ANTIMICROBIAL AGENTS AND CHEMOTHERAPY, May 1989, p. 597–601
0066-4804/89/050597-05$02.00/0

Vol. 33, No. 5

MINIREVIEWS

Infections Associated with Indwelling Devices: Concepts of Pathogenesis; Infections Associated with Intravascular Devices

GORDON M. DICKINSON AND ALAN L. BISNO*

Miami Veterans Administration Medical Center, 1201 N.W. 16 Street, Miami, Florida 33125, and University of Miami School of Medicine, Miami, Florida 33101

INTRODUCTION

One of the major advances in modern medicine has been the development of synthetic materials for temporary or permanent implantation. Much of current-day medical and surgical therapy is predicated upon the use of catheters and tubes. Many patients who once faced certain death or a life of invalidism are now restored to health because of devices that replace diseased or damaged body parts. The precise number of permanent implantations in the United States each year is unknown, but the figure is undoubtedly quite large. It has been estimated, for example, that approximately 59,000 individuals underwent unilateral or bilateral hip joint replacements in the United States in 1980 alone (31). Moreover, the number of intravascular catheters, urinary catheters, endotracheal tubes, and other temporary devices inserted each year probably ranges into the millions. Prosthetic devices are composed of many diverse materials: titanium alloy, cobalt-chromium-molybdenum alloy, and complex polymers (polytetrafluoroethylenes, polythylene, etc.) are but a few of those in use today. The variety of available devices and the frequency with which they are implanted will undoubtedly continue to increase in the coming years.

The major medical complication associated with the use of implanted devices is infection. The impact of such infections is profound, because they often result in tissue destruction, serious dysfunction of the prosthetic device, and systemic dissemination of the pathogen. These infections are difficult to cure with antimicrobial agents and often necessitate the removal of the device. This statement holds true not only for permanently implanted prostheses but also for devices such as intravascular catheters, which are in place for a limited time. The National Nosocomial Infection Surveillance (NNIS) System of the Centers for Disease Control (Fig. 1) found, for example, that 82% of all nosocomial bacteremias occurring in NNIS hospitals between September 1984 and July 1986 were associated with intravascular catheters.

This review summarizes the present knowledge concerning the pathogenesis of foreign body infections and describes briefly the nature and consequences of infections associated with devices situated within the vascular tree. We deal with infections of extravascular prostheses in the following article (9).

* Corresponding author.

INTERACTION OF HOST FACTORS WITH THE PROSTHETIC DEVICE

The defense mechanisms of the host against infection include anatomic barriers, cleansing fluids, cellular and humoral immune systems, and cells that phagocytose and destroy invading organisms. The presence of a foreign body may compromise those defenses by a variety of mechanisms. Many of the devices transect cutaneous and mucosal barriers and thus provide a direct route of invasion for bacteria or fungi. Devices that remain in contact with mucosal surfaces traumatize epithelial tissues, resulting in local inflammation and disturbing clearance mechanisms that normally hold pathogens at bay.

Implanted artificial devices may also directly or indirectly attenuate the local immunity of the host by means that remain poorly understood. These devices are not inert in the environment of living tissues. Metallic prostheses may release metal ions into the immediate environment, while devices fabricated of polymers release esters and residual metal ions from the manufacturing process (17, 26). Some degree of chronic inflammation, the classic foreign body reaction, occurs around most implanted devices. Moreover, Zimmerli and co-workers (46, 47) demonstrated in an animal model that phagocytic and bactericidal capacities of polymorphonuclear cells are decreased in implanted polymethylmethacrylate- or polytetrafluorethylene (Teflon)-perforated cylinders.

The body reacts to foreign implements by coating them with a film containing various proteins, such as fibronectin, laminin, fibrin, collagen, and immunoglobulins. Some of these substances serve as receptors for colonizing organisms. Fibronectin has been found to be a major receptor on respiratory epithelial cells for gram-positive cocci (1, 36). It is a dimeric molecule in tissue fluid but forms an insoluble, multimeric linear molecule on the surfaces of indwelling medical devices. A receptor site for binding *Staphylococcus aureus* has been identified within the 27-kilodalton amino-terminal fragment of fibronectin (32). There may be several fibronectin receptors on *S. aureus*, including sites for soluble as well as solid-phase fibronectin (30, 36). There are conflicting data regarding binding of *Staphylococcus epidermidis* to fibronectin (39, 41), and the binding appears to be less extensive than with *S. aureus*. Collagen (30, 45), laminin (25, 45) vitronectin (S protein) (6, 11), and fibrin (22, 41) may also play a role in bacterial adherence, but their relationship to foreign body infection has not yet been clarified (1, 42, 43).

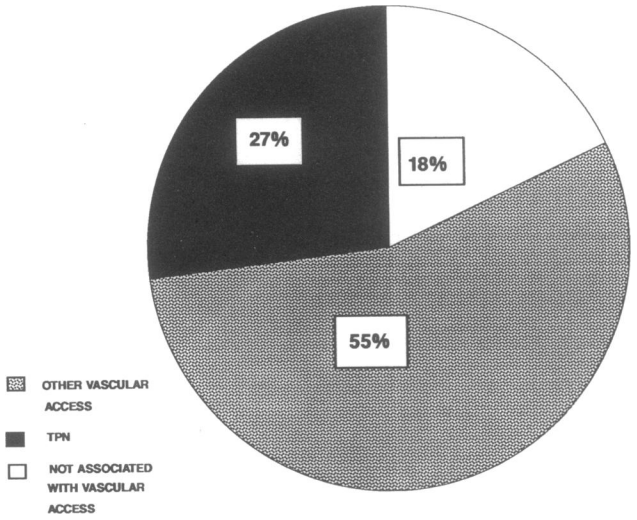

FIG. 1. Association of nosocomial primary bacteremia with total parenteral nutrition (TPN) or other forms of vascular cannulation. Data relate to 2,073 bacteremias. From Centers for Disease Control: National Nosocomial Infection Surveillance System, September 1984 to July 1986 (courtesy of J. Hughes).

MICROBIAL FACTORS PREDISPOSING TO FOREIGN BODY INFECTION: THE ADHERENCE PROCESS

Prosthetic devices provide a surface on which bacteria can multiply at least partially shielded from the humoral and cellular mechanisms that usually clear microorganisms from body tissues. Bacteria that grow on a solid surface (sessile bacteria) behave quite differently from bacteria that grow freely in fluids (planktonic bacteria), a difference particularly notable in terms of host-pathogen interaction (8).

The initial event in foreign body infections is colonization of the device by a microbial pathogen. Bacteria may arrive at the surface of a medical device via a number of routes: inoculation at the time of implantation, transient bacteremias, or because the device is placed within the usual habitat of the organism—the oral cavity, the skin, or the lower urinary tract.

Microbial adherence is a complex process that is not fully understood. Factors involved include basic physiochemical forces governing the interaction of inert particulate bodies, bacterial mechanisms that appear to subserve specific attachment functions, and host-derived substances that coat the foreign body and serve as receptors for bacteria.

Bacterial adherence to a surface is probably initiated by electrostatic attachment when by random chance the bacteria arrive in the proximity of a surface. The DLVO theory of colloid stability (named after Derjaquin and Landau and Verway and Overbeek) (28) describes the electromagnetic forces that attract and repulse colloidal particles. All particles possess certain forces generated by their atomic structures. These electromagnetic forces vary depending upon the particular composition of the particles. Most living cells have negative surface charges and therefore repel one another, but there are forces acting over longer distances that may attract even similarly charged particles or cells. These so-called London-van der Waal's forces of attraction are electromagnetically generated by atomic and molecular vibrations with similar fluctuation frequencies.

For close adherence to occur, the repulsive charges of like-charged surfaces must be overcome. Surface energy, hydrophobic or hydrophilic properties, and specific bacterial mechanisms for attachment provide the necessary attractive forces.

Free energy of bacterial cell surfaces may play a more important role in the attraction or repulsion of the organism to a surface than the London-van der Waal's forces described above (33). The surface forces of various substances in solution lead to direct interaction (bacterium-substrate surface), and there is interaction with the aqueous milieu as well. Hydrophobic cell surfaces prevent or limit cell surface attraction to water molecules (wetting). Hydrophobic particles in aqueous solution, repelled by water molecules, are forced together. Bacterial cell surfaces may not present homogeneous hydrophobic or hydrophilic properties (29), and such heterogeneity may influence the process of attachment, as may the ionic composition of the aqueous milieu (28).

Adhesins are cell surface molecules or structures that attach or bind an organism to specific receptors on substrate surfaces. Lipoteichoic acid on the surfaces of *Streptococcus pyogenes* and *S. aureus* and specific surface proteins (colonization factors) of enterotoxigenic *Escherichia coli* are examples of adhesins that mediate binding to receptors on the surfaces of target cells (3, 5). Fimbriae, filamentous structures that extend for some distance from the cell surface, appear to have a major role in the adherence process for many bacteria. In addition to their ability to adhere to specific biologic surfaces, adhesins may mediate adherence to inanimate surfaces (40).

Bacteria synthesize and excrete a variety of complex polysaccharides which serve to protect them from host defenses and which are known collectively as glycocalyces. When such polysaccharides are closely adherent to the bacterial cell and form its outermost contact with the environment, they constitute the familiar bacterial capsule. In other instances, the exopolysaccharide may diffuse more readily into the extracellular milieu, forming a so-called slime layer (Fig. 2).

Although the function of bacterial slime in the initial stages of adherence remains undefined, slime likely plays a major role in maintaining the organism on a specific surface (7, 34). Bacterial slime coalesces with polysaccharides of other bacteria and with host products to form a thick, adherent, relatively impenetrable biofilm. This biofilm provides a dynamic ecologic niche which traps nutrients and sequesters the organism from phagocytosis, toxins, competing microfloras, and antimicrobial agents (8, 14, 44).

In addition to its more intuitively obvious function as a mechanical barrier to humoral and cellular host defenses, slime has been reported to exert a number of more fundamental biologic effects. These include inhibition of the response to chemotactic stimuli (i.e., zymosan-activated serum and *N*-formyl-methionyl-leucyl-phenylalanine [FMLP]) and acceleration of both FMLP-induced superoxide generation and specific granule release (lactoferrin-stimulated degranulation) (19, 20). Although slime does not appear to affect phagocyte viability or random migration, it has been reported to decrease phagocytosis of *S. epidermidis* (but not *S. aureus*) (20). There is in addition some evidence to suggest that slime impairs the cellular immune responses (15, 16). The effects include decreased natural killer cell function, decreased blastogenic response, and an alteration in the composition of T-lymphocyte cell subpopulations (15, 16).

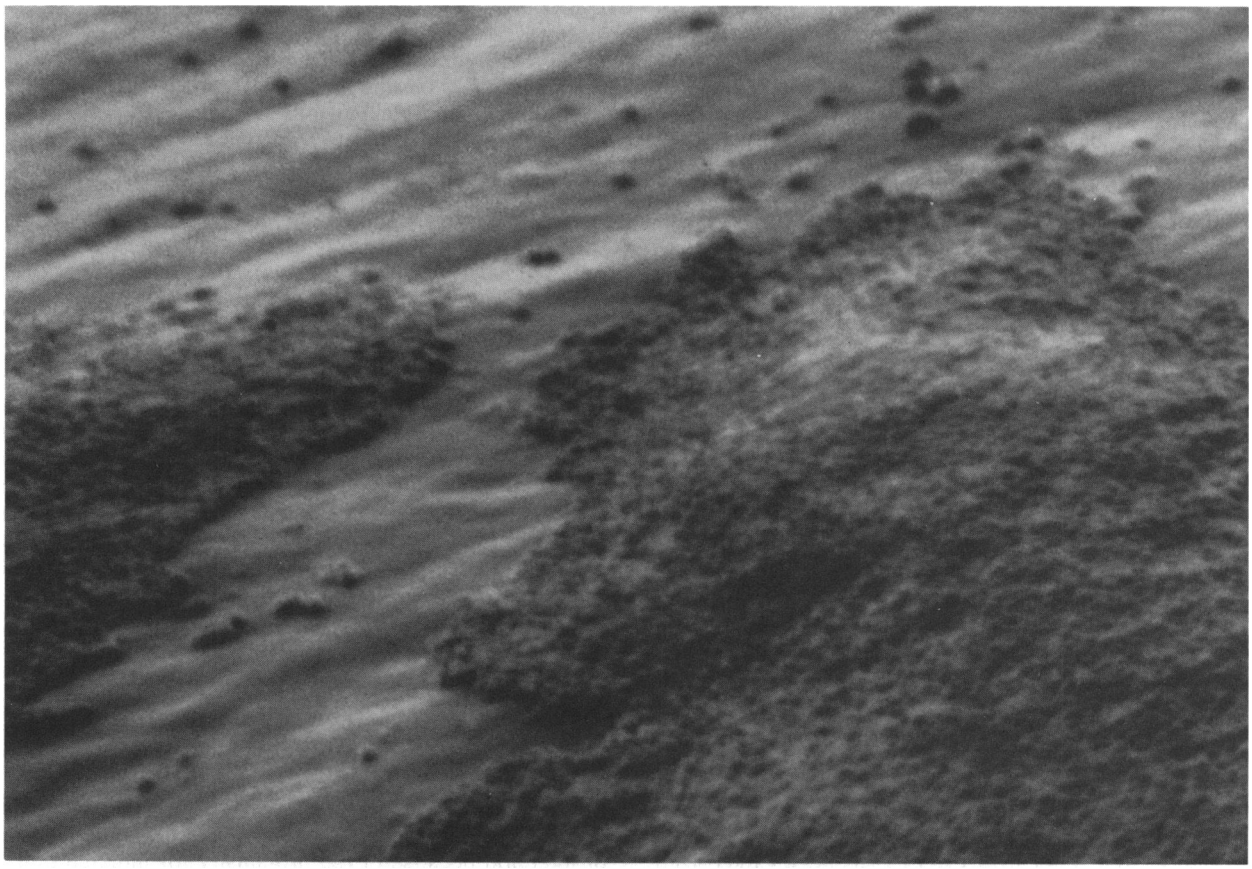

FIG. 2. Scanning electron micrograph of the surface of an intravascular catheter incubated in vitro with microcolonies of a slime-producing strain of *S. epidermidis*. (Reproduced from reference 7 with permission.)

INFECTIONS RELATED TO INTRACARDIAC AND INTRAVASCULAR DEVICES

Catheters. Intravascular devices are used extensively for administration of fluids and medication, as well as for performance of diagnostic studies and therapeutic procedures. They range in complexity from simple 1-in. (2.54-cm) steel needles to aortic balloon pumps. They may remain in place for minutes or for months. The one common denominator for all is that they provide potential pathogens with a direct path from the skin into the bloodstream. Infections related to these devices include cutaneous infections at the insertion site, tunnel infections extending along the course of the catheter within the subcutaneous tissue, septic thrombophlebitis of the catheterized vessel, bacteremia, endocarditis, and metastatic foci of suppuration such as osteomyelitis, septic arthritis, or disseminated abscesses. Microorganisms may contaminate the system at the insertion site with spread along the external surface of the catheter, in the fluids being infused, or at junctions in the external line. The latter is frequently the result of manipulation of the line by medical personnel. There is an association between the route of infection and the type of pathogen involved. *S. epidermidis* and *S. aureus*, the most frequently encountered pathogens in catheter-associated infections, commonly originate from the skin at the insertion site and usually track along the external surface of the catheter. Gram-negative bacteria may also colonize the skin and are probably transferred by contaminated hands of medical personnel during manipulation of the external tubing. Certain gram-negative bacteria which thrive in aqueous environments (e.g., *Enterobacter*, *Flavobacterium*, and *Citrobacter* spp.) may cause nosocomial bacteremia by virtue of their ability to contaminate and persist in infusion fluid. Catheter-related fungal infections are associated with total parenteral nutrition and long-term administration of broad-spectrum antibiotics. Although *Candida* spp. are often the culprits, recent reports have emphasized the occurrence of fungemia caused by *Malassezia furfur* in newborn infants receiving infusion of lipids (2, 24). The JK strain of *Corynebacterium*, usually associated with granulocytopenia, also may cause catheter-related infections in nonimmunosuppressed patients (37).

The diagnosis is easily established when inflammation at the insertion site is followed by systemic symptoms and bacteremia. The seriously ill patient who has multiple potential sources of infection, including multiple catheters and tubes, often presents a diagnostic challenge. Local signs may be absent, and bacteremia may not be detected. Attempts to culture the catheter by aspirating fluid from the line, collecting a specimen at the insertion site, or placing the tip of the catheter in broth are of limited value because of the nonspecificity of positive results. Maki and his co-workers (27) developed a semiquantitative method for culturing the tips of catheters that is relatively simple and an improvement over broth culture methods. This method involves withdrawing the catheter, aseptically removing 5 to 7 cm of the catheter tip, rolling the tip across the surface of a blood agar plate, and counting the colonies of growth. The growth of 15 or more colonies correlates with microbial colonization of the

catheter as opposed to skin contamination at the time of catheter removal. Unfortunately, even this method is not highly predictive of the occurrence of clinically evident catheter-associated infection.

The mainstay of treatment of catheter infections is removal of the device coupled with the administration of an appropriate antibiotic. Temporary venous and arterial catheters are easily changed, but the semipermanent venous Hickman or Broviac catheters require a surgical procedure for replacement. The management of infection in the patient with one of these catheters depends upon the nature of the infection. A study and review of infections in patients with Hickman catheters by Press and co-workers (35) found that exit site infections were successfully treated with antibiotics alone in 55 of 65 cases, while tunnel infections required removal in 20 of 29 cases. Of the 64 bacteremias identified in that study, 38 arose from a source other than the catheter, 3 were associated with tunnel infection, and no source was identified for 23. Press et al. thus concluded that bacteremia per se does not dictate immediate removal of a Hickman or Broviac catheter, since most bloodstream infections do not originate from the catheter and are unaffected by its removal. Septic thrombophlebitis, the most serious local intravenous-catheter-associated infection, always necessitates catheter removal and may require surgical resection of the involved venous segment as well.

Intracardiac and intravascular prostheses. Intracardiac prostheses, routinely used since the 1960s, include both mechanical valves and heterograft valves on metal stints. Synthetic and allograft materials are also used for repair of tissue defects. Intravascular prostheses include grafts composed of a variety of synthetic polymers.

Prosthetic valve endocarditis (PVE) has been categorized according to the time of occurrence following implantation: endocarditis occurring within 60 days of surgery is considered early infection, with the implication that pathogenesis is related to the surgery itself (a nosocomial infection). PVE diagnosed more than 60 days after surgery was previously assumed to arise primarily from intercurrent bacteremias. Calderwood et al. (4), however, noted that *S. epidermidis*, generally held to be a nosocomially acquired pathogen, accounted for the same percentage of infections during the 12 months after surgery as during the first 2 months. They concluded that the break point for distinguishing nosocomial from community-acquired infection should be 12 months rather than 2 months. The high incidence of methicillin-resistant *S. epidermidis* isolated during the first 12 postoperative months supported a nosocomial source for these infections.

The overall rate of infection for prosthetic heart valves has varied from center to center, but collected data suggest an incidence of 0.8% in the early postoperative period, with a rate of 0.2 to 0.5%/year in persons with valves in place for more than 60 days (12). Two studies have found risks of infection during the first 12 months following surgery of 3.1 and 3.0% (4, 18); the cumulative risks were 5.7% at 60 months (4) and 4.1% at 48 months (18). The incidence of infection with heterograft valves is comparable to those with mechanical valves (4, 18). Late infections are probably underrepresented in estimates of frequency because of inadequate follow-up. There is no significant difference in risks of infection with aortic and mitral prosthetic valves (4, 38).

The causative pathogens of early PVE, roughly in order of frequency, are *S. epidermidis*, *S. aureus*, gram-negative aerobic bacilli, and fungi (usually *Candida* or *Aspergillus* species), followed by a vast array of other organisms. Pathogens responsible for late PVE (more than 12 months after surgery) tend to resemble more closely those associated with natural valve endocarditis, although *S. epidermidis* remains a frequent offender.

Successful management of PVE requires aggressive antibiotic treatment, quite often coupled with surgical replacement of the valve. In a review of *S. epidermidis* PVE, Karchmer et al. (21) found that only 39 of 68 episodes (57%) resulted in cures and that surgical intervention was necessary in 72% of the survivors. Such intervention may be required either because of inability to eradicate the infection or because of dysfunction of the prosthetic valve.

The early experience with total artificial hearts indicates that bacterial infection is likely to be a major impediment to their long-term use. Autopsies of two patients who received the Jarvik 7-100 device showed extensive polymicrobial colonization of the artificial heart and adjacent structures (10).

Infection of vascular grafts is usually the result of intraoperative contamination. Seeding of the graft resulting from intercurrent bacteremia is believed to be an infrequent occurrence once the graft is endothelialized. Staphylococci, especially *S. aureus*, predominate as causes of graft infections, but gram-negative bacteria are implicated in a substantial proportion of cases, particularly when the infection occurs in the abdominal area. Morbidity and mortality associated with infection of vascular prostheses are high.

The risk of graft infection is greatest in anastomotic sites in the groin. Infections at these sites are typically manifested by swelling, tenderness, drainage, and pseudoaneurysm formation (13). Conversely, intra-abdominal infection is often subtle in presentation. Gastrointestinal hemorrhage in a patient with an intra-abdominal graft suggests the possibility of infection because of the propensity for infected grafts to erode into the bowel.

The occurrence of an infection mandates total or segmental removal of the graft, as well as administration of appropriate antimicrobial agents (23). To avoid recurrence, the replacement graft should be placed away from the bed of the original prosthesis.

ACKNOWLEDGMENT

We thank Linda Ortiz for secretarial assistance.

LITERATURE CITED

1. **Akiyama, S. K., K. M. Yamada, and M. Hayashi.** 1981. The structure of fibronectin and its role in cellular adhesion. J. Supramol. Struct. Cell. Biochem. **16**:345–348.
2. **Aschner, J. L., A. Punsalang, Jr., W. M. Maniscalco, and M. A. Menegus.** 1987. Pericutaneous central venous catheter colonization with *Malassezia furfur*: incidence and clinical significance. Pediatrics **80**:535–539.
3. **Beachey, E. H.** 1981. Bacterial adherence: adhesion receptor interaction mediating the attachment of bacteria to mucosal surfaces. J. Infect. Dis. **143**:324–345.
4. **Calderwood, S. B., L. A. Swinski, C. M. Waternaux, A. W. Karchmer, and M. J. Buckley.** 1985. Risk factors for the development of prosthetic valve endocarditis. Circulation **72**:31–37.
5. **Carruthers, M. M., and W. J. Kabat.** 1983. Mediation of staphylococcal adherence to mucosal cells by lipoteichoic acid. Infect. Immun. **40**:444–446.
6. **Chhatwal, G. S., K. T. Preissner, G. Müller-Berghaus, and H. Blobel.** 1987. Specific binding of the human S protein (vitronectin) to streptococci, *Staphylococcus aureus*, and *Escherichia coli*. Infect. Immun. **55**:1878–1883.
7. **Christensen, G. D., W. A. Simpson, A. L. Bisno, and E. H. Beachey.** 1982. Adherence of slime-producing strains of *Staphylococcus epidermidis* to smooth surfaces. Infect. Immun. **37**: 318–326.

8. **Costeron, J. W., and L. Watkins.** 1987. Adherence of bacteria to foreign bodies: the role of the biofilm, p. 17–30. *In* R. K. Root, D. D. Trunkey, and M. A. Sande (ed.), New surgical and medical approaches in infectious diseases. Churchill Livingstone Inc., New York.
9. **Dickinson, G. M., and A. L. Bisno.** 1989. Infections associated with indwelling devices: infections related to extravascular devices. Antimicrob. Agents Chemother. **33**:602–607.
10. **Dobbins, J. J., S. Johnson, C. M. Kunin, and W. C. DeVries.** 1988. Postmortem microbiological findings of two total artificial heart recipients. J. Am. Med. Assoc. **259**:865–869.
11. **Fuquay, J. I., D. T. Loo, and D. W. Barnes.** 1986. Binding of *Staphylococcus aureus* by human serum spreading factor in an in vitro assay. Infect. Immun. **52**:714–717.
12. **Gann, J. W., Jr., and C. G. Cobb.** 1985. Infections of prosthetic valves and intravascular devices, p. 530–539. *In* G. L. Mandell, R. G. Douglas, and J. E. Bennett (ed.), Principles and practice of infectious diseases, 2nd ed. John Wiley & Sons, Inc., New York.
13. **Goldstone, J., and W. S. Moore.** 1974. Infection in vascular prosthesis. Am. J. Surg. **128**:225–233.
14. **Govan, J. R. W., and A. M. Fyfe.** 1978. Mucoid *Pseudomonas aeruginosa* and cystic fibrosis: resistance of the mucoid form to carbenicillin, flucloxacillin, tobramycin and the isolation of mucoid variety in vitro. J. Antimicrob. Chemother. **4**:233–240.
15. **Gray, E. D., G. Peters, M. Verstegen, and W. E. Regelmann.** 1984. Effect of extracellular slime substance from *Staphylococcus epidermidis* on the human cellular immune response. Lancet **i**:365–367.
16. **Gray, E. D., W. E. Regelmann, and G. Peters.** 1987. Staphylococcal slime and host defenses: effect on lymphocytes and immune function, p. 45–54. *In* G. Pulverer, P. G. Quie, and G. Peters (ed.), Pathogenicity and clinical significance of coagulase-negative staphylococci. Gustav Fischer Verlag, Stuttgart, Federal Republic of Germany.
17. **Gristina, A. G.** 1987. Biomaterial-centered infection: microbial adhesion versus tissue integration. Science **237**:1588–1595.
18. **Invert, T. S. A., W. E. Dismukes, C. G. Cobb, E. H. Blackstone, J. W. Kirklin, and L. A. L. Bergdahl.** 1984. Prosthetic valve endocarditis. Circulation **69**:223–232.
19. **Johnson, G. M., D. A. Lee, W. E. Regelmann, E. D. Gray, G. Peters, and P. G. Quie.** 1986. Interference with granulocyte function by *Staphylococcus epidermidis* slime. Infect. Immun. **54**:13–20.
20. **Johnson, G. M., W. E. Regelmann, E. D. Gray, G. Peters, and P. G. Quie.** 1987. Staphylococcal slime and host defenses: effect on polymorphonuclear granulocytes, p. 33–43. *In* G. Pulverer, P. G. Quie, and G. Peters (ed.), Pathogenicity and clinical significance of coagulase-negative staphylococci. Gustav Fischer Verlag, Stuttgart, Federal Republic of Germany.
21. **Karchmer, A. W., G. L. Archer, and W. E. Dismukes.** 1983. *Staphylococcus epidermidis* causing prosthetic valve endocarditis: microbiologic and clinical observations as guides to therapy. Ann. Intern. Med. **98**:447–454.
22. **Kuusela, P., T. Vartio, M. Vuento, and E. B. Myhre.** 1985. Attachment of staphylococci and streptococci on fibronectin, fibronectin fragments, and fibrinogen bound to a solid phase. Infect. Immun. **50**:77–81.
23. **Liekweg, W. G., Jr., and L. J. Greenfield.** 1977. Vascular prosthetic infections: collected experience and results of treatment. Surgery **81**:335–342.
24. **Long, J. G., and H. L. Keyserling.** 1985. Catheter-related infection in infants due to an unusual lipophilic yeast *Malassezia furfur*. Pediatrics **76**:896–900.
25. **Lopes, J. D., M. dos Reis, and R. R. Brentani.** 1985. Presence of laminin receptors in *Staphylococcus aureus*. Science **229**:275–277.
26. **Ludwicka, A., R. Locci, B. Jansen, G. Peters, and G. Pulverer.** 1983. Microbial colonization of prosthetic devices v. attachment of coagulase-negative staphylococci and "slime"-production on chemically pure synthetic polymers. Zentralbl. Bakteriol. Hyg. Abt. 1 Orig. Reihe B **177**:527–532.
27. **Maki, D. G., C. E. Weise, and H. W. Safarin.** 1973. A semiquantitative culture method for identifying intravenous-catheter-related infection. N. Engl. J. Med. **196**:1305–1309.
28. **Marshall, K. C.** 1985. Mechanisms of bacterial adhesion at solid water interfaces, p. 133–161. *In* D. C. Savage and M. Fletcher (ed.), Bacterial adhesion: mechanisms and physiological significance. Plenum Publishing Corp., New York.
29. **Marshall, K. C., and R. H. Cruickshank.** 1973. Cell surface hydrophobicity and the orientation of certain bacteria at interfaces. Arch. Microbiol. **91**:29–40.
30. **Maxe, I., C. Rydén, T. Wadström, and K. Rubin.** 1986. Specific attachment of *Staphylococcus aureus* to immobilized fibronectin. Infect. Immun. **54**:695–704.
31. **Melton, L. J., III, R. N. Stauffer, E. Y. S. Chao, and D. M. Ilstrup.** 1982. Rates of total hip arthroplasty: a population-based study. N. Engl. J. Med. **307**:1242–1245.
32. **Mosher, D. F., and R. A. Proctor.** 1980. Binding and factor XIIIa-mediated cross-linking of a 27 kilodalton fragment of fibronectin to *Staphylococcus aureus*. Science **209**:927–929.
33. **Pashley, R. M., P. M. McGuiggan, B. W. Ninham, and D. F. Evans.** 1985. Attractive forces between uncharged hydrophobic surfaces: direct measurements in aqueous solution. Science **229**:1088–1089.
34. **Peters, G., R. Locci, and G. Pulverer.** 1982. Adherence and growth of coagulase negative staphylococci on surfaces of intravenous catheters. J. Infect. Dis. **146**:479–482.
35. **Press, O. W., P. G. Ramsey, E. B. Larson, A. Fefer, and R. O. Hickman.** 1984. Hickman catheter infections in patients with malignancies. Medicine (Baltimore) **63**:189–200.
36. **Proctor, R. A.** 1987. The staphylococcal fibronectin receptor: evidence for its importance in invasive infections. Rev. Infect. Dis. **9**(Suppl.):335–340.
37. **Riebel, W., N. Frantz, D. Adelstein, and P. J. Spagnuolo.** 1986. *Corynebacterium* JK: a cause of nosocomial device-related infection. Rev. Infect. Dis. **8**:42–49.
38. **Rossiter, S. J., E. B. Stinson, P. E. Oyer, D. C. Miller, J. N. Schapira, R. P. Martin, and N. E. Shumway.** 1978. Prosthetic valve endocarditis: comparison of heterograft tissue valves and mechanical valves. J. Thorac. Cardiovasc. Surg. **76**:795–803.
39. **Russell, P. B., J. Kline, M. C. Yoder, and R. A. Polin.** 1987. Staphylococcal adherence to polyvinyl chloride and heparin-bonded polyurethane catheters is species dependent and enhanced by fibronectin. J. Clin. Microbiol. **25**:1083–1087.
40. **Tojo, M., N. Yamashita, D. Goldmann, and G. Pier.** 1988. Isolation and characterization of a capsular polysaccharide adhesin from *Staphylococcus epidermidis*. J. Infect. Dis. **157**: 713–722.
41. **Toy, P. T. C. Y., L.-W. Lai, T. A. Drake, and M. A. Sande.** 1985. Effect of fibronectin on adherence of *Staphylococcus aureus* to fibrin thrombi in vitro. Infect. Immun. **48**:83–86.
42. **Vaudaux, P., D. Lew, and F. A. Waldvogel.** 1987. Host-dependent pathogenic factors in foreign body infection: a comparison between *Staphylococcus epidermidis* and *S. aureus*. Zentralbl. Bakteriol. Suppl. **16**:183–193.
43. **Vaudaux, P., R. Suzuki, F. A. Waldvogel, J. J. Morgenthaler, and U. E. Nydegger.** 1984. Foreign body infection: role of fibronectin as a ligand for the adherence of *Staphylococcus aureus*. J. Infect. Dis. **150**:546–553.
44. **Vaudaux, P. E., G. Zulian, E. Huggler, and F. A. Waldvogel.** 1985. Attachment of *Staphylococcus aureus* to polymethylmethacrylate increases its resistance to phagocytosis in foreign body infection. Infect. Immun. **50**:472–477.
45. **Vercellotti, G. M., J. D. McCarthy, P. Lindholm, P. K. Peterson, H. S. Jacob, and L. T. Furcht.** 1985. Extracellular matrix proteins (fibronectin, laminin and type IV collagen) bind and aggregate bacteria. Am. J. Pathol. **120**:13–21.
46. **Zimmerli, W., P. D. Lew, and F. A. Waldvogel.** 1984. Pathogenesis of foreign body infection: evidence for a local granulocyte defect. J. Clin. Invest. **73**:1191–1200.
47. **Zimmerli, W., F. A. Waldvogel, P. Vaudaux, and U. E. Nydegger.** 1982. Pathogenesis of foreign body infection: description and characteristics of an animal model. J. Infect. Dis. **146**: 487–497.