Active and Passive Immunization Against Staphylococcus aureus Periprosthetic Osteomyelitis in Rats

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Abstract. Background/Aim: Staphylococcus aureus infection associated with orthopedic implants cannot always be controlled. We used a knee prosthesis model with implant-related osteomyelitis in rats to explore induction of an effective immune response with active and passive immunization. Materials and Methods: Fifty-two Sprague-Dawley rats were divided into active (N = 28) and passive immunization groups (N = 24). A bacterial inoculum of 10^3 S. aureus MN8 was injected into the tibia and the femur marrow before insertion of a non-constrained knee prosthesis in each rat. The active-immunization group received a synthetic oligosaccharide of polysaccharide poly-N-acetylglucosamine (PNAG), 9G1cNH2 and the passive-immunization group received immunization with immunoglobulin from rabbits infected with S. aureus. Results/Conclusion: Active immunization against PNAG significantly reduced the consequences of osteomyelitis infection from PNAG-producing intercellular adhesion (ica+) but not ica− S. aureus. Passive immunization resulted in better clinical assessments in animals challenged with either ica+ or ica− S. aureus, suggesting a lack of specificity in this antiserum.
Materials and Methods

Experimental design. Fifty-two male Sprague-Dawley rats, 7-9 weeks-old (Taconic Europe) with a weight of about 300 g were used for these experiments. Rats were divided into active (n=28 at start, two post-surgical deaths, 26 evaluable cases) and passive immunization groups (n=24 at start, three post-surgical deaths, 21 evaluable cases). Rats were infected with 10^3 CFU of PNAG-producing (ica*) wild-type S. aureus MN8 or an isogenic mutant with deletion of the ica genes (ica::tet), referred to as the ica− strain. The rats received the bacterial inoculations into the marrow of the tibia and femur before insertion of a non-constrained knee prosthesis. Each group (n≥5) had a matched control group (n=4-8). Animals were clinically and radiographically followed for 2 weeks and then sacrificed using an intracardiac injection of 2 ml of 200 mg pentobarbital/ml. Histological and microbiological analysis were then carried out.

Immunization procedure. Actively immunized controls received sodium chloride (NaCl) subcutaneously and passively immunized animals were sedated with a subcutaneous injection of hypnorm/dormicum 0.3 ml/100 g given preoperatively and re-administered every 15 minutes at 0.15 ml/100 g.

Operative procedure. Materials required and anesthesia. All rats were sedated with a subcutaneous injection of hypnorm/dormicum 0.3 ml/100 g given preoperatively and re-administered every 15 minutes at 0.15 ml/100 g.

The skin over the left knee was sterilized twice with alcohol. The fur was shaved with a razor. The knee was opened with a para-patellar medial incision and the tendon with the patella was dislocated laterally. The articulating cartilage was osteotomized with bone scissors from the distal femur and the proximal tibia inclusive of the menisci and cruciate ligaments protecting the collateral ligaments. A 2 mm wide and a 10 mm deep hole was bored into the femur and tibia with a hand drill to fit the joint components. A rat-sized, in-house designed and produced non-constrained knee prosthesis was used. The joint capsule and skin were closed with Ethibond 4-0 and Vicryl 50 after placement of the knee prosthesis, a press-fit model, without bone cement (13).

After the operation, a femoralis block of the operated extremity was placed below the inguinal ligament using 1% lidocaine/0.5% bupivacaine in 1 ml.

Radiographic evaluation. Front and lateral X-ray images were taken on days 0 (operation), 7 and 14. In order to assess development and progression of bone infection, the modified scoring system of An et al. (17) was used. The scoring system uses radiographic evaluation of infected bone grading the involved bone for periosteal reaction, osteolysis, soft-tissue swelling, deformity, sequestrum formation, spontaneous fracture and general impression.

Clinical evaluation. Body weight, temperature and well-being of the animal were monitored by a veterinarian.

Microbiological evaluation. After sacrifice, the prosthesis components were explanted and rolled over non-selective solid media (5% Danish blood agar and chocolate agar plates; State Serum Institute, Copenhagen, Denmark) and then cultured. Isolated bacteria were identified as previously described (18) and the plates scored for growth as follows: growth in the first streak: 1, growth in the first two streaks: 2, and growth in all three streaks: 3.

Bone and soft-tissue histology. After removal of the prosthesis, the remnants of the tibia, femur and synovialis were fixed in 4% buffered paraformaldehyde and decalcified in 10% formic acid for 7 days in EDTA. Samples were then embedded in paraffin, and transverse sections of 5 μm, including the implantation site, were cut on a microtome. The sections were stained using hematoxylin-eosin. Semiquantitative scoring of all specimens was performed blind by a pathologist who was not aware of the treatment groups (SSP9). For histological scoring of severity of inflammation, transverse sections of the tibia and femur (with the prosthesis removed) and tissue from the synovialis were investigated. Each of the three tissues (femur, tibia, and synovialis) was given a score ranging from 0 to 4, depending on the severity of inflammation. 0 meant no signs of inflammation, 1 was slight focal accumulation of inflammatory cells (neutrophils), 2 was moderate but consistent inflammation in the transverse sections or moderate inflammation of the entire circumference around the cavity after prosthesis removal, 3 was the start of formation of an abscess in the cavity, and 4 was abscess formation and destruction of bone material with the synovialis completely infiltrated by neutrophils. The scores from the three separate tissues were added, giving a maximum score of 12.

Biochemical analysis. Alpha-(1)-acid glycoprotein (AGP) (normal range=0-130 ng/ml), an acute-phase protein, was measured on days 0 (preoperative), 7 and 14 (19).
Data analysis. Due to the small number of animals per group, the discrete nature and narrow range of the measurements, it was chosen not to perform statistical analyses.

Results

Microbiological results. In the actively-immunized group, a decrease in bacterial numbers in the \( \text{ica}^{+} \) group immunized against PNAG compared to the control was achieved as seen from the microbiological score shown in Figure 1. In the PNAG-immune rats challenged with the \( \text{ica}^{-} \) strain there was a similar decrease. Among passively immunized rats, the anti-PNAG serum resulted in decreased bacterial levels, compared to controls given normal goat serum, regardless of whether they were infected with \( \text{ica}^{+} \) or \( \text{ica}^{-} \) \( \text{S. aureus} \). For mice with antibody to PNAG, the mean microbiological score was threefold in the \( \text{ica}^{+} \) group compared to the \( \text{ica}^{-} \) group but lower than that in the \( \text{ica}^{+} \) control group, although the same as that for the \( \text{ica}^{-} \) controls.

Biochemistry. All data appeared to show an effect of active immunization against the \( \text{ica}^{+} \) strain. In the passively immunized group, there was an effect in groups challenged with either the \( \text{ica}^{+} \) or \( \text{ica}^{-} \) strain compared to the control group receiving normal goat serum after 1 and 2 weeks. The basis for the apparent specificity of protective effects following active immunization against PNAG for the PNAG-producing strain is clear. The apparent lack of specificity for the effect of the anti-PNAG-immune serum on both PNAG and non-PNAG-expressing \( \text{S. aureus} \) is less clear, it may be that this serum has antibodies to multiple \( \text{S. aureus} \) antigens active against both \( \text{ica}^{+} \) and \( \text{ica}^{-} \) strains.

X-Ray examination. The radiological analysis showed signs of an effect in both actively and passively immunized groups, with a minimum factor of 2 (Figure 1).

Histopathological findings. Infiltration by inflammatory cells was clearly observed around the prosthesis (Figure 2A and D) in all control groups. There was a decrease in inflammation in both immunized groups (Figure 2B, C and E), where mean scores were clearly lower in the \( \text{ica}^{+} \) actively immunized group and in the \( \text{ica}^{-} \) passively immunized group (Figure 1).

Clinical results. There were no apparent differences in mean weight loss between the immunized and the control groups. All prostheses were in situ with loosening in the control groups. No deep wounds around the knees were seen in any animals of any group.

Discussion

This in vivo animal study of both active and passive immunization showed that the strongest effects on the parameters measured were seen in rats actively immunized with a vaccine to induce a protective antibody against PNAG that were then challenged with an \( \text{ica}^{+} \) PNAG-producing strain of \( \text{S. aureus} \). When compared to non-immune control groups, lower AGP levels (reflecting microbiologic burden), x-ray scores and pathology scores were achieved by immunizing against PNAG and challenging with a wild-type, \( \text{ica}^{+} \) strain. Passive immunization had a less pronounced effect on the \( \text{ica}^{+} \) strain, with a more pronounced effect on the PNAG-negative \( \text{S. aureus} \) variant. This is most readily explained by the presence of antibodies to multiple \( \text{S. aureus} \) antigens in the passively administered immunoglobulin obtained from an immunized goat. These would be expected to be effective against \( \text{ica}^{-} \) \( \text{S. aureus} \). The greater effect of the post-infection goat antiserum on the \( \text{ica}^{-} \) strain compared to the \( \text{ica}^{+} \) strain suggests that the presence of the PNAG antigen on the bacterial surface reduces the efficacy of the antibodies against the non-PNAG antigens on the bacterial surface.
Figure 2. A: Extensive inflammatory exudate in the femur cavity from an unimmunized control rat. B: Slightly less inflammation in the femur marrow in a rat passively immunized. C: The cavity of the femur from a rat from the group actively immunized showing almost no inflammation. D: Higher magnification of the inflammatory exudate depicted in (A), showing heavy infiltration of inflammatory cells including polymorphonuclear leucocytes in the femur marrow. E: Higher magnification of area from (C), showing almost total absence of inflammatory reaction at the surface of the cavity where the implant is positioned. Stain: Hematoxylin–eosin.
PNAG, also known as intercellular adhesion polysaccharide (20), is a surface polymer produced by both *S. aureus* and *S. epidermidis*, and many other pathogens (21). PNAG promotes biofilm formation and enhances staphylococcal virulence in mouse infection models (12, 22). In other studies, investigators immunized mice, rabbits and goats with either native PNAG, containing >90% acetate substituents on the amino groups in the glucosamine molecule, or dPNAG, wherein the acetate substitution is <20%, conjugated to diphteria toxoid (20). This study and another (22) indicated that antibodies to dPNAG, but not native PNAG, are opsonic and provide protection against experimental *S. aureus* infection. Additional studies using synthetic oligosaccharides of PNAG and dPNAG conjugated to carrier proteins confirmed the need to use only non-acetylated glucosamines for vaccination to achieve protective immunity (14, 21), most likely via opsonic killing of bacteria. Thus, numerous investigations have consistently found an effect on infection and disease when opsonic antibody to PNAG is present due to either active or passive immunization (23-25).

In our study, we saw significant protection against the PNAG<sup>+</sup> strain for the actively immunized group, with scores for either active or passive immunization (23-25). In developing vaccines against *S. aureus* infection. Additional studies using synthetic oligosaccharides of PNAG and dPNAG conjugated to carrier proteins confirmed the need to use only non-acetylated glucosamines for vaccination to achieve protective immunity (14, 21), most likely via opsonic killing of bacteria. Thus, numerous investigations have consistently found an effect on infection and disease when opsonic antibody to PNAG is present due to either active or passive immunization (23-25).

In our study, we saw significant protection against the PNAG<sup>+</sup> strain for the actively immunized group, with scores for 2-3, representing minimal infection and pathology, for all parameters. With the PNAG<sup>−</sup> strain, we saw a reduction in measured parameters compared to controls but not to the same degree as seen with the PNAG<sup>+</sup> strain. It is not surprising that a vaccine targeting the PNAG antigen is much less effective when the ica<sup>−</sup> gene is missing. This diminished effect is indicative of the specificity of the protection induced by vaccination.

Other preclinical animal studies revealed that mice immunized with a recombinant form of an adhesin, which mediates *S. aureus* binding to fibrinogen and promotes the attachment to biomaterial surfaces (26), reduced arthritis and lethality induced by *S. aureus*. However, protection was strain-dependent (27). Another study described a monoclonal antibody for inhibiting the effects of the accessory gene regulator (agr) of virulence in *S. aureus* (28). The monoclonal antibody reduced the expression of the effector molecule of the agr system, AgrC, and protected against infection. Another group showed that a monoclonal antibody to *S. aureus* glucosaminidase protects against implant-associated infections (25). In our study, we saw a significant effect on the various parameters in the rats passively immunized with antibody to PNAG and challenged with the ica<sup>−</sup> *S. aureus* strain when compared to the control group. The effect on the ica<sup>−</sup> strain is somewhat difficult to evaluate as only four control animals given normal goat serum were available for analysis.

The animal model is suitable for reliably inducing implant osteomyelitis. Active immunization was shown to markedly reduce the consequences of infection from ica<sup>+</sup> *S. aureus*-induced osteomyelitis. Passive immunization with a mixture of antibodies to multiple *S. aureus* antigens gave a notable effect in both the ica<sup>+</sup> and ica<sup>−</sup> groups and it seems that the effects observed might be statistically significant if more animals were included in the study. Choosing appropriate antigens to include in an immunization strategy is a major challenge in creating a staphylococcal vaccine. Immunization based on only a single virulence determinant could have limited efficacy because of the multifactorial nature of the pathogenesis of staphylococcal infection. A number of *S. aureus* vaccines composed of inactive toxins or their subunits have been evaluated pre-clinically (29). The value of adding toxin components to multicomponent prophylactic vaccine formulation is unresolved. Overall, an effective vaccine for *S. aureus*-induced osteomyelitis should include candidate antigens that are surface exposed and expressed by most of the clinical *S. aureus* strains.

In developing vaccines against *S. aureus*, both active and passive immunization approaches should be pursued, as these are not mutually exclusive and may well turn out to be complementary.

**Conflicts of Interest**

The Authors alone are responsible for the content and writing of this article. The Authors report the following conflicts of interest: Niels H. Søe, Nina Vendel Jensen, Asger Lundorff Jensen, Janne Koch, Steen Seier Poulsen, Helle Krogh Johansen: No conflict Gerald B. Pier is an inventor of intellectual properties [human monoclonal antibody to PNAG and PNAG vaccines] that are licensed by Brigham and Women’s Hospital to Alopecx Vaccine, LLC, and Alopecx Pharmaceuticals, LLC, entities in which GBP also holds equity. As an inventor of intellectual properties GBP also has the right to receive a share of licensing-related income (royalties, fees) through Brigham and Women’s Hospital from Alopecx Pharmaceuticals, LLC, and Alopecx Vaccine, LLC. GBP’s interests were reviewed and are managed by the Brigham and Women’s Hospital and Partners Healthcare in accordance with their conflict of interest policies.

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**References**
