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An indwelling urinary catheter for the 21st century

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The indwelling urinary catheter is the most common cause of infections in hospitals and other healthcare facilities [1]. As long ago as 1958, Paul Beeson [2] warned '…the decision to use this instrument should be made with the knowledge that it involves the risk of producing a serious disease which is often difficult to treat'. Since then, scientific studies have progressed revealing a greater understanding of the bladder's defence mechanisms against infection and how they are undermined by the Foley catheter [3–5]. In addition, the complications caused by the development of bacterial biofilms on catheters have been recognised and the ways in which these bacterial communities develop on catheters have become clear [5,6]. It is now obvious that fundamental problems with the basic design of the catheter, which has changed little since it was introduced into urological practice by Dr Fredricc Foley in 1937 [7], induce susceptibility to infection. These issues need to be addressed urgently if we are to produce a device suitable for use in the 21st century.

What's known on the subject? and What does the study add?
A vast literature has been published on the prevalence, morbidity and microbiology of catheter-associated urinary tract infections. Research and development in recent years has focused on producing antibacterial coatings for the indwelling Foley catheter with insufficient attention to its design.

This article provides a critical examination of the design of the indwelling Foley catheter. Design specifications are outlined for a urine collection device that should reduce the vulnerability of catheterised urinary tract to infection.

KEYWORDS

indwelling urinary catheter, catheter-associated infections, catheter

CATHETER-ASSOCIATED INFECTIONS

While catheter-associated bacteriuria is usually asymptomatic, patients are at risk of a range of serious complications. These include pyelonephritis, bacteraemia, septicaemia, catheter encrustation and obstruction, stone formation, urethral strictures, urethritis, periurethral abscess, prostatitis and the acquisition of *Candida* and multidrug-resistant bacteria [5,8]. All this morbidity results in increased costs for prolonged hospital stays, antimicrobial agents and management of sepsis. A prospective study in nursing homes for example, showed significantly higher morbidity and mortality rates in patients undergoing long-term catheterisation than in matched controls that were not catheterised. Over a study period of 12 months catheterised patients were significantly more likely to have received antibiotics and to have spent more time in hospital. They were also three-times more likely to have died [9].

Many attempts have been made to prevent catheter-associated infections by blocking the routes of infection with antibacterial agents [5]. None of these have proved to be effective and the lesson has been that the more comprehensive the strategy to erect antibacterial barriers, the less successful they have been in preventing infection. For example, a policy was devised that combined preparing the periurethral skin with chlorhexidine, instilling a gel containing an antiseptic into the urethra to lubricate the passage of the catheter into the bladder, daily cleaning of the catheter-meatal junction with chlorhexidine solution, applying cream containing the antiseptic to the periurethral skin and instilling chlorhexidine into the urine drainage bags every time they were emptied. The result was that despite the attempt to block all the conceivable routes of infection, an extensive outbreak occurred with a chlorhexidine resistant multidrug-resistant strain of *Pr. mirabilis* involving >90 patients. The problem was only resolved when the policy was abandoned [10].

In view of all the difficulties involved in preventing these infections using antibacterial agents in the daily care of catheterised patients, attempts have been made to prevent bacterial colonization and infection by incorporating antibacterial agents into the catheters themselves. Of these only the nitrofurazone silicone catheter marketed by Rochester Medical and Bard's hydrogel/silver-coated latex I.C. catheter have come into clinical use. The evidence that these catheters are effective in preventing infection is not impressive. At best they may delay the onset of asymptomatic bacteriuria but only for a few days. An expert panel of the Infectious Diseases Society of America concluded that the data from clinical studies are insufficient

to recommend the use of these catheters and that the most effective ways to reduce the incidence of catheter-associated UTI are to (i) restrict the use of catheters and (ii) remove indwelling catheters as soon as they are no longer needed [1]. Unfortunately, these recommendations fail to meet the needs of the many older and disabled people who have to rely permanently on an indwelling catheter and for whom no acceptable alternative system is available.

CATHETER COLONIZATION BY BACTERIAL BIOFILMS

The Foley catheter provides particularly attractive sites for bacterial colonization. As contaminated urine flows through the catheter lumen, cells attach to the surface and bathed in a gentle flow of warm nutrients they multiply rapidly, secrete a protective gel around themselves and develop into bacterial biofilms [11]. This is not a major problem for patients who develop bacteriuria in the course of short-term catheterisation, as in these situations the biofilms that form are generally sparse and the catheter will be removed within a few days [12]. However, in long-term patients, extensive biofilms containing $>5 \times 10^9$ viable cells/cm can be found on catheters and can be responsible for the persistence of the infections [13]. Some of these biofilms are mucoid in nature, others generate conditions that result in crystal deposition [6]. The crystalline biofilms are the most troublesome. They can form encrustations on the outer surfaces of the catheter around the balloon and tip causing trauma to the bladder and urethral epithelia. On deflation of the retention balloon, crystalline debris from the biofilm can be shed into the bladder and initiate stone formation. However, the main complications induced by these biofilms result from the build-up of crystalline material in the catheter lumen that then blocks the flow of urine. Leakage of urine along the outside of the catheter can cause incontinence. Alternatively blockage can lead to retention of urine in the bladder. If blockage is not detected and the catheter changed, episodes of pyelonephritis and septicaemia can be triggered [5]. About half of the patients who undergo long-term indwelling catheterisation will eventually experience the complications induced by crystalline bacterial biofilms [14]. An insight into the scale of the problem and the demands made on the health services in caring for these patients was given by a prospective study of 467 catheterised patients in community care in the Bristol area. Over a 6-month period, 506 emergency referrals were recorded for these patients, mostly to deal with catheter blockage [15].

The crystalline material in the biofilms is mainly composed of a mixture of struvite (magnesium ammonium phosphate) and apatite (microcrystalline aggregates of a hydroxylated calcium phosphate) [16,17]. Urease producing bacilli, predominantly *Proteus mirabilis* and less frequently *Providencia* or *Morganella,* are also found in these biofilms [18,19]. The urease is the driving force of the encrustation process, the ammonia it generates, raises the pH of the urine and this induces the crystallization of the magnesium and calcium salts in the urine and the biofilm [20].

Proteus mirabilis has been called 'the master of both adhesion and motility' [21]. It can initiate biofilm formation on catheters by several mechanisms on all types of catheters including those with silver or nitrofurazone coatings. It is a 'sticky' bacillus with numerous hair-like surface projections that facilitate attachment to surfaces [22]. The irregular nature of catheter surfaces, especially latex catheters has been revealed by scanning electron microscopy. The methods used to produce the drainage eyelets tear through the latex and generate surfaces that appear in electron micrographs like rocky landscapes of craters and crevices. The uneven nature of the luminal surfaces is often exacerbated by the common presence of embedded diatom skeletons. These are particularly attractive sites for bacterial attachment and come from the diatomaceous earth used to prevent the latex sticking to the metal formers on which catheters are manufactured. In comparison silicone catheters have smoother surfaces but irregularities can commonly be found around the eye-holes and where the extrusion production techniques have formed striations on the luminal surfaces. All these surface irregularities facilitate bacterial colonization and crystal deposition [23]. An additional problem that adds to their vulnerability to blockage is that central channels of catheters are so narrow. For example while 14 F catheters have external diameters of 4.7 mm, the internal diameters are 3 mm for silicone catheters and only 1.8 mm for latex catheters.

When replacement catheters are inserted into bladders containing alkaline urine that is infected with a urease producer like *P. mirabilis*, a foundation layer composed of microcrystals of apatite forms rapidly on their surfaces. This then becomes colonized by bacteria. The foundation layer forms on silver and nitrofurazone catheters and protects colonizing cells from the antimicrobial activity on the catheter surfaces [24,25]. In addition, when *P. mirabilis* produces alkaline conditions, aggregates of cells and crystals form in the urine and these gravitate to and initiate biofilms formation even on surfaces coated with polymers that are resistant to bacterial adhesion [26]. Therefore, to prevent encrustation it is important to stop the urinary pH rising above the pH at which crystals form. If antimicrobials are to be incorporated into catheters to achieve this they must diffuse out from the catheter surface and reduce the viability of the planktonic urinary urease-producing bacteria.

THE NEED FOR INNOVATIVE CATHETER DESIGNS

The fundamental reason why catheterised patients are so vulnerable to infection is that the catheter violates the integrity of the defence systems that normally protect the bladder against infection. The regular filling and emptying of the bladder is an important mechanical defence against infection. It ensures that any microbes managing to contaminate the urethra or bladder are washed out. The indwelling Foley catheter undermines this defence system. On continuous drainage into a urine collection bag, the bladder does not fill, the retention balloon ensures that a sump of residual urine forms below the drainage eyes at the catheter tip. Urine trickles through the catheter into the drainage bag rather than flushing the urethra. This facilitates the migration of bacteria through the urethra and on arrival in the bladder the microbes are provided with a continually replenished reservoir of an excellent growth medium. Rapid bacterial multiplication results in urinary populations that commonly reach 10^7 colony-forming units/

mL [27,28]. In addition, the tip of the catheter and its balloon can erode the mucosal lining of the bladder. The lateral pressure exerted by the catheter attenuates the blood supply to the urethral surface and can block the lubricating periurethral glands. The catheter also disturbs the hydrophilic mucin layer that is secreted by the urothelial cells and has such important functions in protecting the bladder and urethral epithelia from bacterial adhesion and infection [3,29]. The stressed mucosal surfaces thus provide attractive sites for bacterial colonization and the initiation of infection. The loss of these fundamental defence systems increases vulnerability to infection. Attempts to prevent infections by developing antimicrobial catheters or surface coatings for catheters that inhibit bacterial biofilm development, do nothing to alleviate these problems.

CONCLUSIONS

In an era that has witnessed outstanding technological advances in medical practice it is difficult to understand why we are still unable to perform the relatively simple task of draining urine from the bladder without producing infection and a range of associated complications. The morbidity and mortality caused by the current devices and the costs to health services in managing the complications are surely no longer acceptable in the 21st century. The management of bladder dysfunction is a fundamental aspect of care for older and disabled people and an effective urine collection system should be highlighted as of paramount importance in an ageing community. There is plenty of scope to improve the current Foley catheters with their thick walls, narrow internal diameters, irregular surfaces and roughly engineered eyelets. However, the real challenge to the medical device industry is to produce an instrument that does not undermine the natural defences against infection. The specifications required for such an instrument include a catheter-retention system, which allows the filling and complete emptying of the bladder so that a sump of residual urine does not persist. In addition, the device should not irritate, inflame or cause physical damage to the urethral and bladder epithelia. Some such innovations have been described, e.g. a thin walled collapsible catheter that did not violate the integrity of the urethra was produced and tested successfully [30]. Unfortunately patent disputes, development costs and marketing considerations have confounded the development of these ideas. Catheter manufacturers seem to have been reluctant to make the necessary investments in research and development. We now need doctors, nurses, care providers and patients to persuade medical device companies to take up the challenge. It is time for government and private foundations to alter their emphasis on funding research programmes that focus on how to treat urosepsis, to how to prevent it. Progress will surely be possible if clinicians, engineers and scientists from industry and academic institutions, armed with the insights gained from recent research and with the help of government research councils, apply their talents to the problem. Catheters in the 21st century may well be more expensive but the prize is improving the care of millions of disabled and elderly patients and reducing the enormous costs of managing the complications associated with the indwelling Foley catheter.

CONFLICT OF INTEREST

None declared.

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