A SYSTEMATIC REVIEW OF ANIMAL MODELS FOR
STAPHYLOCOCCUS AUREUS OSTEOMYELITIS

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Abstract

Staphylococcus aureus (S. aureus) osteomyelitis is a significant complication for orthopaedic patients undergoing surgery, particularly with fracture fixation and arthroplasty. Given the difficulty in studying S. aureus infections in human subjects, animal models serve an integral role in exploring the pathogenesis of osteomyelitis, and aid in determining the efficacy of prophylactic and therapeutic treatments. Animal models should mimic the clinical scenarios seen in patients as closely as possible to permit the experimental results to be translated to the corresponding clinical care. To help understand existing animal models of S. aureus, we conducted a systematic search of PubMed and Ovid MEDLINE to identify in vivo animal experiments that have investigated the management of S. aureus osteomyelitis in the context of fractures and metallic implants. In this review, experimental studies are categorised by animal species and are further classified by the setting of the infection. Study methods are summarised and the relevant advantages and disadvantages of each species and model are discussed. While no ideal animal model exists, the understanding of a model’s strengths and limitations should assist clinicians and researchers to appropriately select an animal model to translate the conclusions to the clinical setting.

Keywords: Osteomyelitis; animal models, methicillin-resistant Staphylococcus aureus (MRSA), infection; fracture, implant.

Introduction

Infection and osteomyelitis represent significant complications of orthopaedic surgery. Infection rates associated with total hip arthroplasty and total knee arthroplasty have been historically reported to be 0.88 % and 0.92 %, respectively, and result in substantial morbidity (Kurtz et al., 2008). As the number of total hip and knee replacements are projected to grow between 174 % and 673 %, during the next 20 years in the United States alone (Kurtz et al., 2007), controlling these rates is of great concern. A recent report by Cram et al. has shown the infection rate after total knee replacement to be increasing with time to 3 % (Cram et al., 2012). In contrast to the rates associated with the controlled environment of arthroplasty, the infection rates of open fractures range from several percentage points to a staggering 50 % (Gustilo et al., 1984; Zalavras et al., 2005). Implant associated osteomyelitis inflicts significant morbidity and mortality to the patient and proves a notable challenge for the orthopaedic surgeon.

The increase in antibiotic resistant pathogens has further complicated the management of osteomyelitis (Cardo et al., 2004). S. aureus and coagulase-negative Staphylococci account for 65-80 % of infections (Schmidt and Swiontkowski, 2000); Darouiche, 2004 and a steep rise in the incidence of methicillin-resistant S. aureus and the ongoing emergence of vancomycin-resistant S. aureus is well documented (Parvizi et al., 2009; Loomba et al., 2010). Recent studies have shown that patients with a confirmed methicillin-resistant Staphylococcus aureus (MRSA) infection experience longer hospital stays, require prolonged antibiotic therapy (usually intravenous) and experience a 2.7 fold increase in mortality compared to non-infected inpatients (Nixon et al., 2006; Lee et al., 2010). One estimate of the mean cost attributable to an MRSA infection is $35,367 (Stone et al., 2002); and, in a 2011 APIE (Association for Professionals in Infection Control and Epidemiology) publication (Rebmann and Aureden, 2011), the annual cost to treat MRSA in hospitalised patients in the United States was quoted between $3.2 billion to $4.2 billion. Accordingly, the successful development of novel therapies to prevent and manage MRSA infections promises to deliver vast benefits in patient care and for the healthcare community.

In the face of such infections, infectious disease and orthopaedic researchers collaborate to refine the management of osteomyelitis. Human clinical trials are inherently difficult to conduct secondary to the low incidence of implant-associated osteomyelitis, the heterogeneous population, various treatment modalities
and the broad range of causative pathogens and associated virulence patterns (Lazzarini et al., 2006). Experimental studies in animal models serve to fill this void. While it is difficult to precisely replicate disease onset and progression characteristics of human infection, animal models facilitate our understanding of osteomyelitis and often inform clinical practice (Norden, 1988). In order to address implant associated osteomyelitis, investigators must ask disease specific questions and build on established animal models capable of answering these questions. For this purpose, we have systematically reviewed experimental studies in animals that explore S. aureus osteomyelitis to provide both clinicians and basic scientists with an understanding of current animal models that address the prevention and management of osteomyelitis.

Methods

Search strategy
Two databases, PubMed and Ovid MEDLINE, were used to systematically identify studies exploring osteomyelitis in S. aureus animal models. The PubMed database was systematically searched with the following search string and included articles through December 31st, 2012: ‘(infection) AND (animal model) AND (arthroplasty OR fracture OR internal fixation OR prosthesis).’ The search strategy for Ovid MEDLINE (1902 – December 31st, 2012) is described in Table 1. Three reviewers participated in screening and study selection. Two authors (NO’M and WR) individually reviewed all abstracts of identified articles. Studies that met eligibility criteria during this initial screening were retrieved and reviewed in full. A third reviewer (JH) resolved any discrepancies. Additional publications were identified within the reference section of acquired studies, and additional publications of interest were included to supplement those identified by means of the systematic search.

Inclusion/exclusion criteria
Inclusion criteria included: (1) in vivo experimental study, (2) investigation of the management of S. aureus osteomyelitis, and (3) an experimental model based on an animal species. Exclusion criteria included (1) vertebral osteomyelitis, (2) craniofacial osteomyelitis, and (3) infections not clearly defined as osteomyelitis. Furthermore, letters, abstracts, cases and reviews were excluded. Non-English reports that were unavailable in an English transcript were excluded.

<table>
<thead>
<tr>
<th>#</th>
<th>Search Words</th>
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<tr>
<td>1</td>
<td>exp Infection/</td>
</tr>
<tr>
<td>2</td>
<td>exp Models, Animal/</td>
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<tr>
<td>3</td>
<td>exp Arthroplasty</td>
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<tr>
<td>4</td>
<td>exp Fracture Fixation, Internal/ or exp Fracture Fixation/ or exp Fracture Healing/ or exp Fracture Fixation, Intramedullary/</td>
</tr>
<tr>
<td>5</td>
<td>exp Bone Screws/ or exp Femoral Fractures/ or exp Fractures, Bone/ or exp Fracture Fixation, Internal/ or exp Bone Plates</td>
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<tr>
<td>6</td>
<td>exp “Prostheses and Implants”/</td>
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<tr>
<td>7</td>
<td>1 and 2 and (3 or 4 or 5 or 6)</td>
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<tr>
<td>8</td>
<td>Limit 7 to yr = “1902-2012”</td>
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</table>
reviews, and two studies did not focus on S. aureus. Of the six additional excluded articles, three were non-English studies, two articles were letters, and one was a detailed study proposal that did not possess outcomes. Of note, the number of excluded articles is overestimated as the screening of the PubMed and Ovid MEDLINE searches were done in parallel. Duplicates were calculated only for included studies following the second screening.

Model design characteristics
The experimental studies obtained using the systematic search utilise various animal species, study varying strains of Staphylococcus aureus, and explore distinct aspects of osteomyelitis including diagnostic, prophylactic, and therapeutic measures. Table 2 highlights the major elements of each of the ninety-three experimental studies that met our inclusion criteria. Tables 2-5 provide specific details: (1) the animal species utilised, (2) the pathogenic strain studied, (3) the amount of inoculum and the method of inoculation, (4) the study question/purpose, and (5) the principal findings for each reference. Experimental studies are organised according to the use of an internal fixation, open fracture, periprosthetic, external fixation, or haematogenous model. Of note, this systematic review did not identify any rabbit or murine studies employing an external fixation model.

Animal species
Thirty-six references utilised the rabbit as the animal model (Tables 2a, and 2b), thirty-three of which employed the New Zealand white rabbit (NZW). Twenty-nine references utilised a rat model (Tables 3a and 3b), the majority of which employed either the Wistar rat or the Sprague Dawley rat. Seven references utilised a mouse model (Table 4): either the BALB/c or C57BL/6 strain. Seven references utilised an ovine model, six employed a canine model, four a goat model, two a porcine model, one a guinea pig model, and one a hamster model (Table 5).

Staphylococcus aureus strain
Researchers utilised a wide range of Staphylococcus aureus strains to investigate osteomyelitis. Of note, twenty-eight references possessed a clinical isolate or unspecified strain. The sensitivities of clinical isolates are often detailed in the accompanying reference. Common strains include ATCC 25923, ATCC 29213, ATCC 49230 as well as bioluminescent strains (i.e. ATCC12600). Thirteen experiments explored osteomyelitis secondary to methicillin-resistant Staphylococcus aureus. Nine of these utilised a clinical isolate. MRSA strains included ATCC 33591, ST-021 (a clinical isolate from University of Maryland, Shock Trauma) (Craig et al., 2005), an MLST-80 clone (Poultsides et al., 2008), and the bioluminescent USA300 LAC::lux strain (Niska et al., 2012).

Methods of evaluation
Animal experiments exploring osteomyelitis aim to either investigate the pathogenesis of osteomyelitis, examine diagnostic tools, study the efficacy of prophylactic modalities and consider varying therapeutic options. These studies typically confirmed the presence of osteomyelitis, and those studies exploring the natural course of osteomyelitis or examining the efficacy of prophylactic and therapeutic protocols monitored the progression of the infection in a reproducible and an informative manner.

Studies commonly defined the primary endpoint as rate of clinical infection. This was commonly documented by one or more of the following criteria: gross infection (i.e., purulent drainage from the infection site), histologic analysis, X-ray, serum markers of inflammation or capture of photons using bioluminescent imaging. Nonetheless, the manner in which a study establishes the presence of infection varies. Beyond noting local (erythema, swelling or abscess formation) or systemic (fever or lethargy) clinical signs of infection, studies often conducted advanced imaging (i.e., X-ray, computed tomography (CT) scan or magnetic resonance imaging (MRI)), as well as microbiologic and histologic evaluations. Additionally, researchers cultured intracardial blood samples, bone samples, or swabs from pins sites or hardware. Cultures were grown over nutrient agar or in tryptic soy broth.

Growth was often considered a binary result (i.e., with growth or without growth). Pin site swabs were assessed in a similar manner. When quantifying the magnitude of infection in bone, researchers pulverised bone samples, suspended the samples in sterile phosphate buffered saline solution and determined colony forming units per gram of bone. To expand on the colony forming units per gram of bone measurement, select studies performed polymerase chain reaction (PCR) assays to assess the presence of bacterial DNA and potentially quantify the bacterial load (Nijhoff et al., 2001).

Infections were also qualitatively assessed by radiologic, macroscopic and histologic evaluation. Radiographic evaluation of infected bone is commonly performed according to a score by An et al. (An and Friedman, 1998; Lucke et al., 2003a), grading the involved bone on periosteal reaction, osteolysis, soft-tissue swelling, deformity, sequestrum formation, spontaneous fracture and general impression. One macroscopic approach or lesion scoring employs the Rissing scale (Rissing et al., 1985b; Shandley et al., 2012), converting the appearance of infected bone into a quantitative scale: 0 = no visible evidence of infection; 1 = minimal erythema without bone destruction, without abscess; 2 = erythema with bone formation and minimal bone destruction; 3 = abscess with new bone formation, bone destruction and with purulent exudates; 4 = severe bone resorption, abscess, and total bone involvement. Studies performing a histologic examination of bone samples, such as Huneault et al., analysed periosteal proliferation, cortex remodelling, endosteal proliferation, periosteal neutrophilic inflammation, periosteal lymphoplasmocytic inflammation, marrow lymphoplasmocytic inflammation, sequestrum and bacteria (Petty et al., 1985; Huneault et al., 2004).

In recent years, several research groups have adopted the use of bioluminescent imaging (Kadurugamuwa et al., 2003; Li et al., 2008). Through this technique, bacteria are genetically modified to emit photons when metabolically active following the alteration of a lux operon. Bioluminescent imaging offers in vivo monitoring.
Table 2a. Experimental rabbit studies of Staphylococcus aureus osteomyelitis

<table>
<thead>
<tr>
<th>Species</th>
<th>Strain</th>
<th>CFU Inoculation Method/ Implantation after Implantation</th>
<th>Study Purpose</th>
<th>Principal Findings</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>NZW</td>
<td>Golden (Phage 80-81)</td>
<td>2 x 10⁵ Injected via drill hole into medullary canal (MC.)</td>
<td>Establish a model of chronically infected OM secondary to an internal fixation device.</td>
<td>Chronic staphylococcus OM developed in 88 % of rabbits receiving 2 x 10⁵ CFU after tibia fracture &amp; rod insertion.</td>
<td>Andriele et al., 1973</td>
</tr>
<tr>
<td>NZW</td>
<td>ATCC 8096</td>
<td>1 x 10⁵ Injected at femoral defect</td>
<td>Explore the effect of internal fixation on infection rates.</td>
<td>Inserting a screw significantly increased the infection rate (61.2 %; vs 35.8 %).</td>
<td>Grewe et al., 1987</td>
</tr>
<tr>
<td>NZW</td>
<td>Clinical isolate</td>
<td>2 x 10⁵ Injected into MC via burr hole after rod insertion</td>
<td>Establish a model of post-traumatic OM: femoral IM rod with midshaft bony defect</td>
<td>Chronic OM developed in all rabbits with rod &amp; inoculum without need for infection-promoting chemical agents.</td>
<td>Eerenberg et al., 1994</td>
</tr>
<tr>
<td>NZW</td>
<td>V 8199-94</td>
<td>4 x 10⁴ to 4 x 10⁴ Direct injection into tibia via drill hole</td>
<td>Susceptibility of stainless steel (SLS) versus titanium (Ti) plates to infection.</td>
<td>Infection rates associated with SLS was statistically significantly (SS) higher than for Ti plates (75 % vs. 35 %).</td>
<td>Arens et al., 1996</td>
</tr>
<tr>
<td>NZW</td>
<td>V 8199-94</td>
<td>2 x 10⁴ to 2 x 10⁵ Direct injection into implant site</td>
<td>Infection susceptibility between open surgical approach &amp; minimally invasive plate osteosynthesis (MIPO).</td>
<td>Tendency (not SS) toward lower infection rates both superficially &amp; at bone-implant interface with MIPO.</td>
<td>Arens et al., 1999</td>
</tr>
<tr>
<td>NZW</td>
<td>NC012973: ATCC 25213</td>
<td>(1) In vitro inoculation of wires before implantation</td>
<td>Establish a biofilm model using a femoral IM-implanted device.</td>
<td>In vitro inoculation did not produce adequate levels of bacterial adhesion; whereas, direct inoculation resulted in reproducible biofilm formation. Silver coating demonstrated no appreciable effect on biofilm formation in either metal.</td>
<td>Sheehan et al., 2004</td>
</tr>
<tr>
<td>NZW</td>
<td>ATCC 25923</td>
<td>5 x 10⁵ Puncture wound after surgery with sodium morrhuate</td>
<td>Efficiency of adenosmal transfer of the BMP-2 gene (Ad-BMP-2) in enhancing healing of an infected defect fracture model.</td>
<td>Addition of Ad-BMP-2 led to earlier initial- &amp; bridging callus formation &amp; higher overall callus grade versus Ad-lucifere suggesting Ad-BMP-2 enhances healing early.</td>
<td>Southwood et al., 2004</td>
</tr>
<tr>
<td>NZW</td>
<td>P1</td>
<td>5 x 10⁵ Via drill hole at inter-condylar notch before implantation</td>
<td>Antibiotic(abx)-coated pins had a SS lower colonisation rate &amp; a SS lower rate of device-related OM.</td>
<td>Antibiotic(abx)-coated pins had a SS lower colonisation rate &amp; a SS lower rate of device-related OM.</td>
<td>Darouiche et al., 2007</td>
</tr>
<tr>
<td>NZW</td>
<td>MRSA (Clinical isolate)</td>
<td>1 x 10⁸ Injected into femoral MC after suctioning &amp; saline flush.</td>
<td>Efficacy of gentamicin - vancomycin-impregnated (2:1) PMMA coating nail to treat bone &amp; intramedullary infections.</td>
<td>Abs-impregnated PMMA nails led to a SS better radiologic &amp; histologic assessment compared to rabbits with (a) non-impregnated nail, (b) no therapy, or (c) systemic teicoplanin.</td>
<td>Giavaresi et al., 2008</td>
</tr>
<tr>
<td>NZW</td>
<td>ATCC 6538</td>
<td>2.45 x 10⁴ Injected into femoral MC before treatment.</td>
<td>Treatment efficacy of ciprofloxacin &amp; rifampicin implants.</td>
<td>Rabbits with abs-implants demonstrated reduced bacterial counts and fewer clinical &amp; radiologic signs of infection.</td>
<td>Alvarez et al., 2008</td>
</tr>
<tr>
<td>NZW</td>
<td>V 8199-94</td>
<td>2 x 10⁴ to 2 x 10⁵ Inoculated at implant after implantation.</td>
<td>Effect of polishing an internal fixation device on infection rate.</td>
<td>No significant difference in infection rates between polished &amp; unpolished groups with the same material.</td>
<td>Moriarty et al., 2009</td>
</tr>
<tr>
<td>NZW</td>
<td>JAR</td>
<td>4.5 x 10⁴ to 4.5 x 10⁵ Directly injected into implant site</td>
<td>Susceptibility of non-polished Ti-aluminium-niobium (TAN), polished TAN, &amp; electropolished SLS IM nails.</td>
<td>No SS difference in infection rates among non-polished TAN, polished TAN, &amp; electropolished SLS IM nails.</td>
<td>Moriarty et al., 2010</td>
</tr>
<tr>
<td>JW</td>
<td>ATCC 25923</td>
<td>1 x 10⁸ mL In vitro inoculation of screws.</td>
<td>Antibacterial efficacy of copper-containing 317L stainless steel.</td>
<td>317L-Cu screws reduced inflammation &amp; infection compared to 317L screws. No difference in bone formation.</td>
<td>Chai et al., 2011</td>
</tr>
</tbody>
</table>

as to the degree and extent of infection and offers valuable insight to the metabolic status of the bacteria. These quantitative measurements are made over time in the same animal, in contrast to gross and histologic evaluations that require sacrifice of the test subject. Consequently, one is able to observe the temporal response of infection to an intervention in real-time.

The following section summarises many of the articles that met inclusion criteria and references additional experiments that inform and supplement those found by our systematic approach.

**Literature Review of Animal Models**

**Rabbit models of osteomyelitis**

*Internal fixation models: acute and chronic osteomyelitis*

The original tibial rabbit model was described by Schemen and then later modified by Norden (Norden, 1970), and involved inoculation of a sclerosing agent (5 % sodium morrhuate) via an 18 gauge needle followed by *S. aureus* to produce chronic osteomyelitis of theibia. Insertion of a foreign body (i.e. metallic implants) was introduced by Andriele et al. (Andriele et al., 1973). They fractured the tibia using a simple three-pronged clamp and then used a stainless steel pin for fixation, and were able to monitor infection for up to 18 months. Other authors have used the same technique without fracture (Moriarty et al., 2010). Arens et al. created a model using plate fixation for the tibiae using 6-hole dynamic compression plating (DCP), and in one study, performed it using minimally invasive plate osteosynthesis (MIPO) (Arens et al., 1999). However, no fracture was created and only unicortical screws were inserted, limiting its applications.

With respect to the femur, investigators historically accessed the femoral canal through the greater trochanter (Eerenberg et al., 1994); however, recently published models are accessing the canal through the intercondylar notch using a parapatellar incision (Castro et al., 2003; Sheehan et al., 2004; Darouiche et al., 2007; Giavaresi et al., 2008). Authors report ease of exposure and access to the canal, though this technique compromises the knee joint and thus infection may not be limited to the femoral shaft.

Once access is obtained after reaming, the investigator can perform the bacterial inoculation, place the cement (Castro et al., 2003) or screw (Darouiche et al., 2007), and finally, seal the intercondylar notch with bone wax. As such, these models provide multiple options for treatment and testing techniques. These models could be improved upon by creating a closed fracture to more closely mimic the clinical scenario. Using a simple lateral approach to the femur, Southwood et al. dissected through the soft tissue...
Open fracture rabbit models

Open fracture rabbit models primarily utilise the tibia. Ashhurst et al. first described a fracture model; fractures were created by a saw and were stabilised with plates (Ashhurst et al., 1982). Worlock et al. modified this scheme to generate a model with fixation of an intramedullary rod (Worlock et al., 1988); this method has in turn been employed by others (Kraft et al., 2001). An essential feature of this model is creating a wound over the fracture site where the contamination can take place. Worlock et al. reported 105 colony forming units (CFU) as the minimal dose to produce a consistent infection (> 80%). Subsequently, fixation can take place at the discretion of the investigator to appropriately address the experimental question. The intramedullary (IM) nail described by Worlock lacked rotational stability, differing from human cases where interlocking bolts are used to provide stability.

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Table 2b. Experimental rabbit studies of Staphylococcus aureus osteomyelitis (…continued)

<table>
<thead>
<tr>
<th>Species</th>
<th>Strain</th>
<th>CFU</th>
<th>Insulation Method</th>
<th>Study Purpose</th>
<th>Principal Findings</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>NZW</td>
<td>Y 8189-94</td>
<td>1 x 104 to 4 x 104</td>
<td>Injected adjacent to tibial implant via catheter.</td>
<td>Determine the reliability of radiograph findings for the diagnosis of osteitis.</td>
<td>Radiographically verified periselous reaction is constant &amp; early feature of OM and correlates with degree of infection.</td>
<td>Kraft et al., 2001</td>
</tr>
<tr>
<td>NZW</td>
<td>MRSA (ATCC 3591)</td>
<td>1 x 106</td>
<td>Injected into tibial MC.</td>
<td>Develop &amp; evaluate a biodegradable implantable gentamicin delivery system.</td>
<td>At 2 and 4 weeks, there was a SS decrease in the bacterial count in rabbits treated with the gentamicin implant.</td>
<td>El-Kamel &amp; Buddou, 2007</td>
</tr>
<tr>
<td>NZW</td>
<td>Clinical isolate</td>
<td>3.25 x 107 to 3.9 x 107</td>
<td>Injected into subcutaneous pouch.</td>
<td>Explore the progression of a knee infection &amp; the role of abs, metallic implant debris, intra-articular blood &amp; steroids.</td>
<td>SS increase in ID50 with prophylactic mexiteline, cefazoline, or clindamycin. Presence of metallic debris or autologous blood did not increase susceptibility to infection.</td>
<td>Schuman et al., 1975</td>
</tr>
<tr>
<td>ES</td>
<td>Phage type 95</td>
<td>0 to 108</td>
<td>Inoculated into MC before cement placed.</td>
<td>Establish a model of OM in hip arthroplasty.</td>
<td>ID50 ranged from 50 CFU in rabbits receiving prophylaxis &amp; cement to 1 x 104 CFU in rabbit without implants.</td>
<td>Southwood et al., 1985</td>
</tr>
<tr>
<td>NZW</td>
<td>MRSA (Clinical isolate)</td>
<td>105 to 108</td>
<td>Injected into knee joint immediately after implantation.</td>
<td>Establish a prosthetic joint infection model due to MRSA. Silicon elastomer implant</td>
<td>5 x 104 CFU induced infection in 100% of animals with no mortality. Natural spread of infection without sodium morrhuate. Pathologic &amp; radiologic characteristics defined.</td>
<td>Belmatoug et al., 1996</td>
</tr>
<tr>
<td>NZW</td>
<td>Newman</td>
<td>1 x 105</td>
<td>Injected into femoral MC before SLS screw placed.</td>
<td>Explore the virulence of a strain that produces several surface adhesins.</td>
<td>No SS difference in infection rate or histopathologic assessment between strains with &amp; without surface adhesins.</td>
<td>Danouche et al., 1997</td>
</tr>
<tr>
<td>NZW</td>
<td>Wood-46 (ATCC 10832)</td>
<td>108 to 1010</td>
<td>Injected into femoral MC immediately before placement of cement.</td>
<td>Prophylactic efficiency of tetracycline-containing bone cement in arthroplasty.</td>
<td>Premixed tetracycline-containing bone cement prevented implant-related infection. In controls, SS had a higher infection rate, &amp; more pronounced periosteal reaction and associated signs of infection compared to S. epidermidis.</td>
<td>Nijhof et al., 2000a</td>
</tr>
<tr>
<td>NZW</td>
<td>Wood-46</td>
<td>109 to 1010</td>
<td>Bacterial suspension introduced to tibial MC before implant.</td>
<td>Tobramycin-containing bone cement vs. systemic cefazolin for treatment of infection in a one-stage revision.</td>
<td>Both tetracycline-containing bone cement and systemic cefazolin reduced the size &amp; rate of infection. Bacterial DNA persisted after antibiotic treatment.</td>
<td>Nijhof et al., 2001</td>
</tr>
<tr>
<td>NZW</td>
<td>Clinical isolate</td>
<td>1 x 106</td>
<td>Intrathecal injection.</td>
<td>Evaluate the Te-ciprofloxacin as a marker used in scintigraphy for joint infection.</td>
<td>In rabbits with SS, increased uptake observed at day 5 in 60% &amp; at day 12 and 19 in 100 %. In those without SS, increased uptake at days 12 &amp; 19 in 81 %. Poor specificity.</td>
<td>Sarda et al., 2002</td>
</tr>
<tr>
<td>NZW</td>
<td>MRSA (Clinical isolate)</td>
<td>1 x 105</td>
<td>Injected into knee joint after implantation.</td>
<td>Treatment efficacy of teicoplanin cement &amp; without systemic teicoplanin.</td>
<td>Teicoplanin cement spacers combined with systemic intramuscular teicoplanin was most effective.</td>
<td>Ismael et al., 2003</td>
</tr>
<tr>
<td>NZW</td>
<td>MRSA (ST-021)</td>
<td>0, 108, 109 &amp; 1010</td>
<td>Injected into knee joint after SLS screw &amp; PMMA cement placed.</td>
<td>Establish a total knee arthroplasty infection model.</td>
<td>1 x 109 CFU found to be ID50. 1 x 104 CFU did not result in increased infection rates. No animal in any group developed septicaemia. Successfully established paired knee model.</td>
<td>Craig et al., 2005</td>
</tr>
<tr>
<td>NZW</td>
<td>EDCC 5055</td>
<td>1 x 105</td>
<td>Injected into knee joint after implantation.</td>
<td>Efficacy of two distinct gentamicin-hydroxyapatite (HA) coatings.</td>
<td>Gentamicin-HA-coated &amp; gentamicin-RGD-HA-coated steel K-wires had SS lower infection rates versus HA-coating.</td>
<td>Ahl et al., 2006</td>
</tr>
<tr>
<td>NZW</td>
<td>ATCC 77448</td>
<td>1 x 107</td>
<td>Injected in knee near prosthesis.</td>
<td>Efficacy of a levofloxacin &amp; rifampin combination.</td>
<td>Combination significantly reduced bacterial titres as compared to rifampin alone &amp; control.</td>
<td>Muller-Serjets et al., 2009</td>
</tr>
<tr>
<td>NZW</td>
<td>ATCC 49250C</td>
<td>1 x 105</td>
<td>Injected at implant site.</td>
<td>Prophylactic efficacy of pexiganan acetate for pin tract infections.</td>
<td>75% reduction of pin tract infections in rabbits receiving Ti-Pexigam compared to control with no antimicrobial.</td>
<td>Chou et al., 2010</td>
</tr>
<tr>
<td>NZW</td>
<td>ATCC 25953</td>
<td>5 x 108 to 1 x 109</td>
<td>0.2 mL/kg injected in ear vein.</td>
<td>Histologic study of haemarthrosis following injection.</td>
<td>Combination of a closed phlebogenic injury &amp; bacteria led to a reproducible metaphyseal infection.</td>
<td>Whalen et al., 1988</td>
</tr>
<tr>
<td>NZW</td>
<td>ATCC 25953</td>
<td>4.65 x 107 to 0.01 mL kg &amp; 0.02 mL kg via ear vein.</td>
<td>Establish a model of acute haemarthrosis osteomyelitis.</td>
<td>Animals with fracture &amp; bacteriaemia developed OM in nearly all cases, those with only bacteriaemia had occasional OM focus.</td>
<td>Moseley &amp; Haynes, 1989</td>
<td></td>
</tr>
<tr>
<td>NZW</td>
<td>Wood-46</td>
<td>1 x 106 to 2 x 109</td>
<td>Injected into auricular vein several days after implant.</td>
<td>Susceptibility of SLS versus Ti plates (traditional or PC-FIX design used).</td>
<td>SLS was more susceptible to infection than Ti plates. Ti-PC-FIX plate had infection risk equivalent to 0 CFU.</td>
<td>Ichihashi et al., 1999</td>
</tr>
<tr>
<td>NZW</td>
<td>MRSA (MLST-80 clone)</td>
<td>5 x 105 to 3 x 107</td>
<td>Fraxelfor artery four weeks after tibial IM implants were inserted.</td>
<td>Establish a haemarthrotic OM model due to a community-acquired MRSA strain.</td>
<td>10/10 animals receiving 3 x 106 CFU died within 72 h of septic shock. 8/10 receiving 3 x 105 CFU developed periarticular infection, OM &amp; septic arthritis.</td>
<td>Poulakis et al., 2008</td>
</tr>
</tbody>
</table>

KEY: NZW – New Zealand White; JW – Japanese White; ES – English Shorthair; SA – S. aureus; SS – significantly, statistically significant; OM – osteomyelitis; MC – medullary canal; SLS – stainless steel; Ti – titanium
### Table 3a. Experimental rat studies of *Staphylococcus aureus* osteomyelitis

<table>
<thead>
<tr>
<th>Species</th>
<th>Strain</th>
<th>CFU</th>
<th>Inoculation Method</th>
<th>Study Purpose</th>
<th>Principal Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sprague Dawley</td>
<td>ATCC 49230</td>
<td>3.95 x 10^8</td>
<td>Injected into tibial MC before heads.</td>
<td>Efficacy of gentamicin-loaded hydroxyapatite cement (HAC) &amp; PMMA beads.</td>
<td>Animals with gentamicin-loaded HAC or PMMA beads had SS less bacterial counts than those with debridement only. (Solberg et al., 1999)</td>
</tr>
<tr>
<td>Sprague Dawley</td>
<td>ATCC 49230</td>
<td>1 x 10^6</td>
<td>Injected into tibial MC after K-wire placed</td>
<td>Efficacy of gramicidin-sulfate-macrophage colony-stimulating factor (GSM-CSF) in acute OM.</td>
<td>Addition of GSM-CSF to ampicillin-sulbactam regimen led to greater resolution of infection compared to abx only group. (Subasi et al., 2001)</td>
</tr>
<tr>
<td>Wistar</td>
<td>ATCC 9213 SP</td>
<td>5 x 10^6</td>
<td>Jv in vivo inoculation of implant or injected near implantation.</td>
<td>Explore four models of OM with varying combinations of implant biofilms &amp; suspensions.</td>
<td>4 Groups: (1) biofilm implant, (2) biofilm implant + 10^9 CFU, (3)sterile implant + 10^9, (4) sterile implant + 10^5 Group 1 produced tibial &amp; implant infection most reliably. (Monzon et al., 2002)</td>
</tr>
<tr>
<td>Sprague Dawley</td>
<td>ATCC 49230</td>
<td>10^5, 10^4 or 10^3</td>
<td>Injected into tibial MC at time of K-wire placement.</td>
<td>Establish a model of implant- associated osteomyelitis.</td>
<td>Induction of acute OM was possible with 10^6 CFU. Radiographic &amp; histologic appearance of rats receiving 10^5 were SS worse compared to those receiving 10^6 or 10^4 CFU. (Lucke et al., 2010b)</td>
</tr>
<tr>
<td>Wistar</td>
<td>ATCC 9213 SP</td>
<td>1 x 10^6</td>
<td>Injected into tibial MC after K-wire placed.</td>
<td>Efficacy of gentamicin-loaded poly(D,L-lactide) (PDLLA) coating.</td>
<td>PDLLA + 10 % gentamicin coating SS reduced bacterial growth and radiologic &amp; histologic signs of infection. (Lucke et al., 2010a)</td>
</tr>
<tr>
<td>Sprague Dawley</td>
<td>ATCC 49230</td>
<td>5 x 10^6</td>
<td>Injected into tibial MC before placement of rod.</td>
<td>Efficacy of the combination of fusidic acid impregnated cement &amp; systemic tetracycline.</td>
<td>Combination treatment had an infection elimination rate of 81.8 %, while tetracyclin alone was 55.6 % - not SS. (Ernst et al., 2004)</td>
</tr>
<tr>
<td>Wistar</td>
<td>ATCC 49230</td>
<td>1 x 10^6</td>
<td>Injected into tibial MC before placement of rod.</td>
<td>Prophylactic efficacy of local coated (coated Ti implant) versus systemic tetracyclin.</td>
<td>Systemic abs reduced infection rate by 15 %, while local abs reduced infection rate by 90 %. No additive benefit. (Lucke et al., 2005)</td>
</tr>
<tr>
<td>Sprague Dawley</td>
<td>ATCC 49230</td>
<td>10^8</td>
<td>Femoral defect was packed by collagen with inoculum.</td>
<td>Establish a model of chronic OM – segmental defect stabilised with polyacryl plate &amp; K-wire.</td>
<td>10^8 CFU was smallest inoculum that led to reproducible infection with detectable bony lysis &amp; loss of fixation stability. (Chen et al., 2005)</td>
</tr>
<tr>
<td>Wistar</td>
<td>Xen29</td>
<td>K-wire inci- bulated until biofilm visible.</td>
<td>Biointegrated coated K-wire placed in tibial MC.</td>
<td>Treatment efficacy of 5-aminolevulinic acid (ALA)- mediated photodynamic therapy (PDT).</td>
<td>ALA-mediated PDT inhibited biofilm implants in bone as observed by bioluminescent imaging. (Boland et al., 2006)</td>
</tr>
<tr>
<td>Wistar</td>
<td>ATCC 49230</td>
<td>5 x 10^6</td>
<td>Injected in lateral femoral condyle before rod placement.</td>
<td>Prophylactic efficacy of tetracyclin- &amp; CaSO₄-loaded PMMA bone cement.</td>
<td>Addition of CaSO₄ to tetracyclin-loaded PMMA cement led to reduction in bacterial counts, in periostal reaction &amp; in osteolysis. (Tuzun et al., 2006)</td>
</tr>
<tr>
<td>Wistar</td>
<td>ATCC 9213</td>
<td>1.8 x 10^9</td>
<td>Injected into tibial MC after placement of SLS needle.</td>
<td>Study effect of age on cytokine response in acute osteomyelitis. (3 versus 22 month old rats).</td>
<td>Implants of old rats had a SS higher number of bacteria than in young rats. Surgery plus inoculum induced SS increases of IL-2 &amp; IL-10 in young rats &amp; IL-6 in old rats. (Garcia-Avila et al., 2009)</td>
</tr>
<tr>
<td>Wistar</td>
<td>ATCC 9213</td>
<td>2 x 10^6</td>
<td>Injected into tibial MC after K-wire implantation.</td>
<td>Treatment efficacy of microspherical implants containing tetracyclin.</td>
<td>Significantly more mineralised callus was induced by high dose rhBMP-2 than with low dose and with systemic abs therapy than without. (Chen et al., 2007)</td>
</tr>
<tr>
<td>Wistar</td>
<td>ATCC 29213</td>
<td>5 x 10^5</td>
<td>Injected into femoral MC at intercondylar notch before K-wire placed.</td>
<td>Treatment efficacy of moxifloxacin versus tetracyclin in chronic methicillin-sensitive <em>S. aureus</em> (MRSA) OM.</td>
<td>Teicoplanin-containing implants reduced the bacterial burden greater than intramuscular injection in chronic OM. (Orhan et al., 2010)</td>
</tr>
<tr>
<td>Wistar</td>
<td>ATCC 29213</td>
<td>1 x 10^6</td>
<td>Injected in femoral MC at intercondylar notch before K-wire placed.</td>
<td>Treatment efficacy of tetracyclin versus tetracyclin in chronic methicillin-sensitive <em>S. aureus</em> (MRSA) OM.</td>
<td>Bacterial counts in animals receiving abx were SS reduced as compared to controls. After implant removal, moxifloxacin significantly reduced counts more than tetracyclin. (Orhan et al., 2010)</td>
</tr>
</tbody>
</table>

In a rabbit osteomyelitis model that involved inoculation of bacteria into devascularised bone, Smeltzer et al. demonstrated the importance of virulence factors in establishing osteomyelitis (Smeltzer et al., 1997). Interestingly, the strain Smith diffuse, a strain that had demonstrated enhanced virulence in a murine peritonitis model, exhibited relatively little evidence of osteomyelitis compared to that of the strain UAMS-1. UAMS-1 achieved an infection rate of 75 % with an inoculum of 2 x 10^8 CFU.

**Periprosthetic models**

Rabbits are the smallest animals in which true models of prostheses related osteomyelitis are described in the literature. Knee arthroplasty components exist with modification of existing joint replacements for humans. Belmatoug et al. used a human first metatarsophalangeal (MTP) silicone-elastomer implant for the tibial tray of a knee arthroplasty (Belmatoug et al., 1996). Inoculants of 5 x 10^8 resulted in consistent infections. Of note, a silicone implant allows for MRI and micro-computed tomography (µCT) without artefact distortion, a significant advantage over most implants. Craig et al. produced a novel arthroplasty model in which a metal screw and ultra-high molecular weight polyethylene (UHMWPE) washer was secured to the non-articulating surface of the lateral femoral condyle (Craig et al., 2005). All the various materials seen in a typical arthroplasty are present; however, the same stresses and strains placed on a weight bearing total joint arthroplasty (TJA) are not recreated with this model, which may bias results of therapeutic studies. A one-stage revision model has been described by inserting a standardised cement plug in to the tibial metaphysis, followed by contamination of 10^5 or 10^6 *S. aureus* directly anterior to the insertion of the anterior cruciate ligament of the knee (Nijhof et al., 2001). This plug has a hook, thereby making a single exchange reproducible, even after several weeks of incorporation in the host.
### Table 3b. Experimental rat studies of *Staphylococcus aureus* osteomyelitis (…continued)

<table>
<thead>
<tr>
<th>Species Strain</th>
<th>CFU</th>
<th>Inoculation Method</th>
<th>Study Purpose</th>
<th>Principal Findings</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sprague Dawley Clinical isolate</td>
<td>1 x 10³</td>
<td>Injected at tibial osteotomy after IM device placement</td>
<td>Establish a model of implant-related infected non-unions with detection by fluorescence in situ hybridisation</td>
<td>All rats with 0 CFU had normal bone healing without infection at 8 weeks. 10/11 rats with 10³ CFU developed infected non-union &amp; all 11 IM implants had biofilm growth.</td>
<td>Ali et al., 2011</td>
</tr>
<tr>
<td>Sprague Dawley Clinical isolate</td>
<td>1 x 10³</td>
<td>Injected in femoral MC before IM pin placement</td>
<td>Establish a model of induced implant-associated OM following a fracture.</td>
<td>SS difference in CFU/emin &amp; CFU/pin among three groups – highest in S. aureus only: OM present radiographically &amp; histopathologically in both S. aureus groups – no in controls.</td>
<td>Robinson et al., 2011</td>
</tr>
<tr>
<td>Sprague Dawley Clinical isolates</td>
<td>1 x 10³</td>
<td>Injected in wound 15 minutes before irrigation</td>
<td>Efficacy of surfactant wound irrigation to prevent infection.</td>
<td>Sequential surfactant irrigation protocol led to a SS lower rate of infection than a single 3 L normal saline irrigation.</td>
<td>Marbury et al., 2002</td>
</tr>
<tr>
<td>Sprague Dawley Clinical isolate</td>
<td>5 x 10⁷ to 6.8 x 10⁷</td>
<td>Injected into tibial MC via dorsal defect</td>
<td>Establish a traumatized Guinot Type III tibia; model for acute osteomyelitis.</td>
<td>ID₉₀ &amp; IDₓ values were 1.8 x 10⁷ CFU &amp; 9.2 x 10⁷ CFU. Lavage reduced bacterial load but did not prevent infection.</td>
<td>Buxton et al., 2005</td>
</tr>
<tr>
<td>Sprague Dawley Clinical isolate</td>
<td>10⁵</td>
<td>Injected into tibial MC via dorsal defect</td>
<td>Establish an acute OM model secondary to trauma with a foreign body &amp; thermal injury.</td>
<td>ID₉₀ &amp; IDₓ values were 72 &amp; 977 CFU, respectively. At 1.7 x 10⁵ CFU, all tibiae were infected when exposed to thermal injury, while 4 of 10 of non-thermal group were sterile: Sand increased bacterial load.</td>
<td>McPherson et al., 2008</td>
</tr>
<tr>
<td>Sprague Dawley Clinical isolate</td>
<td>1 x 10³</td>
<td>Injected directly at fracture site</td>
<td>Prophylactic efficacy of interferon-12 (IL-12) coatings for implant infection.</td>
<td>Local IL-12 significantly reduced the infection rate in a dose-dependent fashion. Systemic IL-12 did not reduce rates.</td>
<td>Li et al., 2009</td>
</tr>
<tr>
<td>Sprague Dawley Clinical isolate</td>
<td>1 x 10³</td>
<td>Injected directly at fracture site</td>
<td>Efficacy of monocytes-macrophage-attractant protein-1 (MCP-1) &amp; IL-12 p70</td>
<td>Locally GC-1 &amp; IL-12 p70 significantly reduced infection, independently. No synergy effect when combined.</td>
<td>Li et al., 2010a</td>
</tr>
<tr>
<td>Sprague Dawley Clinical isolate</td>
<td>10⁵ or 10⁶</td>
<td>Injected at both ends of fracture 1 h before K-wire</td>
<td>Establish an open fracture OM model. Blunt trauma, IM K-wire fixation &amp; SLS.</td>
<td>10⁶ had infection rate of 90-100%. Rate with CFU improved from 20% to 30% as surgical technique improved.</td>
<td>Lindsey et al., 2010b</td>
</tr>
<tr>
<td>Sprague Dawley Clinical isolate</td>
<td>1 x 10³</td>
<td>Injected at both ends of fracture 1 h before K-wire</td>
<td>Evaluate effect of interferon-12 systemic therapy in open fracture osteomyelitis.</td>
<td>Infection rate unchanged by IL-12 therapy; but at day 10, bacterial qualitative growth scores were SS lower.</td>
<td>Lindsey et al., 2010a</td>
</tr>
<tr>
<td>Brown Norway Clinical isolate</td>
<td>1 x 10⁸</td>
<td>Injected at fracture site into femoral MC</td>
<td>Effect of gentamicin- &amp; bone morphoge phase protein-loaded scaffold on osteomyelitis.</td>
<td>Gentamicin-treated rats exhibited SS increased fracture healing &amp; bridging callus formation. No SS difference in bacterial bone culture between abx &amp; non-abx groups.</td>
<td>Stewart et al., 2010</td>
</tr>
<tr>
<td>Sprague Dawley Xenograft 38 ATCC 49255</td>
<td>1 x 10⁷</td>
<td>Collagen soaked in 10 x 10⁴ CFU placed in mid-medial defect</td>
<td>Effect of early ceilulitis &amp; debriement on infection in an open fracture.</td>
<td>In rats receiving abx at 2 h, delaying surgery from 2 to 6 SS increased the infection rate. Regardless of the time of surgery, delaying abx at 6 or 24 SS increased the rate.</td>
<td>Penn-Barwell et al., 2012</td>
</tr>
<tr>
<td>Winter ATCC 25923</td>
<td>1 x 10⁷</td>
<td>Injected into femoral MC before Ti rod placement</td>
<td>Prophylactically bound vancomycin Ti rods.</td>
<td>Vancomycin-bound Ti rods led to reduced clinical signs of infection, reduced bacterial load &amp; prevented osteomyelitis.</td>
<td>Autoci et al., 2007</td>
</tr>
<tr>
<td>Winter ATCC 25923</td>
<td>1 x 10⁷</td>
<td>Injected into femoral MC</td>
<td>Treatment efficacy of vancomycin-loaded thin sol-gel coating.</td>
<td>Coating resulted in SS decrease in bacterial count &amp; bacterial adhesion compared to control.</td>
<td>Adams et al., 2009</td>
</tr>
<tr>
<td>Winter ATCC 25923</td>
<td>1 x 10⁷</td>
<td>Injected into tibial MC after K-wire fixation</td>
<td>Efficacy of debriement or abx-loaded cement vs. abx-loaded autogenous bone.</td>
<td>Tetracyclasedebris cement led to SS lower bacterial counts, but this led to extensive infection in 3/8 rats.</td>
<td>Sene et al., 2010</td>
</tr>
</tbody>
</table>

### Table 4. Experimental mouse studies of *Staphylococcus aureus* osteomyelitis

<table>
<thead>
<tr>
<th>Species Strain</th>
<th>CFU</th>
<th>Inoculation Method</th>
<th>Study Purpose</th>
<th>Principal Findings</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Balb/c</td>
<td>FDA208P 5 x 10³</td>
<td>Injected at fracture site before K-wire placement</td>
<td>Study the expression of human β-defensin-3 during osteomyelitis.</td>
<td>The murine homologue, murine β-defensin-3, was upregulated following tibial contamination.</td>
<td>Varoga et al., 2008</td>
</tr>
<tr>
<td>Balb/c Clinical isolate</td>
<td>1 x 10³</td>
<td>Injected into the osseous cavity of the tibia.</td>
<td>Treatment efficacy of hyaluronic acid gel as a carrier of gentamicin.</td>
<td>Gentamicin-containing hyaluronic gel suppressed bacterial growth without interfering with bone growth.</td>
<td>Matias et al., 2006</td>
</tr>
<tr>
<td>C57BL/6</td>
<td>ATCC 49230 Xem29 9.5 x 10³</td>
<td>Injected into a 5 x 10⁴ IM implant before implantation.</td>
<td>Establish a quantitative model of implant-associtated OM utilizing bioluminescent imaging (BLI).</td>
<td>In vivo BLI of Xen29 combined with sotr gene real-time quantitative PCR demonstrated the initial exponential growth phase of bacteria that peaks on day 4, followed by the biolumin growth phase at a lower metabolic rate.</td>
<td>Li et al., 2008</td>
</tr>
<tr>
<td>C57BL/6 MRESA (Clinical isolate)</td>
<td>2.7 x 10³</td>
<td>Injected into a 5 x 10⁴ IM implant before implantation.</td>
<td>Efficacy of hyperbaric oxygen (HBO) therapy in the prophylaxis &amp; treatment of osteomyelitis.</td>
<td>HBO therapy did not decrease bacterial burden. Of note, a positive correlation was found between the receptor activator of NF-κB ligand concentration and lesion score.</td>
<td>Shandley et al., 2012</td>
</tr>
<tr>
<td>C57BL/6</td>
<td>ALC2906 &amp; Xem29 5 x 10³</td>
<td>Injected into joint space after K-wire placement.</td>
<td>Explore a treatment modality for a post-arthroplasty infection of bioluminescent S. aureus.</td>
<td>Ex vivo bacterial counts highly correlated with <em>in vivo</em> bioluminescent signals. Minocycline/trimethoprim-loaded implants reduced infection, inflammation &amp; infection formation.</td>
<td>Benahal et al., 2010</td>
</tr>
<tr>
<td>C57BL/6 MRESA (Xem29)</td>
<td>1.5 x 10³</td>
<td>Injected into knee joint after device implantation.</td>
<td>Prophylactic efficacy of low-dose ciprofloxacin, tigecycline, &amp; vancomycin.</td>
<td>Low- &amp; high-dose ciprofloxacin &amp; tigecycline and high-dose vancomycin resulted in significantly fewer bacterial counts as compared to control.</td>
<td>Niska et al., 2012</td>
</tr>
<tr>
<td>C57BL/6</td>
<td>ALC2906, Xem29, Xem40 &amp; Xem36 10⁴, 10³</td>
<td>Injected into joint space after K-wire implantation.</td>
<td>Establish a chronic post-arthroplasty infection with a bioluminescent S. aureus strain.</td>
<td>Xen29, Xem36 &amp; Xem36 had increased bioluminescent signal through day 42; ALC2906 became undetectable at day 10. Xem36 induced the least inflammation.</td>
<td>Pritha et al., 2012</td>
</tr>
</tbody>
</table>
Several authors have investigated the role of cement with various mixtures of antibiotics. Nijhof et al. describe a method of gaining access to the femoral canal by the trochanter tertius (Nijhof et al., 2000a; Nijhof et al., 2000b). Once the bone is exposed and the canal accessed, a silicone sleeve is inserted into the shaft. This sleeve will both house the inoculum and the cement which serves to seal off the bony defect and prevents subsequent leakage of the inoculum into the surrounding soft tissues.

### Haematogenous models

Morrisy et al. and Whalen et al. first published a haematogenous model involving trauma to the proximal epiphysis of theibia (Whalen et al., 1988; Morrissey and Haynes, 1989). A three point bending force over the proximal part of the tibia creates a reproducible shearing injury to the tibia. This is followed by intravenous (IV) injection of a high bacterial load (10⁶ CFU) and provides good analysis of histologic parameters. This model was adapted by Johansson et al. (Johansson et al., 1999) who implemented the presence of metallic hardware in the distal part of the tibia, although no fracture was created prior to fixation. Exposure to the distal diaphysis was made through a lateral approach, and a 5 x 35 mm dynamic compression plate (DCP) was applied followed by skin closure. Three to five days later, after the incision had healed, 10⁶ S. aureus were injected into the auricular vein. This model had a relatively poor infection rate with a high mortality rate for the animals. Again, the addition of an injury or fracture may create an area of weakness to the host immune system, theoretically allowing greater infection rates as first published by Morrissey et al. (1989).

Poultsides et al. produced a haematogenous infection after insertion of a porous tantalum intramedullary implant press-fit into the proximal part of the tibia, which was capped by a silicone cup to permit load transmission within the knee joint (Poultsides et al., 2008). Four weeks later, the femoral artery was cannulated and a catheter was advanced to 20 mm proximal to the knee joint where 1 mL of bacterial inoculum was injected to maximise the implant exposure to bacteria. While a higher inoculum (5 x 10⁹) resulted in 100% mortality due to septic shock, lower inoculates did not consistently produce infection reliably. This reinforces the difficulty of injecting the smallest load to ensure infection without overwhelming the animal immune system.

### Advantages and disadvantages

Rabbits are employed in a large portion of the reviewed experiments. As an intermediate-sized animal, they possess distinct versatility and are relatively easy to handle, manipulate and maintain. Consequently, rabbits are relatively inexpensive. While their size lends itself to easy maintenance, their bones remain large enough to perform plate and screw fixation. The medullary canal of both the rabbit and fur can easily accommodate a modified nail and are sizeable enough to house implants, in which an investigator can remove and replace in a reproducible

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### Table 5. Other experimental animal studies of Staphylococcus aureus osteomyelitis

<table>
<thead>
<tr>
<th>Animal</th>
<th>Strain</th>
<th>CFU</th>
<th>Inoculation Method</th>
<th>Study Purpose</th>
<th>Principal Findings</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guinea Pig</td>
<td>ATCC 29213</td>
<td>4 x 10⁷/ml</td>
<td>Exploited &amp; mini-screws bathed for 1 h</td>
<td>Establish a model of multiple OM &amp; explore the role of surgical &amp; bone-healing</td>
<td>SS reduction in adhesion of the fibrocartilage-defective model of S. aureus</td>
<td>Fischer et al., 1996</td>
</tr>
<tr>
<td>Guinea Pig</td>
<td>ATCC 29213</td>
<td>2.5 x 10⁶</td>
<td>Injected via catheter into osteotomy site</td>
<td>Effect of hydrophobic polycarbonate implant coatings on bone healing &amp; bone-healing.</td>
<td>Both Ti &amp; SLS implants coated by N,N-dodecyl methylenephil exhibited SS less biofilm formation &amp; greater bone healing compared to uncemented implants.</td>
<td>Schaer et al., 2012</td>
</tr>
<tr>
<td>Guinea Pig</td>
<td>ATCC 29213</td>
<td>7.6 x 10⁶</td>
<td>Inoculated on pin after insertion.</td>
<td>Prophylactic efficacy of vancomycin-loaded PMMA pin sleeve.</td>
<td>Abs-loaded sleeves had no gross evidence of infection. At 48 h, all untreated pins were colonised; treated had no growth.</td>
<td>Voss et al., 1999</td>
</tr>
<tr>
<td>Guinea Pig</td>
<td>ATCC 29213</td>
<td>3 x 10⁶</td>
<td>Inoculated on pin before insertion.</td>
<td>Efficacy of hydroxyapatite-chlorhexidine coating on SLS &amp; Ti pins.</td>
<td>Coating SS decreased pin tract infections from 100% in uncemented pins to 83.3% with no growth in coated pins.</td>
<td>Dejong et al., 2001</td>
</tr>
<tr>
<td>Guinea Pig</td>
<td>ATCC 29213</td>
<td>5 x 10⁶</td>
<td>Inoculated in wound around pin.</td>
<td>Establish a model of osteomyelitis (OM).</td>
<td>When a fluid reservoir was maintained around the pin, the infection rate was significantly greater (7 of 9 versus 0 of 9).</td>
<td>Clauser et al., 2001a</td>
</tr>
<tr>
<td>Guinea Pig</td>
<td>ATCC 29213</td>
<td>2.4 x 10⁶</td>
<td>Inoculated in wound at pin two weeks before IM nailing</td>
<td>Explore the outcome of secondary IM nailing following pin tract infection.</td>
<td>IM nailing in the setting of no abx led to sepsis in all sheep. Local debridement, MC lavage, and systemic and local abx controlled spread of infection; did not prevent chronic OM.</td>
<td>Clauser et al., 2001b</td>
</tr>
<tr>
<td>Guinea Pig</td>
<td>Phage types 52, 80, 81</td>
<td>1 x 10⁶</td>
<td>Injected into tibial nutrient artery.</td>
<td>Establish a canine model of acute haematogenous OM.</td>
<td>At 48 h, 10% died of septicaemia. Surviving dogs developed medullary destruction, spontaneous fractures, &amp; notable persistent bone formation.</td>
<td>Dey вне et al., 1976</td>
</tr>
<tr>
<td>Guinea Pig</td>
<td>Phage type 80/81</td>
<td>5 x 10⁶</td>
<td>Injected into tibial nutrient artery.</td>
<td>Explore progression of acute haematogenous OM into chronic infection.</td>
<td>At 2 years, dogs exhibited clinical, histologic, radiologic &amp; microbiologic changes associated with chronic OM.</td>
<td>Deyenne et al., 1983</td>
</tr>
</tbody>
</table>
multi-staged fashion. Based on the included rabbit studies, the typical inoculation dose ranges from $10^3$-$10^6$. Higher doses are typically required when manually coating implants with bacteria in contrast to direct inoculation in order to successfully initiate an infection.

**Rat models of osteomyelitis: Internal fixation models: acute and chronic osteomyelitis**

There are few studies designed to model acute osteomyelitis. The rat is known to possess a strong immune system that at times can complicate infection models in this species. Nonetheless, Subasi et al. explored acute osteomyelitis after pre-drilling the medial cortex of the proximal part of the tibia, directly inoculating bacteria and sealing the hole with bone cement in the absence of a sclerosing agent (Subasi et al., 2001). A similar method was used by a group that used photodynamic therapy to eradicate acute *S. aureus* tibial osteomyelitis (Burch et al., 2005).

Chronic tibial osteomyelitis was initially described by Zak et al. (Zak et al., 1982) and has been modified by several investigators since that time. Zak et al. used sodium morrhuate as a sclerosing agent to help establish an infection; arachidonic acid has also been described (Rissing et al., 1985a; Mendel et al., 1999). More recent models, however, do not rely upon a sclerosing agent, which may cause variability in the inflammatory pathology of the infection. They describe a craniomedial approach to the proximal tibia. This is ideal, as there is minimal soft tissue for dissection and for placement of desired instrumentation. Groups have used either a short segment of wire or needle tip as the metallic implant into the medullary canal (Hamblen, 1968; Korkusuz et al., 1993; Solberg et al., 1999; Ersoz et al., 2004). While these are adequate models of developing osteomyelitis, they are not directly comparable to a human subject. A model designed by Lucke et al. (Lucke et al., 2003b), though technically more challenging, mimics the human condition more accurately. It requires placement of a Kirschner wire (K-wire) or needle down the length of the medullary canal of the tibia with contamination prior to implanting the metal implant, which has been reproduced by other investigators (Lucke et al., 2005; Bisland et al., 2006; Garcia-Alvarez et al., 2009). Others have modified this technique to include internal fixation of the tibia after performing an osteotomy of the tibial diaphyseal area (Alt et al., 2011).

Several rat models designed to recreate femoral implant associated chronic osteomyelitis. Skott et al. (Skott et al., 2006) originally described a medial parapatellar approach, which allowed reaming of the distal femur generating easy access to the canal for intramedullary fracture fixation. This has been modified to implant a bacterial inoculum and steel pin with the hole subsequently sealed by bone wax or cement to develop intramedullary osteomyelitis (Tuzuner et al., 2006; Ozturan et al., 2010; Robinson et al., 2011). A novel model of extramedullary fixation was first described by Chen et al. They used a 6-hole polyacetyl plate with threaded K-wires to secure the femur after creation of a 6 mm defect (Chen et al., 2005). A disadvantage to this model is the need to expose the entire femur laterally for application of the hardware.

**Open fracture osteomyelitis**

The majority of open rat models involved the femur, in which a comminuted midshaft femur fracture was created by dropping a weighted blade onto the hind leg. Lateral exposure of the fracture ensued and the fixation took place by intramedullary K-wire placement. The fracture site is then contaminated and left open to air for 1 hour to mimic environmental exposure of the trauma patient prior to treatment (Li et al., 2009; Li et al., 2010a; Lindsey et al., 2010a). Stewart et al. used this same technique to generate the femur fracture, though they removed small pieces of bone to create a 5.0 mm gap and implemented a polypropylene fumarate scaffold, to serve as a carrier for their treatment (Stewart et al., 2010). Similarly, an open femur fracture model with polymethylene plate and threaded K-wires has been performed (Penn-Barwell et al., 2012). A 6.0 mm defect is created after fixation and the bone is contaminated and closed prior to treatment.

Two studies identified described an open tibial fracture model. Both studies used a 1.0 mm burr to create a 10 mm longitudinal trough in the cranial tibial cortex to expose the medullary canal. Using cautery, the endosteal blood supply was subsequently disrupted and bacterial contamination performed (Buxton et al., 2005). No instrumentation was used. This technique was later modified with the addition of sand as the foreign body and *Escherichia coli* and *S. aureus* as bacterial contaminants (McPherson et al., 2008).

**Periprosthetic osteomyelitis**

Given the small size of the rat, it is difficult to generate a true model for total joint arthroplasty. Antoci et al. provide a limited model of arthroplasty-related osteomyelitis (Antoci et al., 2007), which is similar to the chronic femoral model by Skott et al. The notable difference is that after bacterial inoculation, a titanium rod is press-fitted into the femoral notch, effectively sealing the canal. Consequently, the titanium implant still has direct exposure to the joint, in contrast to being sealed off by bone wax, effectively simulating the pathogenesis of arthroplasty-related osteomyelitis. It should be stated that models in larger animals, where joint replacement is possible, is preferred as it clinically replicates the infection.

**External-fixation osteomyelitis-related model**

There are few rat studies specifically addressing the question of external fixation induced osteomyelitis despite being a recognised risk factor for infection. One citation identified independently of the systematic search described a model that inserted three 2.0 mm diameter pins into the third, fourth and fifth tail vertebrae (Holt et al., 2011); however, no direct inoculation took place at the time of implantation. No additional models of external fixation of the rat were identified.

**Haematogenous models**

Hienz et al. established a haematogenous rat model to allow study of the initiating events of osteomyelitis (Hienz et al., 1995). They injected a sclerosing agent (i.e. sodium morrhuate) directly into the mandible and tibia followed by intravenous injection of *S. aureus* into the femoral vein.
for haematogenous spread, effectively generating acute osteomyelitis.

Advantages and disadvantages

Rats possess a distinct set of pros and cons. Rat bones are of sufficient size to reproduce fracture patterns, and to perform drilling and fixation, as well as intramedullary nailing. The medullary canal is large enough to implant foreign objects and despite their small size, screws and plate fixation has been well documented (Histling et al., 2011). As an alternative to larger animals, such as the rabbit or sheep, rats are inexpensive, abundant in supply, and are easily housed and maintained for prolonged periods of time during an experiment. Rats require inoculation doses ranging from $10^3$-$10^5$ CFU, with several open fracture models reporting inoculation doses as low as $10^5$ CFU.

Mouse models of osteomyelitis

Acute and chronic osteomyelitis

The work by Funao et al. (Funao et al., 2012) utilised a femoral implant and monitored the infection with bioluminescence imaging. A midline lower limb arthrotomy was performed to allow introduction of an intramedullary inoculate of $S. aureus$ through the distal part of the femur, without contaminating the actual joint space. Bone wax was used to seal the access burr hole and sequential study of the infectious process and establishment of osteomyelitis was observed. Both Sottnik et al. (Sottnik et al., 2010) and Yoshii et al. (Yoshii et al., 2002a; Yoshii et al., 2002b) utilise a transcortical hole in the proximal part of the tibia with implanted $S. aureus$ seeded suture material as the source of the osteomyelitis. Varoga et al. (Varoga et al., 2008; Varoga et al., 2009) modified a rat model initially described by Lucke et al. (Lucke et al., 2003b), in which an access hole in the proximal part of the tibia allowed access to the medullary canal for the introduction of an inoculum. Mariott et al. (Marriott et al., 2004; Marriott et al., 2005) accessed the femur with a burr for inoculation with $S. aureus$, based on original work by Spagnolo et al. (Spagnolo et al., 1993). In 2006, Matsuno and colleagues (Matsuno et al., 2006) described a mouse model in which the femur was surgically exposed and fractured with surgical scissors, followed by placement of $S. aureus$ and an intramedullary Kirschner wire. They do not specify whether the fracture site is closed at the superficial level or left open, both methods would be suitable depending on the desired clinical scenario being modelled.

Li et al. described a reproducible murine model with the use of bioluminescent $S. aureus$ (Xen29) for an implant-associated osteomyelitis in which a stainless steel pin is coated with $S. aureus$ and implanted transcortically, medial to lateral, through the tibial metaphysis (Li et al., 2008; Li et al., 2010b). This has the advantage of not involving the knee joint. This led to a highly reproducible localised abscess in greater than 90% of the mice, without any detectable haematogenous spread, sepsis or mortality. The method was subsequently reproduced by Shandley et al. (Shandley et al., 2012). Johansson et al. (Johansson et al., 2001) similarly inserted 0.4 mm cerclage wire through a 0.6 mm drill hole in the medial tibial metaphysis, before an inoculation suspension was injected close to the metaphyseal drill hole.

Periprosthetic models

Bernthal et al. (Bernthal et al., 2010) used a model of periprosthetic infection established through a medial parapatellar approach and then introduced a Kirschner wire into the murine femur with 1.0 mm left protruding into the knee joint before inoculation with $S. aureus$. This model is also similar to an arthroplasty infection and could be used to assess synovial response, but fails to adequately recreate the environment of a total joint arthroplasty. Other authors have published long term (42 days) evaluation with this model (Pribaz et al., 2012).

Advantages and disadvantages

In recent years, mice have served as the animal of choice to establish models utilising bioluminescent imaging. Given the superior knowledge into the function and regulation of their immune system, the choice of utilising a mouse model is not surprising (Patel et al., 2009). Supplement this advantage with their small size, ease of handling, and overall lower cost, and it becomes evident why mouse models are quickly becoming a frequently used model for the study of osteomyelitis. While the size of mice offers many advantages, it is noteworthy that the smaller size makes two-stage revisions and multiple procedures in a single mouse more challenging.

Nonetheless, with the advent of bioluminescent imaging, the advantages of mouse models abound. As imaging photon emissions through thicker tissues skews the ability of researchers to interpret the metabolic activity of bacteria, small animals, such as mice and rats, prove valuable. As bioluminescent imaging permits real-time assessment of the degree of infection in a single animal longitudinally without sacrificing the animal, the sheer number of animals needed in an experiment is reduced; and more importantly, researchers are able to examine the response of bacteria to an intervention in a single animal over time. Researchers need not compare the degree of infection in mouse ‘a’ at time ‘t’ to the degree of infection in mouse ‘b’ at time ‘t + 1.’ Consequently, animals can serve as their own control and experimental variability is greatly reduced. No models of external fixation for the mouse were identified in this review.

Other animal models of osteomyelitis

Internal fixation models: acute and chronic osteomyelitis

In 1983, Fitzgerald developed a dog model of chronic osteomyelitis (Fitzgerald, 1983). The authors removed a 1.0 cm$^2$ cortical window, injected $S. aureus$ and filled the defect with intramedullary polymethylmethacrylate (PMMA) cement. After twelve weeks, each specimen revealed radiographic, clinical, histological and microbiologic evidence of osteomyelitis. Another canine model uses the lateral aspect of the femur, in which $S. aureus$ is directly dripped onto a 2.0 mm cortical screw, which is subsequently placed through cortex with the end of the screw resting in the intramedullary cavity (Huneault et al., 2004).
The Schaer lab has established an internal fixation model of the proximal part of the tibia of a sheep. They exposed the tibia using a standard medial incision. Next, they pre-drilled screw holes, they then used an oscillating saw to create the fracture. The internal fixation was inserted into the previous drilled holes after being inoculated with \textit{S. aureus} (Stewart et al., 2012).

Experimental models in guinea pigs have been described. One group of authors described an experimental model to reproduce internal fixation devices and study bacterial colonisation in guinea pigs. Pure titanium mini-plates and screws (Synthes) were implanted into the proximal aspects of the iliac wings. Identical plates and screws were implanted subcutaneously as controls (Fischer et al., 1996).

Open fracture models
Williams et al. recently published a model simulating type IIIIB Gustilo open fracture using the proximal part of the tibia of sheep (Williams et al., 2012b). They used two 20 x 20 mm metal plates separated by 10 mm that could accommodate a membrane that was coated with a MRSA biofilm. Khodaparast et al. incised the skin over the proximal part of canine tibiae and created a fracture. The fracture was stabilised with a locked intramedullary nail and \textit{S. aureus} was inoculated into the medullary canal proximal and distal to the fracture (Khodaparast et al., 2003).

Another study of open fractures in sheep utilised a fracture created in the hind limb using a chevron osteotomy. A patch of bovine type I collagen was used to locally deliver a standard inoculum of \textit{S. aureus} to the fracture site. An 8.0 mm IM nail was placed into the tibia (Hill et al., 2002). This model was unique compared to other models used to study IM nailing in open fractures, in that it placed contamination at the osteotomy site prior to IM nailing. Consequently, the pathogen is disseminated with reaming and insertion of the nail distal to the fracture site. This appropriately mimics the clinical complications when placing an IM nail after an open fracture.

In a goat model of open fractures, a unicortical circular defect was created using a coring reamer distal and medial to the tibial tubercle (Wenke et al., 2006). This defect was inoculated with \textit{S. aureus}. After three weeks, animal groups treated with antibiotics demonstrated no evidence of infection, whereas, animals that were not treated developed necrosis and abscess formation at the site of the cortical defect.

Periprosthetic models
In their canine total joint arthroplasty model, Petty et al. reamed the femoral canals of dogs and simultaneously introduced PMMA cement as well as \textit{S. aureus}, \textit{S. epidermidis}, or \textit{E. coli} resulting in infection by all three organisms at a later time point (Petty et al., 1988). The authors cautioned against the use of their model for the more common setting of chronic infections of joint prostheses, as the femoral medullary canals in their experiment were acutely infected. The transition from an acute to chronic infection is typically based on development of radiographic changes including periostal reaction, new bone formation, sequestered bone, and histologic changes of acute and chronic inflammation. All models of chronic infection begin as acute infections that progress with time.

External fixation models
Casper et al. examined sheep models of osteomyelitis associated with external fixators in tibiae. Three bicortical pins were implanted subcutaneously as controls (Fischer et al., 1996). S. aureus was applied to the wound around the pin (Casper et al., 2001a). After only 1 hour, one group of sheep that had a stagnant fluid reservoir at the pin site displayed evidence of extension of the infection. Another ovine model addressed secondary intramedullary (IM) nailing after pin tract infections from external fixators (Casper et al., 2001b). Two external fixator pins were placed into the tibia and contaminated with \textit{S. aureus}. After fourteen days, the pins were removed and an 8.0 mm modified IM nail was placed. Without treatment, animals developed effusions of the stifle joints (joint of hind limb equivalent to the human knee) on which they were reluctant to bear weight; they were euthanised at a mean of 10.5 days with sepsis of the stifle joint, soft tissues, and entire tibia.

In order to study external fixation-related infections in goats, Voos et al. placed three 4.0 mm half-pins through one cortex of an iliac crest (Voos et al., 1999). Sixteen days after contamination with \textit{S. aureus}, infection was apparent in 100 % of untreated controls. Another group put two 3.0/4.0 mm external fixator pins into the anteromedial surface of the tibia and inoculated the pins with \textit{S. aureus} (DeJong et al., 2001). After 14 days, untreated controls showed clinical signs of infection in 96 % of pins and were culture positive in 100 %.

Haematogenous models
Emslie and Nade describe a model of acute haematogenous osteomyelitis in chickens caused by intravenous injection of \textit{S. aureus} into the wing veins of one-month-old chickens (Emslie et al., 1983). After 24 h, 96 % of animals had evidence of osteomyelitis. This highly reproducible model is unique and closely mimics human disease of acute haematogenous osteomyelitis seen in paediatric populations and permits researchers to study the natural progression of osteomyelitis seen in children. Unlike the other animals presented in this section, chickens also have the advantage of being economical to maintain and the materials required for this model are inexpensive.

Johansen et al. investigate the potential of human and porcine \textit{S. aureus} isolates to induce acute haematogenous osteomyelitis upon inoculation in the femoral artery (Johansen et al., 2012). As supported by computed tomography, microscopic evaluation and peptide nucleic acid fluorescence \textit{in situ} hybridisation, the onset of haematogenous osteomyelitis and biofilm formation was dependent on bacterial strain.

Advantages and disadvantages
A variety of other animals are utilised in the study of osteomyelitis; albeit less frequently than rabbits, rats, and mice. These animals (i.e. dogs, sheep, goats) tend to be larger and are consequently more expensive and difficult to maintain. In general, these animals have larger bones and joints, which enable the use of hardware that better
approximates the prosthesis used in humans. In fact, such animal models may employ commercially available implants, enabling an additional level of reproducibility among research groups. Moreover, these larger animals are able to tolerate multiple procedures and undergo more blood draws. This size results in increased purchase price and maintenance costs, a notable concern when studying chronic conditions such as osteomyelitis. For this reason, there are relatively few osteomyelitis studies performed in these other animals when compared to rabbits, rats and mice. Inoculation doses for these studies is as follows: $10^5 - 10^6$ CFU in canine models, $10^5 - 10^6$ CFU in ovine models, $10^5 - 10^8$ CFU in porcine models, $10^5 - 10^6$ CFU in goat models, and $10^5$ CFU in a guinea pig model.

Non-bone infection models and their impact on clinical practice

One non-bone infection models has had a profound effect on clinical practice in treatment of bony infection. This is the tissue cage model. The tissue cage model is a simple one in which a plastic tissue cage is placed in the subcutaneous tissue of the animal and infected with bacteria. John et al. (John et al., 2009) described the efficacy of daptomycin in implant-associated infection due to methicillin-resistant Staphylococcus aureus: importance of combination with rifampin. Other important findings have also been made with the tissue cage model but this is beyond the scope of this manuscript.

Conclusion

Osteomyelitis caused by Staphylococcus aureus remains a prevalent complication in clinical orthopaedics. A comprehensive review of available animal models to mimic human osteomyelitis has been presented in this paper and their implementation has generated several novel techniques. To trial the effectiveness of novel treatment adjuvants for osteomyelitis, an appropriate understanding of the current models is required to ensure that clinical questions of interest are adequately addressed. Experimental animal studies need to be reproducible and meticulously detailed to enable future groups to build upon established results. Such details include animal species, bacterial strain, amount and method of inoculation, and the methods of evaluation: radiologic, microscopic, macroscopic, and histologic assessment. One need, identified by the authors, is a unified definition and a gold standard for diagnosis of osteomyelitis for animal models. Traditional approaches to quantify bacterial load by means of CFU and PCR assays, which can only be used in cross-sectional studies, have recently been replaced with in vivo bioluminescence (BLI) and radiological outcomes that have their own challenges as indirect measures of bacterial load. Thus, establishment of a quantitative standard is considered to be the next major advance in this field.

While there may be no ideal animal model, increasingly effective modes of inoculation and refined methods of assessing infection continue to aid in the understanding and management of osteomyelitis.

The authors recognise the need for some new clinically relevant models to mimic prosthetic joint infection with two stage exchange. A large animal model for two stage exchange of infected internal fixation hardware would be another useful adjunct in the study of Staphylococcus aureus osteomyelitis. Another model that would be useful would be an animal model for culture negative infection mediated by biofilm. This is a serious clinical problem and is very challenging to study without a validated animal model. Finally, development of genetically modified animals may permit future research on the host immune response to Staphylococcus aureus, which has developed numerous methods of tricking the host immune response. For assessment, the authors anticipate increased utilisation of newer biomarkers including host antibody response, PCR, fluorescent in situ hybridisation (FISH) and Ibis Assay (Ibis, Carlsbad, CA, USA).

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**Editor’s Note:** All questions/comments by the reviewers were answered by text changes. There is hence no Discussion with Reviewers.