significantly more cracks (*p*<0.000).

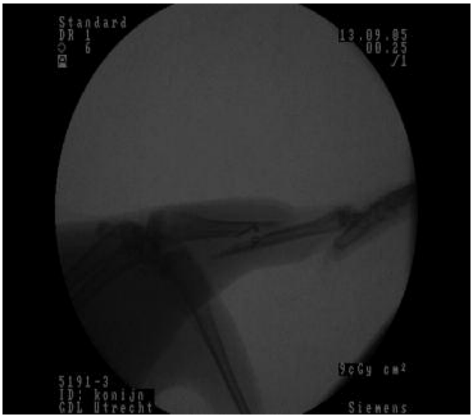

Figure 2. Broken tibia one day after K-wire insertion

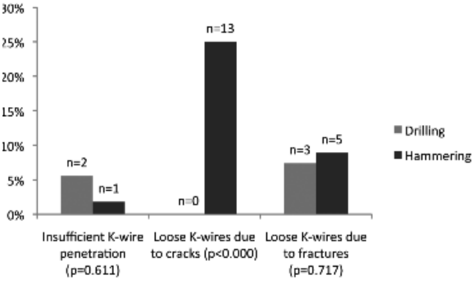

Figure 3. Percentage of excluded measurements for hammered and drilled K-wires

Biomechanical measurements

Biomechanical measurements showed no significant difference for both time points. Extraction forces are presented in *figure 4a* and torque forces in *figure 4b (table 1)*.

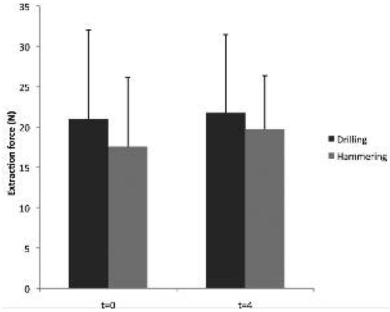

Figure 4a. N = Newton. Mean values and standard deviations are denoted by *boxes* and *error bars*, respectively. p=0.374 at t = 0 and p=0.722 at t = 4.

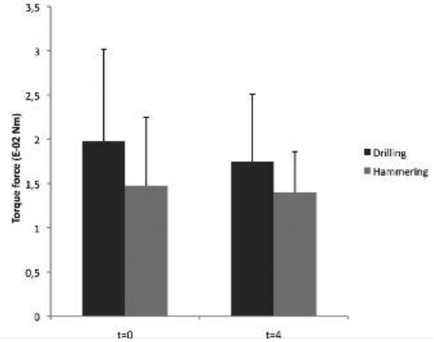

Figure 4b. Nm = Newton meter. Mean values and standard deviations are denoted by *boxes* and *error bars*, respectively. p=0.113 at t = 0 and p=0.516 at t = 4.

Article	Animal model	K-wire Ø (mm)	Drilling speed(rpm)	Extraction force (N)
Present results	Rabbit femur/ tibia	0.6	1200 (t = 0) 1200 (t = 4)	21.0 ± 11.0 21.8 ± 9.7
Wassenaar et al.[18]	Pig ribs	1.25	600	57.4 ± 25.0
Rubel et al.[20]	Bovine femur	2.0	n a*	37.7 ± 13.6
Namba et al.[19]	Canine metacarpals	1.57	800 400	45.8 ± 24.5 113.30 ± 36.9
Graebe et al.[21]	Canine metacarpals	1.57	400 200	77.8 ± 37.3 148.0 ± 27.2
Zohman et al.[22]	Canine metacarpals	1.57	215	137.8 ± 20.6

*n a = not available, N = Newton, RPM = Revolutions Per Minute

Table 1. Drilled Kirschner wires: extraction force

Duration

Insertion time was significantly longer for drilling compared to hammering: 142 ± 21 vs 13 ± 1.6 s, respectively ($p<0.000$).

DISCUSSION

The most important findings of this experiment are that (1) extraction and torque forces of drilled vs hammered inserted K-wires are equal (2) hammering K-wires results in a significant shorter insertion time but (3) results in increased occurrence of cracks.

Compared to other reports in the literature, our extraction measurements for drilled K-wires were lower (*table 1*). A reason for these lower extraction forces is the use of smaller-diameter K-wires in the present study[19]. This was necessary because bigger-diameter K-wires cause unacceptable bone damage in this model. An additional reason could be the currently used drilling speed, which was higher compared to that used in other published experiments, resulting in lower extraction forces[19,21]. We choose a drill speed of 1,200 rpm because this is the maximum drill speed used in our clinic.

This is the first experimental study to compare these insertion modalities *in vivo*. In an earlier report, our study group presented results of *in vitro* comparisons between drilling and hammering. *In vitro*, extraction and torque forces were more than doubled when the hammering technique was used in stead of the drilling technique. Surprisingly, results of the present study show that, *in vivo*, extraction and torque forces are equal for hammered and drilled K-wires. The same equipment was used in a previous study, but during this experiment, the insertion force was increased during K-wire insertion[18]. We think, however, that the contrast is due to the models used, pig ribs vs rabbit limbs.

On the other hand, the present study shows a significantly shorter insertion time when K-wires were hammered. This is in agreement with previous *in vitro* results of Wassenaar et al.[18] and Zegunis et al.[9]. It must be stated, however, that drilling time in the present experiment was relatively long compared to that of studies mentioned above. We found that the use of a weight greater than 1.0 kg when hammering K-wires causes an unacceptable amount of bone damage. Despite the low 1.0 kg weight, cracks occurred more frequently when K-wires were hammered. This was unexpected because collagen of human and rabbit bone tissue are comparable[8,23] and other studies comparing K-wires with different osteosynthesis material also using the rabbit as model never mentioned cracks or fractures[24-26]. An exception was the paper of Zegunis et al.. In this report, it was advised to lower the power produced by the pneumatic hammer in fragile and small bones to prevent fractures[9]. Our results confirm this advice by demonstrating that a low weight of 1.0 kg still is sufficient to cause cracks.

To optimize comparability of hammering and drilling in the present study, a low insertion force weight of 1.5 kg was chosen for drilling, resulting in longer drilling insertion times[27].

Drilling and hammering were both associated with fractures during the first day follow up period. The limbs operated on were not immobilized as would be the case in humans[28]. Stress on the operated limb could not be avoided. This caused the rabbits to use their operated limb freely immediately post-operatively, causing fractures and exclusions from further analysis.

In summary, this is the first study to compare drilling and hammering of K-wires in vivo. Both techniques result in equal extraction and torque forces. Hammering results in significantly reduced insertion times but is associated with increased occurrence of cracks. Based on these results, neither of these methods can be identified as a superior technique to insert K-wires in fragile bones.

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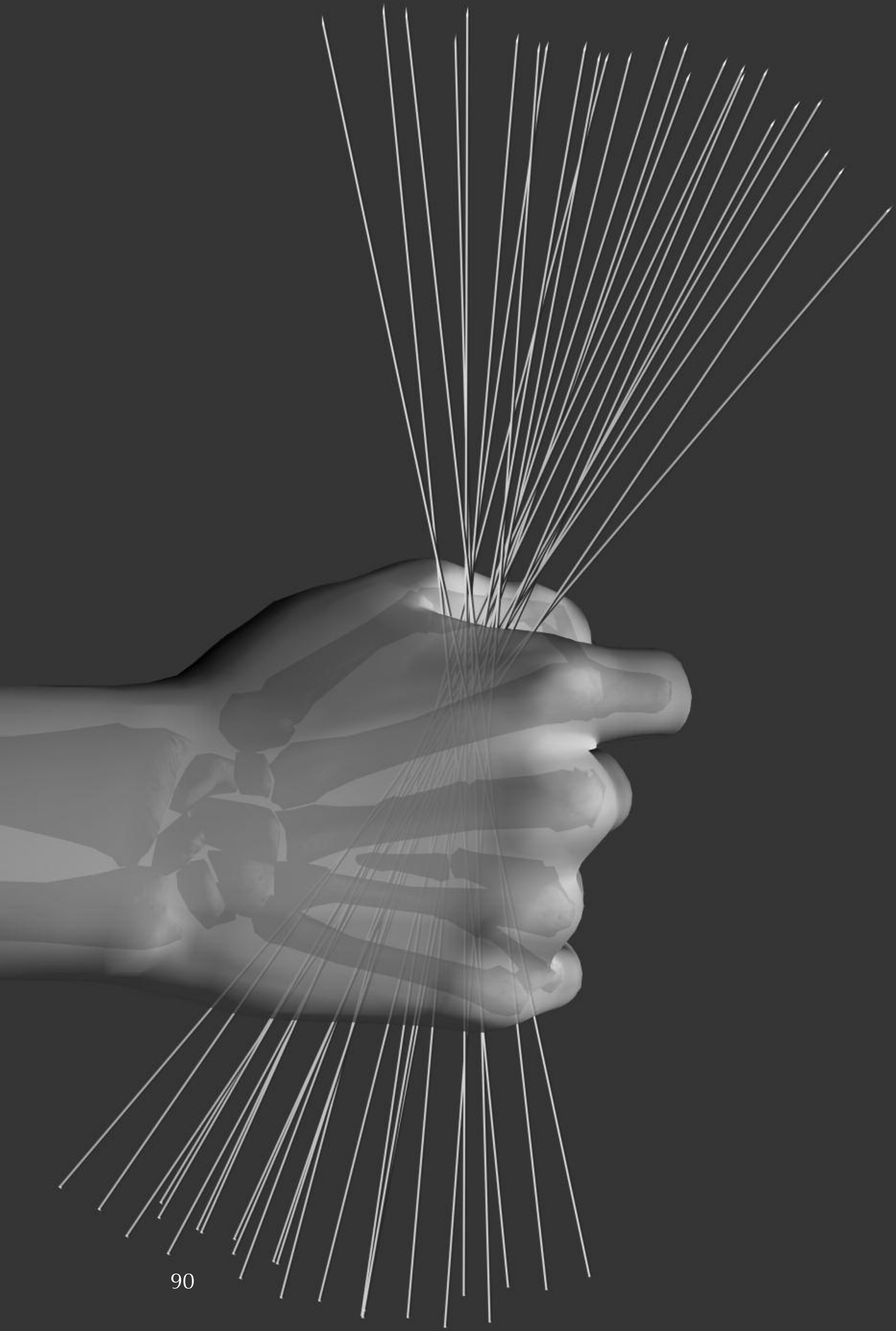

CHAPTER 7

Hammering K-wires is superior to drilling with irrigation

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AH Schuurman
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HAND (N Y). 2009; 4(2): 108-112

ABSTRACT

Background

Cooling during drilling Kirschner wires is not always effective in preventing thermal damage.

Material and Methods

In this study, we used a human *in vitro* model and compared temperature elevation, insertion time and extraction force between three Kirschner wire insertion methods – drilling with and without irrigation and pneumatic hammering. Forty five Kirschner wires were inserted into 15 fresh human cadaver metacarpals. All three insertion methods were applied in each metacarpal.

Results

Drilling without irrigation resulted in a temperature elevation of 67.25 ± 5.4ºC with significantly lower values for drilling with irrigation (4.15 ± 0.6ºC) and pneumatic hammering (31.52 ± 3.4ºC). The insertion time for pneumatic hammering (47.63 ± 8.8s) was significantly lower compared to drilling without irrigation (263.16 ± 36.5s) and drilling with irrigation (196.10 ± 28.5s). Extraction forces after drilling without irrigation, drilling with irrigation and pneumatic hammering were 39.85 ± 4.1N, 57.81 ± 6.5N and 62.23 ± 6.7N, respectively.

Conclusion

Pneumatic hammering is superior to drilling without irrigation, especially when irrigation is not possible.

INTRODUCTION

Kirschner wires (K-wires) are often used in hand surgery because it is a quick and simple method for stabilization of fractures[1]. Multiple passes, type of k-wire configuration, quality of soft tissues, and accuracy of placement are important issues in K-wire fixation. The drilling technique itself may play an important role in the occurrence of frictional-heat-related complications like necrotic bone around the wires[2,3]. This predisposes to pin-track infections and loosening of K-wires which can result in early removal or even osteomyelitis[4,5]. Thermal necrosis is a product of time[6,7], temperature[8,9], drill speed[7,10], insertion force[11,12], K-wire characteristics[13,14] and the factor irrigation[15,16].

The influence of heat generation on bone has long been recognized. Hippocrates (500 BC) even recommended that the trepanning tool must be cooled during bone removal to avoid injury to the surrounding bone[17]. Temperature elevation during drilling into bone is nowadays kept to a minimum by external or more effectively by internal irrigating[16,18]. Internal irrigation however is not useful when drilling K-wires, because it is not possible to let the cooling agent passing down the center of the K-wire[15]. Therefore, the external irrigation technique must be used. This technique is effective when a constant flow is provided at the point of insertion. In areas of limited access, however, this can not be realized and therefore will result in less or no cooling effect at all[16,18,19]. Also, constant external irrigation at the opposite cortex or during percutaneous drilling is usually impossible, resulting in a very low or absent cooling effect[20].

The ultimate K-wire insertion method would be a technique without the necessity of irrigation but with the advantages of drilling and without thermal related complications. K-wire insertion by hammering using a pneumatic hammer could prove to be effective in reaching this goal[21-23]. It has been shown that hammering of K-wires results in lower heat generation, shorter insertion time, less thermal damage and equal or even better initial fixation compared to drilling without irrigation. All together, this suggests that hammering is a good alternative for drilling. These experiments, however, have one major drawback as they used *in vivo* or *in vitro* animal models. Eriksson showed that temperatures measured in animal models are not applicable to the clinical situation[20]. Furthermore, these experiments did not compare drilling with irrigation versus hammering. We therefore designed a study to determine the insertion time, extraction force, and maximum bone temperature while inserting K-wires into human cadaver metacarpals using a pneumatic hammer and comparing these data to conventional drilling with and drilling without irrigation.

MATERIAL AND METHODS

Fifteen fresh human cadaver metacarpals were used. They were collected from two male human cadavers who had no reported history of disorders or diseases related to bone which was verified by X-ray examination. Their ages at death were 75 and 77 years. The metacarpals were denuded of all soft tissue and were measured at two places at the diaphysis resulting in an average diameter of 10.3 mm (SD = 2.1 mm). The experiment was conducted at room temperature (21.6ºC, SD = 1.12ºC) with the bones rigidly fixed (*figure 1*). The fixator was placed on the operation device as described before[2,23]. A weight of 0.5 kg was used for forwards movement of the drill and pneumatic hammer. Three stainless steel trocar tip K-wires (1.0 mm x 150 mm, Synthes, Zeist, The Netherlands) were inserted, by hammering, drilling without irrigation and drilling with irrigation (10 ml/s, 21.1ºC (SD = 1.16ºC)) in the diaphysis of each metacarpal. Each metacarpal has a proximal, mid, and a distal location for K-wire placement. The three techniques were alternated between these locations, which resulted in five times K-wire insertion for each technique per location. The temperature was measured with two 4.0-millimeter-diameter Type K chromel-alumel thermocouples placed into the cortex of the metacarpals at a depth of 1.0 mm at a distance of 0.5 and 1.0 mm from the periphery of the insertion site at 180º to each other. The thermocouples were attached to a Pico USB TC-08 8-channel thermocouple data logger with a measuring range of -270 till 1,370ºC (accuracy ± 0.5ºC). The temperature was recorded at 1-s intervals. Canals for the thermocouples, 0.5 mm in diameter, were predrilled by a Rosa XY-table (Milan, Italy) with a drill speed of 3,000 rpm. Friction between the thermocouples and the walls of the predrilled canals was sufficient to hold them in place. K-wires were drilled with a speed of 1,200 rpm (*figure 1*)[23].

For hammering K-wires, an adapted Micro-Aire 1500 (Micro-Aire Surgical Instruments Inc., Valencia, California, USA) was used (*figure 2*). This is a from origin air-powered osteotome apparatus which we used as pneumatic hammer. The hammering frequency (maximum of 10,000 pulses/min) depends on the air pressure in the hammer and has an inlet pressure varying between 80 and 100 psi (5-7 kg/cm^2 or 5.52-6.9 bar) .

Trocar tip K-wires were cut to a length of 60 mm to prevent side bending. The duration of each experiment was counted from the beginning of insertion until the K-wire had penetrated both cortices. After insertion, the K-wires were removed using a 1,000 N (± 0.022%) Mecmesin Advanced Force Gauge, (Newton House, West Sussex, United Kingdom). Differences in temperature, insertion time and extraction force were analyzed by Bonferroni Multiple Comparisons. Statistical significance was determined based on $p < 0.05$. The data were analyzed using SPSS 12.0.1 for Microsoft Windows.

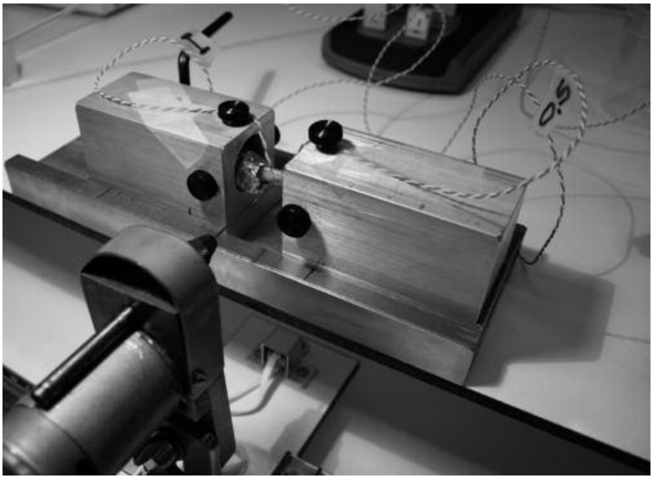

Figure 1. Experimental setup. Drilling Kirschner wire into bone. Two thermocouples are placed at a distance of 0.5 and 1.0 mm from the periphery of the K-wire insertion place.

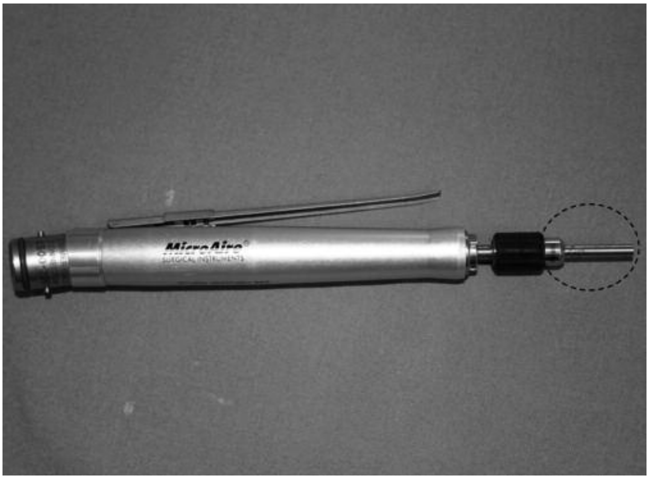

Figure 2. Pneumatic hammer, MicroAire 1500 osteotome, with encircled the adapter for the K-wire.

RESULTS

In total, 45 K-wires were placed. The cortical temperatures recorded by the thermocouple positioned 0.5 mm from the drilling site were always higher than those recorded by the thermocouple located 1.0 mm from the drilling site. Therefore, temperature data presented below were recorded by the thermocouple located 0.5 mm from the K-wire insertion place. The elevation of the bone temperature during drilling with irrigation was significantly lower compared to hammering and drilling without irrigation. The temperature elevation during hammering however was significantly lower compared to drilling without irrigation (*figure 3*).

Hammering further, resulted in a significantly shorter insertion time compared to drilling without irrigation and drilling with irrigation. There was however no significant difference between drilling with and drilling without irrigation (*figure 4*).

The extraction force of the K-wires inserted by pneumatic hammering and drilling with irrigation was not found to be significantly different. K-wires inserted without irrigation showed significant lower extraction force compared to hammering (*figure 5*).

We had to exclude two measurements from the hammering group. The K-wires stuck in the anterior cortex, where after, it was not possible to hammer the K-wire through the posterior cortex.

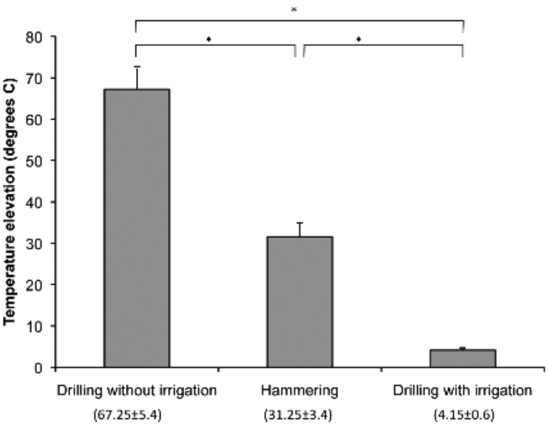

Figure 3. Temperature elevation during K-wire insertion at 0.5 mm from the K-wire insertion site. Mean value and standard error of mean of the temperature elevation during K-wire insertion. The asterisk (*) indicates statistical significance, $p < 0.01$ (Bonferroni Multiple Comparisons).

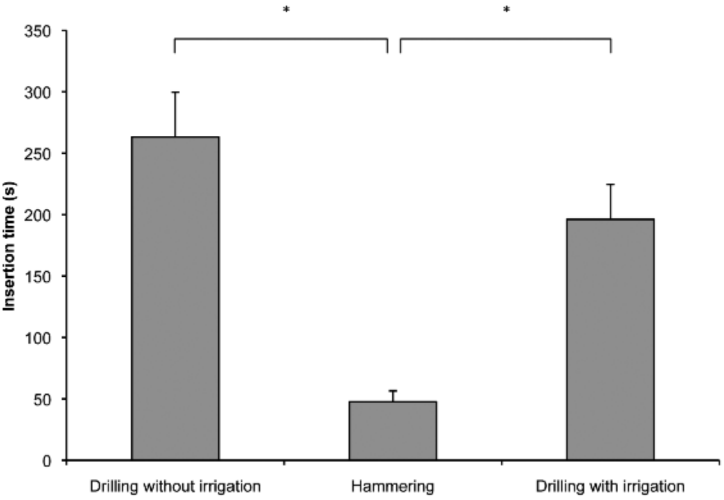

Figure 4. K-wire insertion time. Mean value and standard error of mean of the K-wire insertion time. The asterisk (*) indicates statistical significance, $p < 0.01$ (Bonferroni Multiple Comparisons).

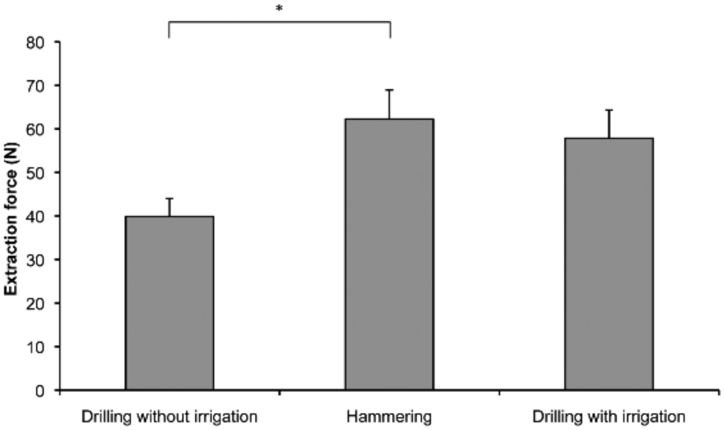

Figure 5. Extraction force needed to remove the K-wire directly after insertion. Mean value and standard error of mean of the extraction force needed to remove the Kirschner wire. The asterisk (*) indicates statistical significance, $p < 0.05$ (Bonferroni Multiple Comparisons).

DISCUSSION

Our experiment showed the lowest temperature rise during drilling with irrigation compared to drilling without irrigation and hammering. This can be explained because the denuded cortex was exposed directly to the constantly provided cooling agent at the point of penetration resulting in an optimal irrigation effect. The temperature increase with hammering was not as low as drilling with irrigation, but was significantly lower compared to the temperatures reached with drilling without irrigation. These results confirm the previously reported findings of Zegunis et al., who showed temperatures of 54°C for drilling and 34°C for hammering[22]. The significant lower maximum temperatures reached using the hammering technique can result in less thermal damage during K-wire insertion without the need for irrigation.

In our experiment, we standardized the insertion force for both techniques. Half a kilogram was found to be the optimal weight for forwards movement of the pneumatic hammer. This weight, however, was relatively low for the forward movement of the drill, resulting in relatively long insertion times. Although one would think that this also can lead to an increase in temperature, similar findings were seen in three previous experiments. Zegunis et al. showed a difference of 9 s, needing 41 and 50 s for hammering and drilling, respectively[22]. The measured temperatures were 34°C for hammering and 54°C for drilling. They did not mention standardizing the insertion force. Wassenaar et al. used a variable insertion force of 7 N and 16.9±4.9 N for hammering and drilling respectively, this resulted in insertion times of 18.4 s for hammering and 73.6 s for drilling[21]. Finally, our research group used weights of 1.0 and 1.5 kg for hammering and drilling respectively. This resulted in insertion times of 13 s for hammering and 142 s for drilling[23]. In our present research using K-wires with different tip shapes, similar differences were obtained. The short insertion time, seen in all experiments with different insertion forces, is an important characteristic of the hammering technique. Thermal-related osteonecrosis is a product of insertion time and the temperature reached. We further know that osteonecrosis will occur when bone is heated to a temperature of 50°C for 1 min[24]. Therefore, when using the hammering technique, the bone is exposed to lower temperatures during a shorter insertion time with the same insertion weight or with optimized weights for each method. Theoretically, this should result in less thermal damage resulting in better fixated K-wires.

Our results suggest such a relation since the highest extraction forces were needed to remove the faster inserted hammered K-wires.

These results confirm the experiments of Wassenaar et al. in which K-wires were hammered and drilled into ribs of pigs. Those K-wires needed 129.0 N and 57.4 N, respectively, to remove them[21]. Notwithstanding the fact that significant more extraction force was needed to remove the hammered K-wires in both, our and Wassenaar et al.[21] experiments, there is an absolute difference between the extraction forces needed in both experiments. This is probably due to the fact that Wassenaar et al.[21] drilled with 600 rpm, used a variable insertion force, pig ribs, and a different diameter K-wire. On the other hand, in one of our earlier *in vivo* experiments we showed no significant difference in the extraction forces[23]. We suggested that there was no significant difference due to the rabbit model we used. Based on these results, we conclude that hammering K-wires is a good alternative for drilling with irrigation and is superior when irrigation can not be properly applied using the drilling technique.

Despite our promising results concerning hammering K-wires, we have to keep in mind that we used a human cadaver model. Our experimental conditions differ from the clinical setting in several aspects. The metacarpals were stripped of soft tissue, were at room temperature instead of body temperature and there was no cortical blood flow. The function of this cortical blood flow, however, is debatable. It is possible that it may absorb heat generated in vital bone, but on the other hand, the cortical blood flow rate is normally very low and coagulation of small vessels occurs very rapidly when heated[25]. The relative differences, however, may still be significant and need further investigation.

In two cases, it was not possible to insert the K-wire through the opposite cortex using the pneumatic hammer. This is probably due to the maximum "hammer" power produced by the Micro-Aire 1500 we used. The apparatus which was originally designed for performing osteotomies was not powerful enough to penetrate the two K-wires which were stuck in the first cortex, through the opposite cortex. It is likely that this can be prevented in the near future by using a more powerful pneumatic hammer.

This experiment suggests that hammering can be superior to drilling without irrigation because it results in lower temperatures, higher extraction forces, and short insertion times. The latter was managed in this experiment by using similar insertion forces for both insertion techniques. This of course is not comparable with drilling in the clinical setting because K-wires are normally inserted much faster with unknown raise in bone temperature around the wire. The only advantage of drilling with irrigation compared to hammering is the lower mean maximum temperature, which is, however, difficult to realize in daily practice. We therefore conclude that hammering is a good alternative for drilling K-wires and is the preferable method when proper external irrigation is not possible.

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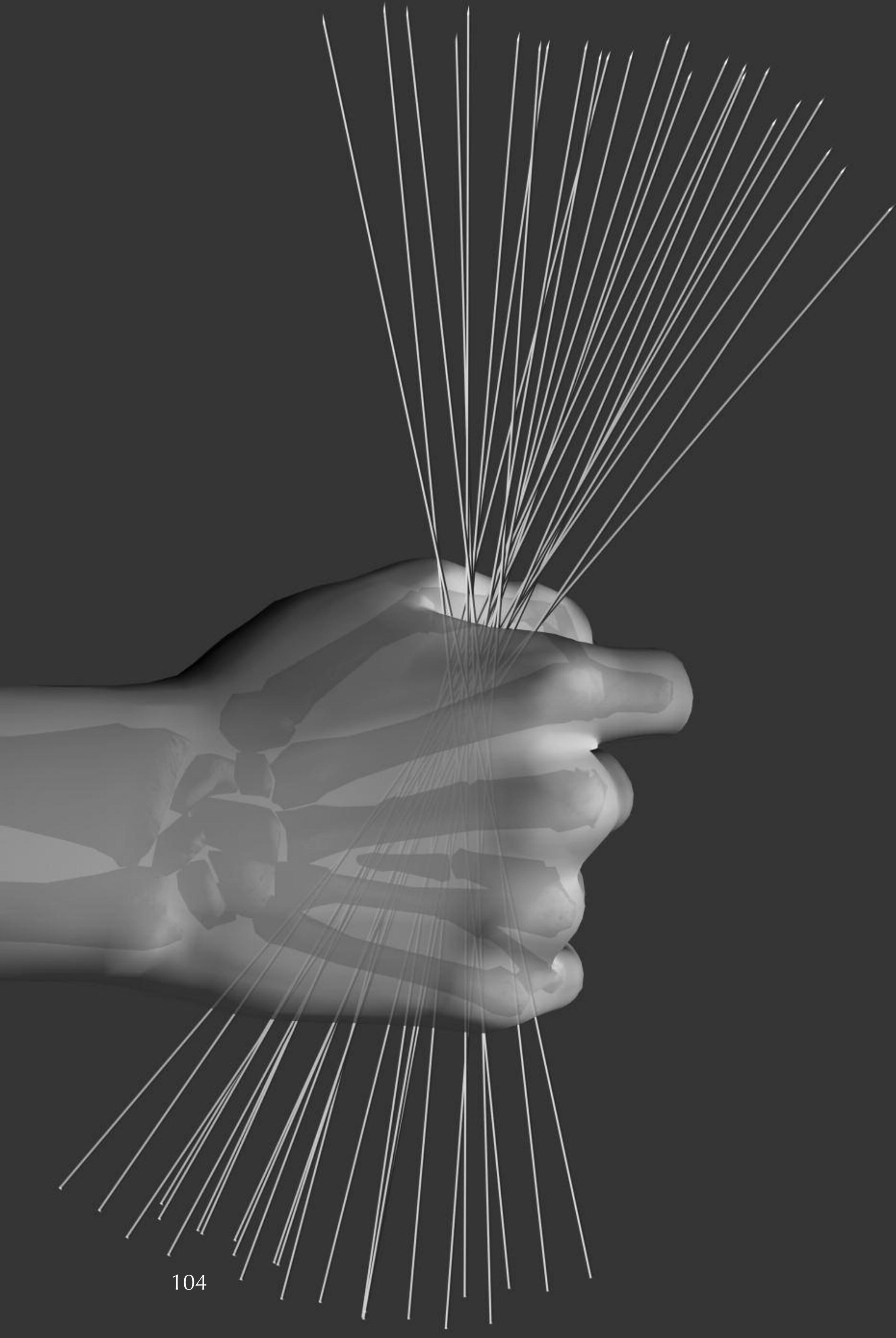

CHAPTER 8

Hammering versus drilling of sharp and obtuse trocar point K-wires

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AB Mink van der Molen
M Kon

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ABSTRACT

Background

Kirschner wire characteristics affect the heating of bone during insertion and the subsequent strength of fixation. We inserted 90 sharp and 90 obtuse trocar tip K-wires into 90 fresh frozen human cadaver metacarpals using either a drill or a pneumatic hammer.

Materials and Methods

The temperature elevation, insertion time and extraction force were measured for four K-wire insertion combinations: drilling sharp; drilling obtuse; hammering sharp; hammering obtuse.

Results

Hammering resulted in significantly lower temperature elevations than drilling. Hammering sharp K-wires resulted in the highest extraction forces. The first and fifth metacarpals showed significantly lower temperature elevations than the other metacarpals, while the insertion time was significantly higher in the second and third metacarpal than in the other metacarpals.

Conclusion

Hammering sharp trocar-tip K-wires minimises thermal damage to bone and gives the strongest fixation.

INTRODUCTION

Kirschner wire (K-wire) fixation is a simple but important technique in hand surgery that offers the possibility of percutaneous placement. It is of great importance that thermal damage to the bone during insertion is minimised to prevent thermal osteonecrosis. K-wire characteristics strongly influence heat-related trauma. For example, thinner K-wires generate more heat than thicker ones[1]. Another important characteristic is the type of K-wire tip. Trocar tips, for instance, produce significantly more heat but lead to better fixation in bone than diamond tips[1-4]. These results are all based on experimental insertion of K-wires with a high-speed drill. Other studies suggest that the pneumatic hammer may have advantages over drilling[5-8].

The configuration of trocar tips varies between manufacturers. We examined two types of trocar tip K-wires. Each had a length of 150mm, a diameter of 1.0mm and a trocar tip with three facets. However, one K-wire had a sharp (i.e. long acute angle tip) while the other K-wire had an obtuse tip. We could find no studies that examined the impact of different trocar tip angles on the insertion time, temperature elevation and fixation strength in bone. We measured the insertion time, extraction force and temperature elevation, using a high speed drill and a pneumatic hammering device for insertion of two trocar tip K-wires with different tip angles. The differences between the five metacarpals were also analyzed.

MATERIAL AND METHODS

Ninety fresh frozen human cadaver metacarpals from the first to the fifth digit were used. They were collected from 13 males and five females. Seven right and 11 left hands were used.

The hands were stored at -23°C. Before testing, the metacarpals were denuded of all soft tissues and the diameter was measured at two places at the diaphysis, giving a mean diameter of 8.6 mm (SD = 1.5 mm). Radiographs were taken to exclude pathology that might affect the bone properties and the metacarpals were allowed to warm to room temperature (21.8°C, SD = 0.9°C). The experiments were conducted with the bones rigidly fixed between two aluminium blocks on a rail, which was placed on an operation device as described previously[5,9]. This device made it possible to position the pneumatic hammer or drill with the K-wire exactly in front of the insertion point (*Figure 1*).

We compared four K-wire insertion technique combinations: 1) drilling with a sharp trocar tip K-wire; 2) drilling with an obtuse trocar tip K-wire; 3) hammering with a sharp trocar tip K-wire; and 4) hammering with an obtuse trocar tip K-wire. In each metacarpal one obtuse stainless steel trocar K-wire with a tip angle of 60º (1.0mm x 150 mm, Synthes GmbH, Oberdorf, Switzerland) and one sharp stainless steel trocar K-wire with a tip angle of 30º (1.0 mm x 150 mm, Biomet UK Ltd, Bridgend, UK) (*Figure 2*) was inserted, either by hammering or drilling. Each metacarpal had a proximal and a distal location for K-wire placement. The sharp and obtuse K-wires were alternated between these locations. To prevent side bending during insertion, the K-wires used for drilling and hammering were cut to a length of 60 mm and 30 mm respectively, so that 25 mm protruded out of the drill and hammer.

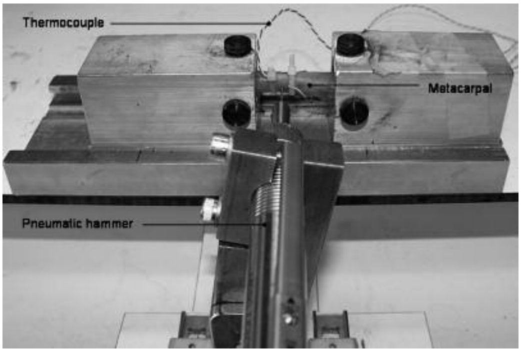

Figure 1. Experimental setup, the metacarpal is rigidly fixed between two aluminium blocks, in front of the pneumatic hammer. Two thermocouples are placed in the cortex.

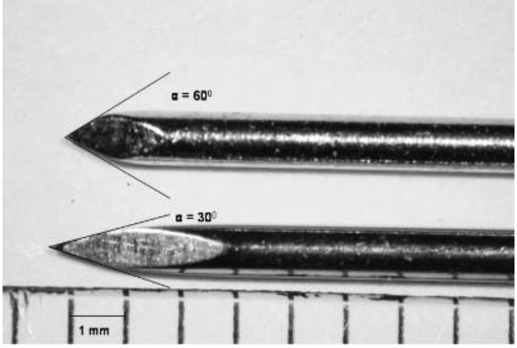

Figure 2. Sharp (α=30º) and obtuse (α=60º) stainless steel trocar tip Kirschner wires, with a diameter of 1.0mm, used in our experiments.

For hammering K-wires a Micro Impactor 2500-100 (Micro-Aire Surgical Instruments Inc., Charlottesville, Virginia, USA) was used. This is an air-powered apparatus with a linear impulse motor. We created an adapter to fix the K-wire, so we could use the device as pneumatic hammer. The hammering frequency (maximum of 10,000 pulses/minute) depends on the air pressure in the hammer, which has an inlet pressure varying between 38 and 100 psi (2.5-7 kg/cm2 or 2.62-6.9bar). If the instrument is powered by compressed nitrogen the inlet pressure varies between 40 and 115 psi (2.81-8.09 kg/cm2 or 2.76-7.93 bar). K-wires were drilled with a speed of 1,200 rpm, which is the maximum speed used in daily practice (*Figure 1*)[5]. Forward movement of the drill and pneumatic hammer was initiated by a weight of 1.5 kg and 0.5 kg respectively. The difference between the weights used for forward movement was necessary to optimise the K-wire insertion conditions for both techniques.

The temperature development was measured with two 0.4 mm diameter Type K chromel-alumel thermocouples placed into the cortex of the metacarpals at a depth of 1.0 mm, at a distance of 0.5 and 1.0 mm from the periphery of the insertion site at 180° to each other. The thermocouples were attached to a Pico USB TC-08 8-channel thermocouple data logger with a measuring range of -270 to 1,370ºC (accuracy ± 0.5ºC). The temperature was recorded at 1 sec intervals. Canals for the thermocouples, 0.5 mm in diameter, were predrilled by a Rosa XY-table (Milan, Italy) with a drill speed of 3,000 rpm. During the experiments, each thermocouple was held in place by a cable tie. The insertion time was from commencing the insertion to the moment of penetration of the far cortex. After insertion the K-wires were removed using a 1,000 N (± 0.022%) Mecmesin Advanced Force Gauge, (Newton House, West Sussex, United Kingdom).

Maximal temperature, insertion time and extraction force for the different combinations were analysed by repeated measurements. When there was a significant difference between the five metacarpals, pair-wise comparisons with Bonferroni correction were used to examine which metacarpals differ. Statistical significance was based on $p < 0.05$. The data were analyzed using SPSS 12.0.1 for Microsoft Windows.

RESULTS

Ninety obtuse and 90 sharp K-wires were inserted into 90 metacarpals using a high speed drill or pneumatic hammer as insertion device, resulting in four groups: drilling sharp, drilling obtuse, hammering sharp and hammering obtuse, with 45 measurements in each group.

The means and standard error of means (SEM) of temperature elevation, insertion time and extraction force are summarized in *Table 1*.
Five cracks arose during hammering of the K-wires, four in the cortex of two fourth metacarpals and one in the cortex of a third metacarpal. In three cases the wire tip was obtuse and in two cases it was sharp.

	Temperature elevation (^{o}C)	Insertion time (s)	Extraction force (N)
Group 1: drilling sharp	37.99 ± 3.8	27.09 ± 4.9	73.57 ± 3.5
Group 2: drilling obtuse	29.50 ± 2.9	27.42 ± 6.1	50.98 ± 3.0
Group 3: hammering sharp	9.56 ± 1.6	16.33 ± 2.4	152.98±12.4
Group 4: hammering obtuse	7.24 ± 1.4	12.99 ± 1.9	61.83 ± 6.9

Table 1. Results (mean ± SEM) concerning temperature elevation, insertion time and extraction force for each group.

Hammering resulted in much smaller temperature elevations than drilling (p<0.0001). The temperature elevation was lower in the first metacarpal than the second (p=0.01), third (p<0.001) and fourth (p=0.04) metacarpal. Sharp tip K-wires gave higher temperatures for both drilling and hammering than obtuse tip wires, but the differences were not significant. There were no statistically significant interactions between insertion technique, K-wire type and metacarpal (*Figure 3*).

The only factor which did effect the insertion time was the difference between the five metacarpals of the hand (p<0.0001). The insertion time was significantly higher in the second metacarpal than the first (p=0.01), fourth (p=0.02) and fifth (p=0.01) metacarpal and in the third metacarpal compared to the fifth (p=0.03). The insertion time was shorter for hammering than for drilling, but the difference was not significant (p=0.094) (*Figure 4*). The first (mean 9.24 cm, SD 1.2 cm), second (mean 9.46 cm, SD 1.2 cm) and third (mean 9.35 cm, SD 1.1 cm) metacarpals were significant thicker than the fourth (mean 7.50 cm, SD 1.1 cm) and fifth (mean 7.44 cm, SD 1.0 cm) metacarpals (Bonferroni; p<0.0001).

Hammering gave a larger extraction force, which was especially marked for the sharp tip wires (p<0.0001) (*Figure 5*) and greater in the second and third metacarpals than in the other bones.

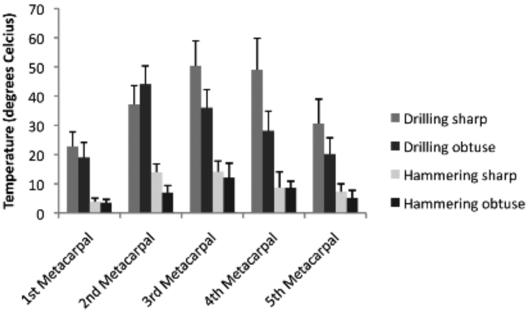

Figure 3. Temperature development in degrees Celcius (mean ± SEM) during insertion of sharp and obtuse trocar tip Kirschner wires by using a high speed drill or pneumatic hammer.

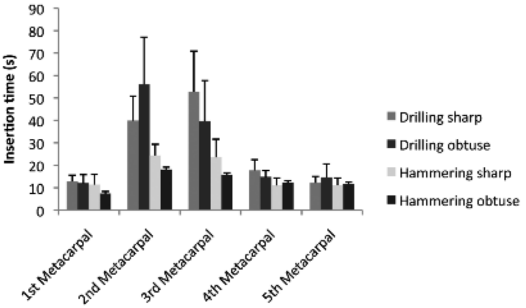

Figure 4. Insertion time in seconds (mean ± SEM) of sharp and obtuse trocar tip Kirschner wires inserted with high speed drill or pneumatic hammer.

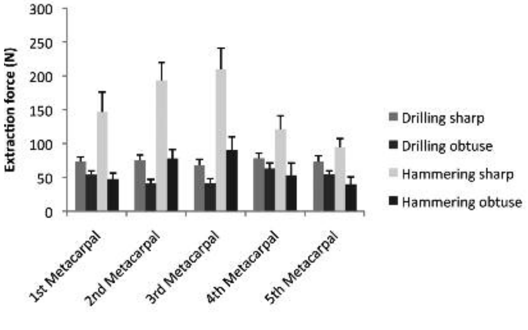

Figure 5. Extraction force in Newton (mean ± SEM) needed to remove sharp and obtuse trocar tip Kirschner wires after insertion by high speed drill or pneumatic hammer.

DISCUSSION

This experiment shows that hammering produced lower temperature elevations and stronger fixation than drilling K-wires. The lower temperature elevation with hammering than with drilling corresponds with previous studies[7,9].The difference in fixation between sharp and obtuse K-wires inserted with the pneumatic hammer may be related to cortical microfractures, as described in our histological study in rabbit bone[6] that showed that small bone fragments fractured from the inner cortex during hammering of K-wires. It is probable that hammering obtuse tip K-wires results in larger and/or more numerous bone fragments than sharp tip K-wires, with a detrimental effect on the wire's purchase in the cortex.

A cortical crack appeared around five K-wires during hammering but the wires remained well fixed. Our histological study shows that these cracks disappear after four weeks, and although we do not feel that they are the likely to be a problem in clinical practice[6], clinical experience of the technique would be required to confirm this. It may be possible to minimise the formation of cracks by using a lower insertion force. In the present study we chose to standardise the insertion force at 0.5 kg for hammering, but lower forces could be chosen in clinical practice.

The differences between metacarpals with regard to temperature elevation, insertion time and extraction force are probably related to differences in cortical thickness, because the differences cannot be explained by the different metacarpal diameters. Based on the differences between the metacarpals, we expect that osteonecrosis is more likely to occur in the second and third metacarpals, since thermal osteonecrosis is a product of temperature elevation and insertion time when drilling K-wires[10].

A potential drawback of the pneumatic hammer is the high force needed to remove the K-wire, in the event that the surgeon is not satisfied with its position. Hammering devices designed for clinical practice would benefit from a mechanism that allows reversal of the hammer force.

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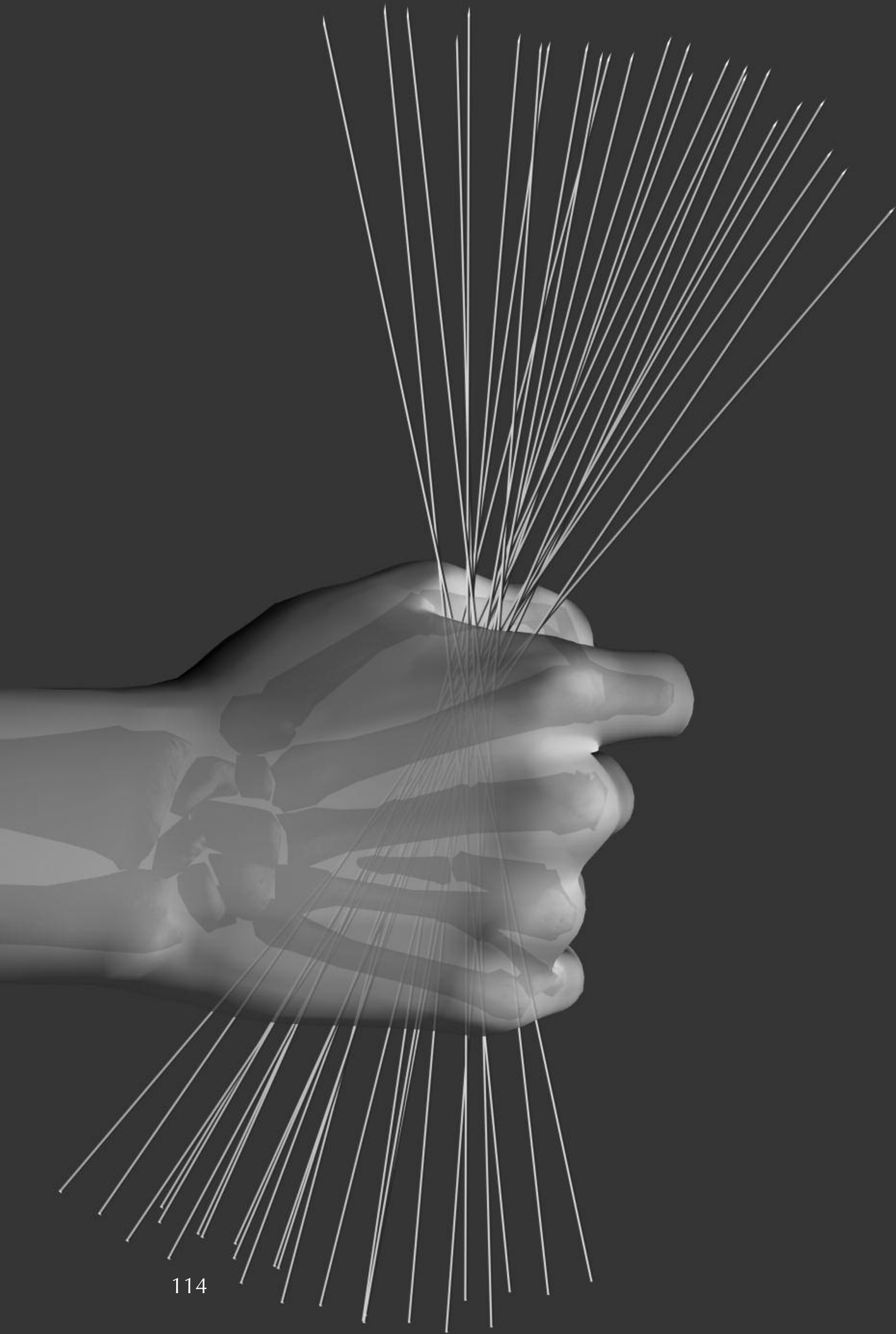


CHAPTER 9

Summary, conclusions and future perspectives

SUMMARY

Introduction

The first part of this thesis describes the history of the Kirschner wire. Almost a century ago, in 1909, Martin Kirschner (1879 – 1942) introduced a smooth pin which is now known as a Kirschner wire (K-wire). The K-wire was initially used for skeletal traction, but its use is now more widespread in orthoplastic surgery. The initial development of the K-wire and the method of insertion was mainly driven by the surgical goals and the development of more efficacious antibiotic therapy. The early versions of the K-wire were hammered through a pre-drilled hole in the cortex before drilling became the standard technique of insertion. Drilling is considered as a simple insertion technique with many advantages, including the ability to insert wires percutaneous and relatively atraumatically. This technique 's major drawback is the production of heat, resulting in osteonecrosis and other temperature related complications. Despite these complications, the use of drilled K-wires is a widely accepted method for the treatment of hand fractures.

In 1942, Martin Kirschner mentioned the hammering of K-wires in his final publication, which was published shortly after his death. He had developed a device which made K-wire hammering by hand possible. Following his death, the possibility of hammering K-wires into position was unexplored until 1993 when Zegunis and co-workers suggested that the pneumatic hammering of K-wires resulted in less risk of thermal related injury. (**Chapter 1 and 2**)

To our knowledge, no further research has been done regarding hammering K-wires since the work of Zegunis. The aim of this thesis was to investigate the viability of hammering K-wires using a pneumatic hammer. The main goal was to compare the efficacy of drilling versus hammering and to study the side effects of both techniques. The ultimate goal was to propose a new, efficacious and safe evidence based technique for K-wire insertion.

Histology

In the second part of this thesis, the comparative histology of bone following drilling and hammering K-wires was studied. It is well known that osteocytes play an important role in osteogenesis as the death of osteocytes results in osteoclastic bone resorption.

Osteocyte necrosis due to increased heat production by drilling may increase the risk of K-wire loosening. By drilling K-wires into the femur and tibia of rabbits, we aimed to investigate the temporal reduction in the osteocyte population and to measure the extent of the empty osteocyte lacunae surrounding the drill tract. We measured this at two time points – at the time of insertion and at four weeks. Trocar tipped K-wires (70 mm length and 0.6 mm thickness) were drilled into the femur and tibia of 14 New Zealand White Rabbits. Six rabbits were sacrificed following surgery and eight rabbits were sacrificed four weeks after surgery. All osteocyte lacunae were empty around the K-wires in 50% of the cases at the time of insertion and in 87% of the cases at four weeks. A positive time correlation was seen regarding the distance of the empty osteocyte lacunae surrounding the drill holes. Although only drilling without cooling was studied, short drilling times may prevent the disappearance of osteocytes in case cooling is not used in clinical practice, as is the case in percutaneous K-wire insertion. (**Chapter 3**)

The next step was to study the insertion time and histological effects of drilling versus hammering of K-wires into femurs and tibias of ten rabbits. Four K-wires, inserted in one hind limb, were used for histological examination directly after insertion and four K-wires inserted in the contra lateral hind limb were used for the same measurements four weeks later. Our study showed that the insertion time needed for drilling K-wires was significantly longer than that of hammering. In addition, drilling resulted in osteocyte necrosis in almost all sections. Hammering did not seem to result in significant osteocyte necrosis, however this technique did result in more microfractures. On the basis of these results, we postulated that the hammering of K-wires may be a safe alternative to drilling as it prevents osteonecrosis and requires a shorter insertion time. (**Chapter 4**)

Biomechanics

The final part of this thesis studied the biomechanical aspects of K-wire insertion. We investigated the insertion time, torque, extraction force and temperature changes comparing the drill and pneumatic hammer as insertion devices. An *in vitro* study with porcine ribs showed statistically significant higher mean peak extraction forces for hammering than drilling and the mean peak torque for hammering was nearly double that of drilling. We also found the K-wire insertion time by drilling was longer when compared to hammering. At the exit site we found splinters of bone in 18 of the 22 hammered K-wires and only in two of the 22 drilled K-wires.

Hammering of K-wires in our porcine rib model resulted in better initial fixation and had a shorter insertion time at the expense of splintering of bone at the exit site. (**Chapter 5**)

In **Chapter 6** we described an *in vivo* study concerning the insertion time and biomechanics comparing hammered and drilled K-wires. The insertion time of drilled and hammered K-wires into the femur and tibia of 16 New Zealand White Rabbits was compared. Four K-wires inserted in one hind limb, were used to measure extraction and torque forces directly after insertion and four K-wires inserted in the controlateral hind limb were used for the same measurements four weeks after insertion. In our study, the insertion time when hammering K-wires was significantly shorter compared to that of drilling. Extraction and torque properties measured directly and four weeks after insertion were equal for both techniques. Although hammering K-wires into the femur and tibia was quicker, hammering resulted in more microfractures.

One method which may prevent heat generation during the drilling of K-wires is intra-operative cooling using irrigation.

To our knowledge, no data on pneumatic hammered K-wires using a human *in vitro* model has been published and this technique has never been compared to drilling with irrigation. To investigate this further, we measured the temperature, insertion time and extraction force using three K-wire insertion methods – drilling with irrigation, drilling without irrigation and hammering. Forty-five K-wires were inserted into fifteen fresh human cadaver metacarpals with two thermocouples placed at 0.5 and 1.0 mm from the periphery of the insertion point. All three insertion methods were applied to each metacarpal. External irrigation using water was applied at 10 ml/min. Hammering and drilling were performed at a constant 0.5-kg load with 10.000 pulses per minute and 1200 revolutions per minute respectively. Extraction forces were measured directly after insertion. Drilling without irrigation resulted in a temperature elevation of 67.25 ± 5.4 ºC with significantly lower values for drilling with irrigation (4.15 ± 0.6 ºC) and hammering (31.52 ± 3.4 ºC). The insertion time for hammering (47.63 ± 8.8 s) was significantly lower compared to drilling without irrigation (263.16 ± 36.5 s) and drilling with irrigation (196.10 ± 28.5 s). Extraction forces after drilling without irrigation, drilling with irrigation and hammering were 39.85 ± 4.1 N, 57.81 ± 6.5 N and 62.23 ± 6.7 N, respectively. This data suggests that in terms of the parameters studied, hammering was superior to drilling without irrigation, which is the most widely used method of percutaneous K-wire insertion (**Chapter 7**).

The physical characteristics of K-wires also influence the temperature increase in bone during insertion and the strength of fixation. The angle of the K-wire tip is one of these characteristics of interest.

In Chapter 8 we compared two different angled K-wire tips using the drill and pneumatic hammer as insertion techniques. We measured the effects of insertion in five human cadaveric metacarpals. Ninety sharp (α = 30°) and ninety obtuse (α = 60°) trocar tip K-wires were inserted into ninety fresh frozen human cadaver metacarpals with thermocouples placed into the cortex. We measured the temperature elevation, insertion time and extraction force between four K-wire insertion combinations – 1) drilling sharp; 2) drilling obtuse; 3) hammering sharp; 4) hammering obtuse. Again we found that hammering resulted in significantly lower temperature elevations compared to drilling. Furthermore, the first and fifth metacarpal showed significantly lower temperature elevations compared to other metacarpals, whilst the insertion time was significantly higher in the second and third metacarpal compared to the other metacarpals. This is likely caused by differences in bone thickness. Hammering sharp K-wires resulted in the highest forces needed to remove the K-wire. We concluded that hammering sharp trocar tip K-wires reduced thermal related damage whilst leading to the most rigid fixation.

Conclusions and future perspectives

The efficacy, strength and side effects of K-wire insertion are important in contemporary orthoplastic surgery.

Our experiments suggest that the strength of K-wire fixation following drilling depends mainly on thermal necrosis of osteocytes due to increased temperature levels during insertion. Drill speed, insertion time and force, irrigation, K-wire diameter and tip configuration are important factors which can affect temperature elevation and subsequent disappearance of osteocytes in the immediate surrounding of the K-wire (*Figure 1*).

One of the main aims of this thesis was to test our hypothesis that the hammering of K-wires could prevent or decrease osteonecrosis due to high speed drilling.

Our results support the assumption that hammering of K-wires prevents osteonecrosis due to shorter insertion times and less severe temperature elevations. Due to reduced osteonecrosis surrounding the K-wire tract, the rigidity of fixation was superior when the K-wire was hammered, especially when sharp trocar tip K-wires were used.

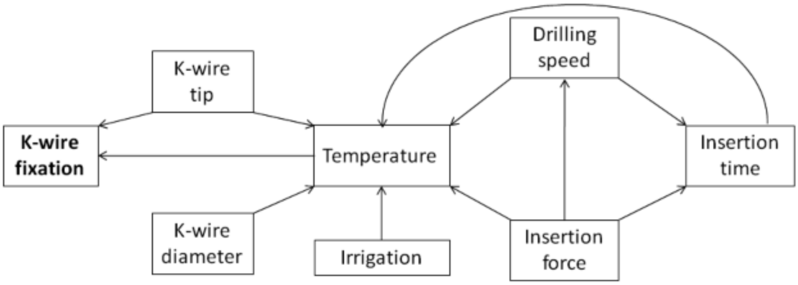


Figure 1. Factors which influence the degree of fixation after drilling K-wires. 1) K-wire characteristics: tip and diameter. 2) Drill properties: insertion force, drilling speed and insertion time. 3) The factor irrigation.

Despite our promising initial results mentioned above, a perfect hammering device does not exist at present. The different pneumatic hammering devices used in our experiments were effective but had some drawbacks. We found that the LithoClast produced too much force during each initial tap, leading to microfractures in the cortex. In some cases, the microfractures were so significant that they resulted in K-wire loosening. Following these initial findings, we switched to a more gentle device, the Micro-Aire 1500 which had a fast repetitive linear impulse motor. This was an improvement over the LithoClast and the incidence of K-wire loosening was reduced. However in two cases, the force generated by this device was not sufficient to penetrate the second cortex. In the end, we used the Micro Impactor 2500-100. In some cases we still found microfractures in the cortex but the K-wires nevertheless were all well fixed.

We believe that in order to use the pneumatic hammer in the clinical setting, certain improvements and modifications need to occur.

1) The pneumatic hammer needs to have *variable insertion forces*. Clearly the force must be strong enough to penetrate both cortices whilst resulting in a low number of microfractures.

The best results in our study were achieved with the Micro Impactor 2500-100 (**Chapter 8**), which is an air-powered apparatus with a linear impulse motor, with a maximum frequency of 10,000 pulses per minute. The inlet pressure varies between 38 and 100 psi (2.5-7kg/cm^2). The new to develop hammering device should at least have these properties.

2) Standard K-wires had to be shortened for use in the Micro Impactor 2500-100 to prevent side bending during hammering because they could not

be put full length in the apparatus. Therefore this hammering device needs to be adapted to allow the full length of the K-wire to be inserted, conform the options provided by the high speed drill.

3) In some cases the hammered K-wires were so strongly fixed that it was difficult to remove them. Intra-operatively, the surgeon will often want to remove the K-wire if (s)he is not happy with the position of the wire. In these circumstances it is preferable to remove the K-wire atraumatically, often by drilling in the reversed direction. With the pneumatic hammers we used, such a removal was not possible. A pneumatic hammer is needed with a reversed hammering function to allow removal and re-insertion.

It is important to note that our studies focused on rabbit, porcine and human models using the pneumatic hammer to insert K-wires into rigid fixed non-fractured bones. We do not know if this technique (with the above suggested modifications) can be translated immediately into the clinical setting when faced with fractured bones requiring reduction and fixation.

In our experiments, all K-wires were placed at an angle of 90 degrees to the bone. It is well known that there is a risk of skidding along the cortex when drilling a K-wire under a different angle than 90 degrees, which is often the case in the clinical setting. How the K-wire will behave when it is hammered at such an acute angle has not yet been analysed.

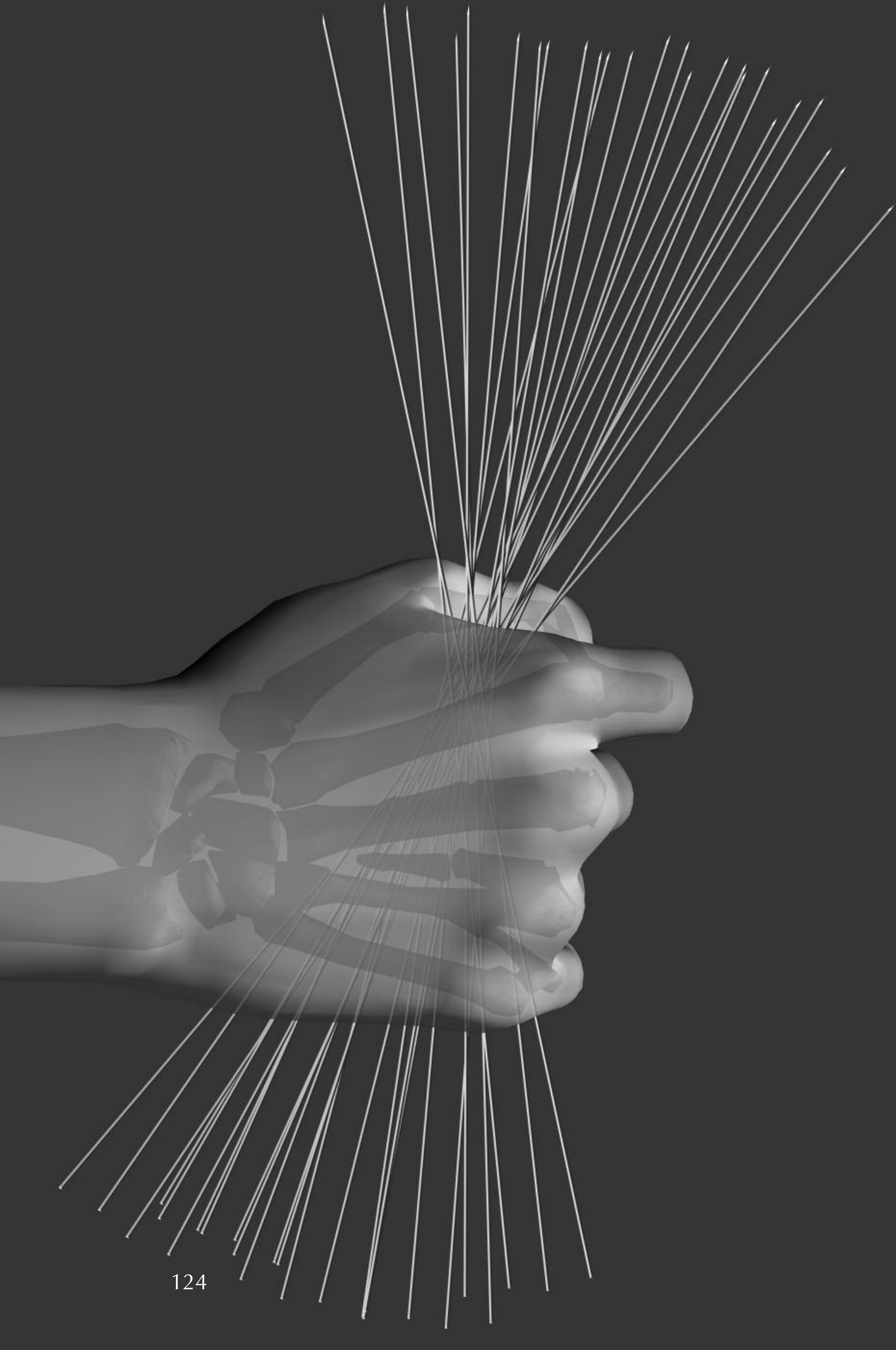
These two aspects, should be investigated in an *in vitro* study when a suitable hammering device is developed.

We believe that following a favourable outcome of these suggested *in vitro* experiments, a prospective randomized clinical trial, using two groups of patients (drilling versus hammering) with metacarpal or phalangeal fractures should be performed. This study should address the ease of use of the hammering device, dislocation of bone fragments, strength of fixation, presence of microfractures and infection.

K-wires have been used successfully for over a hundred years, and are used by contemporary surgeons in a wide range of clinical settings. The cost effectiveness, reliable and reproducible results, availability of equipment and the ease of use make them a very attractive option.

Recently, a resorbable pin kit (ReUnite Orthopedic Fixation System, Arthrotek, Warsaw) has been introduced. The K-wire is replaced by a resorbable pin,removing the need for K-wire removal and theoretically reducing the infection risk.

The main aims of this thesis was to test the hypothesis that the hammering of K-wires could prevent or decrease osteonecrosis due to high speed drilling and result in rigid fixation. Our initial results support this assumption especially when sharp trocar tip K-wires were used. At present the only viable clinical option is to insert K-wires using the high speed drill. Future modifications, based on our research efforts and initial findings may result in the development of a K-wire hammering device for clinical use in the 21st century.



CHAPTER 10

Summary in Dutch (Nederlandse samenvatting)

Acknowledgements

Curriculum vitae

SAMENVATTING

Introductie

Het eerste deel van dit proefschrift beschrijft de geschiedenis van de Kirschner draad (K-draad). Martin Kirschner introduceerde een eeuw geleden, in 1909, een gladde pin welke wij tegenwoordig kennen als de K-draad. De K-draad werd in eerste instantie alleen gebruikt voor tractie van de lange beenderen van het skelet maar wordt tegenwoordig op een veel bredere schaal toegepast. De ontwikkeling van de K-draad en de bijbehorende apparaten voor het plaatsen ervan werd in het bijzonder beïnvloed door de verandering van de chirurgische indicaties en de introductie van antibiotica.

De eerste versie van de K-draad werd handmatig op zijn plaats getikt in een van te voren geboord gat. In de daarop volgende jaren werd het direct plaatsen door middel van boren de standaard techniek. Boren wordt nog steeds beschouwd als een relatief simpele techniek met vele voordelen, zoals de mogelijkheid om de draden percutaan en zonder veel schade te plaatsen. Het grootste nadeel van de techniek is de warmte ontwikkeling welke gepaard gaat met necrose en andere temperatuur gerelateerde complicaties. Ondanks deze complicaties is het boren van K-draden wereldwijd de standaard voor de behandeling van verschillende soorten handfracturen.

In 1942, kort na het overlijden van Martin Kirschner, verscheen zijn laatste publicatie waarin hij het tikken van K-draden beschreef. Hij had zelfs een apparaat ontwikkeld waarmee K-draden handmatig met een hamer konden worden geplaatst. Maar na zijn dood werd het onderwerp "tikken van K-draden" niet verder onderzocht tot het jaar 1993. In dat jaar suggereerden Zegunis en mede auteurs dat het tikken van K-draden door middel van een pneumatische hamer resulteerde in een verminderd risico op temperatuur gerelateerde schade. (**Hoofdstuk 1 en 2**)

Voor zover wij konden nagaan heeft er sindsdien geen onderzoek meer plaatsgevonden met betrekking tot het tikken van K-draden. Daarom werd dit onderzoekstraject opgezet, waarbij de validiteit van het tikken van K-draden met behulp van een pneumatische hamer werd onderzocht. Het belangrijkste doel was om het boren en pneumatisch tikken met elkaar te vergelijken en de daarbij behorende neveneffecten te bestuderen met het ultieme doel, om een nieuwe, verbeterde en evidence-based K-draad insertie techniek te introduceren.

Histologie

In het tweede deel van dit proefschrift hebben we de histologie van het bot, na het boren en tikken van K-draden, bestudeerd. Het is bekend dat osteocyten een belangrijke rol spelen in de osteogenese omdat de dood van osteocyten resulteert in een sterke osteoclastische bot resorptie. Wanneer de osteocyten sterven ten gevolge van het boren neemt het risico op het loslaten van de K-draad toe. Door K-draden in het femur en de tibia van konijnen te boren konden de minimale boortijd die nodig is om de osteocytenpopulatie aanzienlijk te laten verminderen en de afstand van de lege osteocytlacunae rond het boorgat in relatie tot de tijd, worden bestudeerd. Deze metingen werden gedaan, direct na het inbrengen van de K-draad en vier weken later. Trocar punt K-draden (70mm lang en 0.6mm doorsnede) werden in de femura en tibiae van 14 *New Zealand White* konijnen geboord. Zes konijnen werden direct na de ingreep getermineerd en de resterende acht konijnen vier weken na de ingreep. Direct na de ingreep waren in 50% van de gevallen alle osteocyt lacunae rondom de K-draden leeg en na vier weken werd dit bij 87% van de gevallen waargenomen. Daarnaast werd er een positieve tijdscorrelatie gezien met betrekking tot de afstand van de lege osteocyt lacunae rondom de boorgaten. Ondanks het feit dat alleen boren zonder koelen werd onderzocht kunnen we stellen dat een korte boortijd het verdwijnen van osteocyten kan voorkomen indien er geen gebruik wordt gemaakt van koeling, zoals het geval is bij het percutaan plaatsen van K-draden (**Hoofdstuk 3**).

De volgende fase in ons onderzoekstraject was de bestudering van de insertie tijd en het histologisch beeld bij verschillende insertietechnieken. Er werden K-draden geboord en getikt in het femur en de tibia van tien konijnen. Vier K-draden, geplaatst in één achterpoot, werden gebruikt voor histologisch onderzoek direct na het plaatsen en de vier K-draden in de contralaterale achterpoot werden gebruikt voor dezelfde metingen vier weken later. De insertietijd die nodig was voor het boren van K-draden was significant langer ten opzichte van het tikken. Daarnaast resulteerde het boren in bijna alle gevallen in het verdwijnen van de osteocyten terwijl de osteocyten bij het tikken in leven bleven. Het tikken resulteerde echter wel in meer microfracturen. Op basis van deze resultaten kunnen we stellen dat het tikken van K-draden een alternatief voor boren kan zijn omdat het osteonecrose voorkomt en een kortere insertietijd behoeft. (**Hoofdstuk 4**)

Biomechanica

Het laatste deel van dit proefschrift is toegespitst op de biomechanische aspecten van K-draad insertie. We onderzochten de insertie tijd, koppel- en extractiekracht en temperatuur ontwikkeling bij het gebruik van de boor en pneumatische hamer als insertie apparaat. Een *in vitro* studie met varkensribben toonde een statistisch hoger gemiddelde piek extractiekracht aan voor de getikte K-draden ten opzichte van de geboorde K-draden. Daarnaast was er sprake van een gemiddelde piek koppelkracht welke bijna twee keer zo hoog is voor het tikken ten opzichte van het boren en tenslotte ging het plaatsen door middel van tikken ook veel sneller vergeleken met boren. Maar op de plek waar de K-draad weer uit het bot tevoorschijn kwam, waren bij 18 van de 22 getikte K-draden splinters zichtbaar, terwijl dit slechts bij twee van de 22 geboorde K-draden werd gezien. Samengevat toont deze studie aan, dat het pneumatisch tikken van K-draden in varkensribben resulteert in een betere initiële fixatie en kortere insertie tijd maar daarentegen ook splintervorming van het bot aan de uittreedplaats veroorzaakt (**Hoofdstuk 5**).

In **Hoofdstuk 6** worden in een *in vivo* studie, de insertie tijd en biomechanica van getikte en geboorde K-draden vergeleken. De insertie tijd werd gemeten gedurende het boren en tikken van K-draden in de femura en tibiae van 16 *New Zealand White* konijnen. Vier K-draden werden geplaatst in een achterpoot en deze werden gebruikt om de koppel- en extractiekracht direct na het plaatsen te meten. Vier andere K-draden werden in de contralaterale achterpoot geplaatst en deze werden gebruikt voor dezelfde metingen vier weken later. De resultaten toonden aan dat de insertietijd die nodig was voor het tikken van K-draden significant korter was vergeleken met boren. De gemeten koppel- en extractiekrachten, direct en vier weken na het plaatsen, waren gelijk voor beide technieken. Samengevat kan worden geconcludeerd dat het tikken van K-draden in de femora en tibiae van konijnen resulteert in een significant kortere insertietijd in combinatie met dezelfde biomechanische eigenschappen als boren, maar dat daarnaast tikken wel weer in meer microfracturen resulteert.

Een methode om hitte ontwikkeling tijdens het boren van K-draden te voorkomen is koelen. Voor zover ons bekend bestaan er geen data over het pneumatisch tikken van K-draden in een menselijk *in vitro* model en is deze techniek nooit vergeleken met boren in combinatie met koelen. Om dit verder te onderzoeken werd de temperatuur, insertietijd en extractiekracht vergeleken tussen drie K-draad insertie methoden – boren met en zonder koelen en tikken. Vijfenveertig K-draden werden in vijftien verse humane kadaver metacarpalia geplaatst met twee thermokoppels op 0.5 en 1.0mm afstand van de periferie van de insertieplaats. Alle drie de insertiemethoden werden in elke metacarpaal afzonderlijk toegepast. Externe koeling vond plaats door water te laten stromen met een snelheid van 10ml/min. Het boren en tikken vond plaats met een constant gewicht van 0.5 kg en respectievelijk 10.000 pulsen per minuut en 1.200 wendingen per minuut. De extractiekracht werd direct na het inbrengen gemeten.

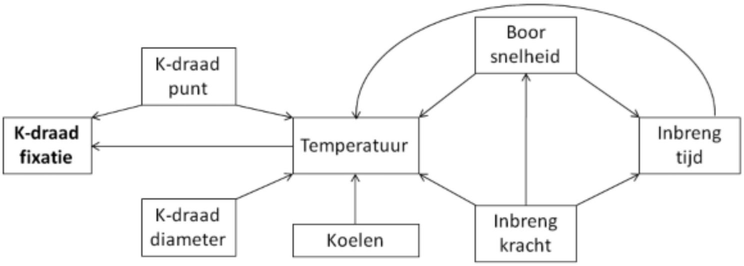
Boren zonder koelen resulteerde in een temperatuurstijging van 67.25 ± 5.4 ºC met significant lagere waarden voor boren met koelen (4.15 ± 0.6 ºC) en tikken (31.52 ± 3.4 ºC). De insertietijd voor tikken (47.63 ± 8.8 s) was significant lager vergeleken met boren zonder koelen (263.16 ± 36.5 s) en boren met koelen (196.10 ± 28.5 s). De extractiekrachten na boren zonder koelen, boren met koelen en tikken waren respectievelijk 39.85 ± 4.1 N, 57.81 ± 6.5 N and 62.23 ± 6.7 N. Hieruit kan worden geconcludeerd dat tikken superieur is ten opzichte van het boren zonder koelen, waarbij de laatst genoemde de meest gebruikte techniek is voor het percutaan plaatsen van K-draden (**Hoofdstuk 7**).

Andere aspecten die invloed hebben op de temperatuur ontwikkeling in bot tijdens het inbrengen en de mate van fixatie zijn de fysieke eigenschappen van de K-draad zelf. De hoek van de K-draad punt is een van die eigenschappen.

In (**Hoofdstuk 8**) werden twee trocar punt K-draden met ieder een andere hoek vergeleken. De K-draden werden ingebracht middels een boor en een pneumatische hamer en de resultaten in de vijf metacarpalia van de hand werden geanalyseerd. Negentig scherpe ($\alpha = 30°$) en negentig stompe ($\alpha = 60°$) trocar punt K-draden werden geplaatst in negentig vers gevroren humane kadaver metacarpalia met thermokoppels geplaatst in de cortex. De temperatuurontwikkeling, insertietijd en extractiekracht tussen vier K-draad insertie combinaties – 1) scherp boren; 2) stomp boren; 3) scherp tikken; 4) stomp tikken, werd onderzocht. De resultaten toonden aan dat tikken in een significant lagere temperatuur ontwikkeling resulteerde vergeleken met boren. Tevens was de temperatuur ontwikkeling significant lager in de eerste en vijfde metacarpaal vergeleken met de andere metacarpalia, terwijl de insertietijd significant hoger was in de tweede en derde metacarpaal vergeleken met andere metacarpalia. Het meest waarschijnlijk werd dit veroorzaakt door het verschil in dikte van het bot. Tenslotte was bij het tikken van scherpe K-draden de hoogste extractiekracht nodig om de K-draad te verwijderen. Hieruit kan worden geconcludeerd dat het tikken van scherpe trocar punt K-draden, temperatuur gerelateerde schade voorkomt en leidt tot de sterkste fixatie.

CONCLUSIES EN TOEKOMST PERSPECTIEF

De kwaliteit van de K-draad fixatie na boren hangt af van diverse factoren, maar wordt voornamelijk beïnvloed door de mate van schade toegebracht aan de osteocyten. Boorsnelheid, insertie tijd en kracht, koelen, K-draad diameter en punt configuratie zijn belangrijke factoren welke kunnen leiden tot temperatuurstijging en het verdwijnen van osteocyten in de directe omgeving van de K-draad (*figuur 1*).



Figuur 1. Factoren die de mate van fixatie beïnvloeden bij het boren van K-draden. 1) K-draad eigenschappen: punt en diameter. 2) Boor eigenschappen: insertie kracht, boor snelheid en insertie tijd. 3) De factor koelen.

In dit proefschrift werd in verschillende studies gekeken of het tikken van K-draden de schade aan het bot, welke bij het boren wordt gezien, kan verminderen dan wel kan voorkomen.

Wij hebben aangetoond dat osteonecrose voorkomen kan worden door het tikken van K-draden omdat deze techniek gepaard gaat met een kortere insertie tijd en met een lagere temperatuur stijging. Ook is de initiële fixatie van de K-draad beter vergeleken met boren vanwege de zeer beperkte bot schade rond de K-draad, met name wanneer scherpe trocar punt K-draden gebruikt worden.

Ondanks de veelbelovende resultaten die beschreven zijn, bestaat er momenteel nog geen optimale pneumatische hamer. De verschillende pneumatische hamers die wij gebruikt hebben in onze experimenten waren effectief maar hadden ook elk hun nadeel. De LithoClast produceerde teveel kracht tijdens elke initiële tik wat in sommige gevallen resulteerde in microfracturen in de cortex en in enkele gevallen zelfs tot het volledige verlies van de K-draad fixatie. Daarom zijn we overgestapt naar een subtieler apparaat, de Micro-Aire 1500 met een snel repetitieve lineaire impuls motor. Dit was een hele verbetering ten opzichte van de Lithoclast. De incidentie van het losraken van K-draden was verminderd, maar in twee gevallen konden we de K-draad niet door de tweede cortex tikken door een gebrek aan kracht. Uiteindelijk, gebruikten we de opvolger van de Micro-Aire 1500, de Micro Impactor 2500-100. In sommige gevallen vonden we nog wel microfracturen in de cortex maar desondanks waren alle K-draden goed gefixeerd.

Om de pneumatische hamer uiteindelijk in de kliniek te kunnen gebruiken moet het apparaat verbeterd en aangepast worden.

Er zijn ten minste drie belangrijke modificaties nodig voordat het apparaat in de dagelijkse praktijk kan worden gebruikt.

Ten eerste moet de pneumatische hamer over een variabele insertie kracht beschikken. De kracht moet sterk genoeg zijn om beide cortices te penetreren, maar de chirurg moet ook in staat zijn om de kracht te reguleren om op die manier microfracturen te voorkomen. In onze experimenten zijn de beste resultaten behaald met de Micro Impactor 2500-100 (**Hoofdstuk 8**). Dit is een door middel van perslucht aangedreven apparaat met een lineaire impuls motor. Het apparaat heeft een maximale frequentie van 10.000 pulsen per minuut en hoe groter de druk, hoe hoger de frequentie van de impuls motor. De druk van de perslucht varieert van 38 tot 100 psi (2.5-7 kg/cm^2). De nieuw te ontwikkelen pneumatische hamer moet tenminste aan deze voorwaarden voldoen.

Ten tweede, de Micro Impactor is een op perslucht aangedreven osteotoom dat wij hebben aangepast met een speciale adapter voor het plaatsen van K-draden. De standaard K-draden moesten worden ingekort om doorbuigen tijdens het inbrengen te voorkomen aangezien ze niet geheel in het apparaat pasten. Het is in de praktijk echter belangrijk dat de totale K-draad, zonder inkorten, in de pneumatische hamer geplaatst kan worden, zoals dat ook bij de *"high speed"* boor het geval is.

Ten derde waren in sommige gevallen de door middel van de pneumatische hamer ingebrachte K-draden zo sterk gefixeerd dat het lastig was om ze te verwijderen. In de kliniek is het niet ongewoon om een K-draad opnieuw te plaatsen als de chirurg niet tevreden is met de positie van de draad. Hiervoor is het nodig om de K-draad voorzichtig te verwijderen en in geval van boren gaat dit door middel van boren in tegenovergestelde richting. Met de pneumatische hamers die wij gebruikt hebben is deze manier van verwijderen niet mogelijk. Het is belangrijk om een pneumatische hamer te ontwikkelen met een twee-weg hamerfunctie, waarmee de K-draad in het bot kan worden getikt en verwijderd.

Wij gebruikten de pneumatische hamer in onze experimenten als een insertie apparaat voor het plaatsen van K-draden in stevig gefixeerde intacte botten in een experimentele setting. We weten niet of deze techniek in de kliniek hetzelfde effect heeft als er sprake is van gebroken botten welke goed gereponeerd en gefixeerd moeten worden.

In onze experimenten werden K-draden geplaatst onder een hoek van 90 graden op het bot. Het is bekend dat er een risico bestaat op het slippen van de K-draad over de cortex, wanneer de draad onder een andere hoek dan 90 graden wordt ingebracht. Hoe de K-draad zal reageren wanneer deze onder een andere hoek getikt wordt zal verder onderzocht moeten worden.

Deze twee aspecten, het fixeren van fracturen en het tikken onder een andere hoek kunnen *in vitro* bestudeerd worden indien de optimale pneumatische hamer geproduceerd is. Als er gunstige resultaten behaald worden met deze *in vitro* studies, kan er gestart worden met een gerandomiseerde klinische studie. Hierbij kunnen de K-draden bij de ene groep patiënten, met een phalanx of metacarpale fractuur, middels de pneumatische hamer geplaatst worden en bij de andere groep patiënten middels de boor. Deze studie moet aantonen of het apparaat in de praktijk eenvoudig te gebruiken is. Verder moet er worden gekeken naar de eventuele dislocatie van de bot fragmenten, de fixatie van de K-draad, het optreden van microfracturen, de fractuurgenezing en het optreden van infectie.

K-draden worden al meer dan een eeuw succesvol gebruikt; ook nog steeds in de hedendaagse chirurgie voor een breed scala aan klinische toepassingen. De lage kosten, de betrouwbaarheid, de beschikbaarheid van de apparatuur en het gebruiksgemak, maken het gebruik van K-draden erg aantrekkelijk. Recent is er een *"resorbable pin kit"* (ReUnite Orthopedic Fixation System, Ahrtrotek, Warsaw) geïntroduceerd. Hierbij wordt de K-draad vervangen door een oplosbare pin, waardoor het verwijderen van de K-draad overbodig wordt en theoretisch de kans op infectie vermindert.

Het belangrijkste doel van dit proefschrift was om de volgende hypothese te testen. Kan het tikken van K-draden osteonecrose, welke gezien wordt bij het boren van K-draden, voorkomen of verminderen en tevens tot een goede fixatie leiden? De beschreven *in vitro* en *in vivo* resultaten van de hamertechniek zijn veelbelovend aangezien ze even goed en vaak zelfs beter zijn in vergelijking met de boortechniek, met name wanneer scherpe trocar punt K-draden worden gebruikt.

Momenteel is de *"high-speed"* boor de gouden standaard voor K-draad insertie. Maar ons onderzoek en de door ons gevonden resultaten kunnen mogelijk leiden tot de ontwikkeling van een klinisch toepasbare pneumatische hamer voor gebruik in de 21ste eeuw.

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CURRICULUM VITAE

The author of this thesis, Bas Bernhard Gijsbrecht Maria Franssen, was born in Tegelen, The Netherlands, on May 18th 1978. He graduated from Sint Thomascollege Venlo in 1998 (HAVO and atheneum). In the same year he started his medical education at Utrecht University.

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