Airborne Multidrug-Resistant Bacteria Isolated from a Concentrated Swine Feeding Operation

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The development and persistence of multidrug-resistant bacteria pose increasing challenges to public health (Institute of Medicine 1998). Although the use of antibiotics in human medicine has influenced the emergence of antibiotic-resistant bacteria, the use of antibiotics in animal agriculture has markedly contributed to this critical problem as well (Cohen and Tauxe 1986; Gorbach 2001; Institute of Medicine 1998; National Research Council 1999; van den Boogard and Stobberingh 1999). In animal agriculture, antibiotics are administered for therapeutic purposes to treat infections, prophylactic purposes in advance of observed symptoms, and nontherapeutic purposes to promote growth and improve feed efficiency (Wegener 2003). In general, antibiotics are administered at higher concentrations for therapeutic and prophylactic use and lower concentrations for nontherapeutic use (Wegener 2003). It has been estimated that the nontherapeutic use of antimicrobials in livestock production comprises 60–80% of total antimicrobial production in the United States (Mellon et al. 2001). The swine industry alone uses an estimated 10.3 million pounds of antibiotics annually for nontherapeutic purposes. Among the antibiotics used are ampicillin, bacitracin, erythromycin, lincomycin, virginiamycin, and tetracycline (Food and Drug Administration 2004), some of which are important in human clinical medicine. The use of antibiotics for nontherapeutic purposes such as growth promotion has been shown to select for resistance to high concentrations of antibiotics in both pathogenic and commensal bacteria in swine (Aarestrup et al. 2000a, 2000b; Bager et al. 1997; Jensen et al. 2002; Wegener et al. 1999). For this reason, attention has been given to retail pork products as a source of human exposure to antibiotic-resistant bacteria (Donabedian et al. 2003; Gamarroto et al. 2001; Hayes et al. 2003; Sorensen et al. 2001; White et al. 2001). Yet the ingestion of pork products is not the only pathway of exposure for the transfer of resistant organisms from swine to humans. Environmental pathways of exposure may be equally important.

Along with the pork products, more than 110 million tons of swine waste—containing antibiotic-resistant bacteria—is produced annually in swine concentrated animal feeding operations (CAFOs) in the United States each year (Environmental Defense 1997). The practice of storing this waste in pits and open-air lagoons and subsequently applying the waste to land can lead to the contamination of soils and nearby surface and groundwaters. Several studies have reported the appearance of antibiotic residues and antibiotic-resistant bacteria in surface and groundwaters proximal to swine CAFOs (Campagnolo et al. 2002; Chee-Sanford et al. 2001). Campagnolo et al. (2002) suggested that swine waste may be a source of antimicrobial drugs in surface and groundwaters near swine facilities, and Chee-Sanford et al. (2001) found that groundwater can be affected by swine waste and serve as a potential source of exposure to antibiotic-resistance genes.

However, few studies have examined the air within swine CAFOs as an additional source of environmental exposure to antibiotic-resistant bacterial pathogens. It has been well documented that the air within swine CAFOs is highly contaminated with bacteria, yeasts, and molds. Mean total bacterial concentrations can range from 10^3 to 10^7 colony forming units (CFU)/m^3 (Clark et al. 1983; Cormier et al. 1990; Crook et al. 1991; Predicala et al. 2002). Specific bacteria detected in the air of swine CAFOs include the following potential human pathogens: Enterococcus, Staphylococcus, Pseudomonas, Bacillus, Listeria, and Escherichia coli (Cormier et al. 1990; Crook et al. 1991; Predicala et al. 2002). Yet, to date, these airborne pathogens have not been assessed for resistance to antibiotics that are commonly used in both swine production and clinical medicine. Hamscher et al. (2003) assessed the presence of antibiotics in dust samples collected at a swine production facility over two decades. Several different antibiotics, including tetracycline, tylosin (an analog to erythromycin), and chloramphenicol, could be detected in 90% of the dust samples tested (Hamscher et al. 2003). In abstract form within conference proceedings, Zahn et al. (2001) reported on the presence of tylosin and tylosin-resistant bacteria in the air released from three mechanically ventilated swine CAFOs. Their air sampling, airborne bacteria, antibiotic resistance, CAFO, concentrated swine feeding operation, multidrug-resistant bacteria. Environ Health Perspect 113:137–142 (2005). doi:10.1289/ehp.7473 available via http://dx.doi.org/ (Online 22 November 2004)
study indicated that tylosin-resistant bacteria, primarily *Corynebacterium*, accounted for 80% of total culturable bacteria detected. These results provided the first evidence of airborne antibiotic-resistant bacteria in swine CAFOs.

The goal of this study was to test air samples collected within a swine CAFO for the presence of antibiotic-resistant enterococci, gram-positive, catalase-negative cocci that are not only members of the normal intestinal flora of humans and animals but also capable of causing a variety of human and animal infections [National Nosocomial Infections Surveillance (NNIS) 2001]. Resistance to erythromycin, clindamycin, tetracycline, and virginiamycin has been described previously (Murray et al. 2003). Resistance to erythromycin, clindamycin, virginiamycin (streptogramin A and B combination), tetracycline, and vancomycin was tested. Erythromycin, clindamycin, tetracycline, and vancomycin were obtained from Sigma (St. Louis, MO). Virginiamycin was obtained from Research Products International Corp. (Mt. Prospect, IL). Concentrations of antibiotics tested ranged from 0.5 µg/mL to 256 µg/mL for erythromycin and tetracycline, 0.03 µg/mL to 128 µg/mL for clindamycin, 0.03 µg/mL to 32 µg/mL for virginiamycin, and 0.03 µg/mL to 64 µg/mL for vancomycin.

In preparation for the agar dilution tests, the air sample isolates, as well as the MIC reference strain *E. faecalis* 29212, were streaked from –80°C archived stocks onto tryptic soy agar No. 2 with 5% debrinibrated sheep blood (QuadFive, Ryegate, MT) and incubated for 24 hr at 37°C under aerobic conditions. After 24 hr, each isolate was suspended in 3 mL Mueller-Hinton broth with a sterile cotton swab and adjusted to a 0.5 McFarland standard using a Vitek colorimeter (Hach, Loveland, CO). Two hundred microliters of each suspension was transferred to a well within a Cathra replicator plate (Oxoid Inc., Ogdensburg, NY) and replicated with 1-mm pins in accordance with NCCLS guidelines onto Mueller-Hinton agar plates that were previously prepared with the appropriate concentrations of antibiotics (NCCLS 2002). Plates were incubated for 24 hr at 37°C under aerobic conditions. After 24 hr, the plates were read manually and MICs were determined. Specifically, the MIC was recorded as the minimum antibiotic concentration that completely inhibited bacterial growth. According to the MIC, isolates were categorized as susceptible, intermediate, or resistant to each antibiotic using the following MIC breakpoints established by the NCCLS for *Enterococcus* erythromycin, susceptible ≤ 0.5 µg/mL, intermediate 1–4 µg/mL, and identified as *Micrococcus luteus*. Each *Staphylococcus* isolate was inoculated onto 0.5 mL rabbit plasma (Becton Dickinson) to test for the production of coagulase. Catalase-negative isolates were differentiated further by pyrrolidonyl-arylamidase activity using Remel’s PYR kit (Remel, Lenexa, KS). The following biochemical tests were performed on the isolates displaying pyrrolidonyl-arylamidase activity: manitol, arabinose, sorbitol, raffinose, lactose, and sucrose carbohydrate fermentation tests; arginine deamination; acidification of methyl-α-D-glucopyranoside; pyruvate utilization; and isolate pigmentation.

Antimicrobial susceptibility testing. Antimicrobial susceptibility testing was conducted using the minimal inhibitory concentration (MIC) agar dilution method [National Committee for Clinical Laboratory Standards (NCCLS) 2002]. *E. faecalis* 29212 was used as the quality control reference strain. Susceptibility to erythromycin, clindamycin, virginiamycin (streptogramin A and B combination), tetracycline, and vancomycin was determined. Erythromycin, clindamycin, tetracycline, and vancomycin were obtained from Sigma (St. Louis, MO). Virginiamycin was obtained from Research Products International Corp. (Mt. Prospect, IL). Concentrations of antibiotics tested ranged from 0.5 µg/mL to 256 µg/mL for erythromycin and tetracycline, 0.03 µg/mL to 128 µg/mL for clindamycin, 0.03 µg/mL to 32 µg/mL for virginiamycin, and 0.03 µg/mL to 64 µg/mL for vancomycin.

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resistant ≥ 8 µg/mL; clindamycin, susceptible ≤ 0.5 µg/mL, intermediate 1–2 µg/mL, and resistant ≥ 4 µg/mL; tetracycline, susceptible ≤ 4 µg/mL, intermediate 8–16 µg/mL, and resistant ≥ 16 µg/mL; and vancomycin, susceptible ≤ 4 µg/mL, intermediate 8–16 µg/mL, and resistant ≥ 32 µg/mL (NCCLS 2002).

## Results

### Bacterial concentrations in air and bacterial identification

The mean concentration of presumptive *Enterococcus* present in the air of the swine CAFO on both 9 December 2003 and 5 January 2004 was 4 × 10⁴ CFU/m³. After bacterial speciation was completed on 137 presumptive *Enterococcus* isolates, only 47 out of 137 isolates (34%) were confirmed to be *Enterococcus* (Table 1). Forty-four isolates (32%) were identified as staphylococci, 45 isolates (33%) were viridans group streptococci, and 1 isolate was identified as *Micrococcus luteus* (Table 1).

### Antibiotic resistance

Ninety-eight percent (121 of 124) of the bacterial isolates that grew successfully during the antimicrobial susceptibility tests were resistant to high levels of at least two antibiotics commonly used in swine production (erythromycin, clindamycin, virginiamycin, or tetracycline), and 93% of the isolates (115 of 124) were resistant to at least three antibiotics commonly used in swine production. Individually, 98% of the isolates were resistant to erythromycin, 94% were resistant to clindamycin, 90% were resistant to tetracycline, and 37% were resistant to virginiamycin. None of the isolates displayed resistance to vancomycin. Because none of the *E. avium*, *E. pseudoavium*, or *E. raffinosus* isolates (all belonging to the *Enterococcus* physiologic group I) grew successfully on the control or antibiotic-amended MIC plates after being suspended as 0.5 McFarland standard solutions, MIC data for these isolates were not determined. MIC distributions among all other isolates were similar for erythromycin, clindamycin, tetracycline, and vancomycin, regardless of bacterial genus or species (Tables 2 and 3). For instance, across all organisms, most isolates (96%) had MICs > 256 µg/mL for erythromycin (Tables 2 and 3). In contrast, resistance to virginiamycin was more prevalent among coagulase-negative staphylococci versus *Enterococcus* or *Streptococcus* isolates (Tables 2 and 3). Phenotypes of antibiotic resistance among the bacterial isolates appear in Table 4.

## Discussion

In this study, multidrug-resistant *Enterococcus*, coagulase-negative staphylococci, and viridans group streptococci were isolated from the air of a swine CAFO. Ninety-eight percent of the isolates were resistant to at least two of the following antibiotics: erythromycin, clindamycin, virginiamycin, and tetracycline, all of which are approved for use in swine production for growth promotion. In contrast, none of the isolates were resistant to vancomycin, which has never been approved for use in swine production in the United States. These results support the findings of previous reports that nontherapeutic use of antibiotics results in the presence of antibiotic-resistant bacteria in swine (Aarestrup et al. 2000a, 2000b; Bager et al. 1997; Jensen et al. 2002; Wegener et al. 1999). In addition, these results provide evidence that in the absence of nontherapeutic antibiotic use—vancomycin in this case—no resistance is detected among bacteria present in the swine environment.

Furthermore, these findings suggest that, in addition to the ingestion of retail pork products (Gambarotto et al. 2001; Hayes et al. 2003; Sorensen et al. 2001; White et al. 2001)
The types of bacteria detected within the air of the swine facility investigated in this study are associated with a variety of human infections. *Enterococcus*, particularly some of the species isolated in this study including *E. faecalis* and *E. faecium*, has emerged as one of the leading causes of nosocomial bacteremias, urinary tract infections, and wound infections in the United States (NNIS 2001). Similarly, coagulase-negative staphylococci are the third most common causes of nosocomial infections and the most common causes of nosocomial bacteremias. The presence of multidrug-resistant *Enterococcus* and coagulase-negative staphylococci in patients significantly limits the treatment options available for these life-threatening infections. Although viridans group streptococci are part of the normal flora of the human respiratory tract, they also have been implicated as the cause of infective endocarditis and life-threatening sepsis in neutropenic patients. In addition, viridans group streptococci have been implicated as reservoirs of erythromycin-resistance genes, possibly capable of transferring resistance determinants to more pathogenic species including *Streptococcus pneumoniae* and *Streptococcus pyogenes* (Bryskier 2002).

Of particular concern to the health of individuals with direct or indirect contact with swine environments is the finding of virginiamycin-resistant gram-positive bacteria in the air of the swine CAFO. Virginiamycin, a streptogramin A and B combination, which has been used extensively as a growth promoter in swine, is an analog to quinupristin-dalfopristin, an injectable streptogramin A and B combination that is often the drug of last resort for multidrug-resistant gram-positive infections characterized by methicillin-resistant *Staphylococcus aureus* and glycopeptide-resistant *E. faecium* and coagulase-negative staphylococci (Johnson and Livermore 1999). Bacteria expressing resistance to virginiamycin are cross-resistant to quinupristin-dalfopristin, and a previous study has suggested that the transfer of streptogramin-resistant *Enterococcus* can occur between animals and humans in the livestock environment (Jensen et al. 1998). Thus, the inhalation of virginiamycin-resistant gram-positive bacteria in the swine environment could contribute to the appearance of quinupristin-dalfopristin-resistant gram-positive infections in humans, leaving few or no treatment options for the affected individual.

The finding of airborne clindamycin-resistant gram-positive bacteria in this study also is a potential concern to public health. Clindamycin is indicated for the treatment of human staphylococcal and streptococcal pneumonia (among other aerobic and anaerobic infections). Specifically, clindamycin has been used for the treatment of community-acquired methicillin-resistant *S. aureus* (Marcinak and Frank 2003). Clindamycin also has been shown to be significantly more potent than penicillin in inhibiting both invasive and noninvasive group A streptococci such as *S. pyogenes* (Mascini et al. 2001). The findings of airborne clindamycin-resistant coagulase-negative staphylococci and viridans group streptococci in the swine environment raise the question as to whether these organisms could serve as reservoirs of clindamycin-resistant genes [as

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### Table 3. MIC distributions for five antibiotics observed in airborne *Staphylococcus* and *Streptococcus* collected from a swine CAFO.

| Bacteria, antibiotic | Number of bacterial isolates with the following MICs (µg/mL) | %S | %I | %R |
|----------------------|-------------------------------------------------|----|----|----|
| **Staphylococcus** | | | | | |
| *S. aureus* (42) | Ery, Tet 1 (2) | 100 | | |
| *S. aureus* (1) | Ery, Clin, Tet 1 (100) | | | |
| *Enterococcus* | | | | | |
| *E. faecalis* (6) | Tet 1 (17) | | | |
| *E. faecium* (1) | Ery, Clin, Tet, Virg 1 (100) | | | |
| **Streptococcus** | | | | | |
| *S. mutans* (43) | Tet 2 (5) | | | |
| *S. mitis* (43) | Ery, Clin, Tet 35 (81) | | | |
| *S. sanguinis* (43) | Ery, Clin, Tet 3 (7) | | | |

Abbreviations: %I, percent intermediate; %R, percent resistant; %S, percent susceptible.

*Analyzed using the following breakpoints: erythromycin, susceptible ≤ 0.5 µg/mL, intermediate 0.5–2 µg/mL, resistant ≥ 2 µg/mL; clindamycin, susceptible ≤ 0.25 µg/mL, intermediate 0.5 µg/mL, resistant ≥ 1.0 µg/mL; virginiamycin, susceptible ≥ 1 µg/mL, intermediate 2 µg/mL, resistant ≥ 4 µg/mL; tetracycline, susceptible ≤ 1 µg/mL, intermediate 2 µg/mL, resistant ≥ 4 µg/mL; vancomycin, susceptible ≤ 1 µg/mL, intermediate and resistant not available (NCCLS 2002).

### Table 4. Phenotypes of antibiotic resistance among airborne bacteria collected from a swine CAFO.

| Bacteria | Antibiotic resistance pattern | No. of isolates (%) |
|----------|-------------------------------|---------------------|
| *Enterococcus* |  | |
| *E. dispar* (4) | Ery, Clin, Tet | 4 (100) |
| *E. durans* (2) | Ery, Clin | 1 (50) |
| *E. faecalis* (6) | Tet | 1 (17) |
| *E. faecium* (1) | Ery, Clin, Tet, Virg | 1 (17) |
| *E. hirae* (14) | | |
| *Staphylococcus aureus* (42) | Ery, Clin, Tet | 1 (100) |
| **Coagulase-negative staphylococci** (42) |  | |
| *S. epidermidis* (26) | Ery, Clin, Tet | 2 (62) |
| *S. hominis* (2) | Ery, Clin | 1 (2) |
| *S. lugdunensis* (2) | Ery, Clin | 2 (5) |
| *S. simulans* (35) | Ery, Clin, Tet | 3 (81) |

Abbreviations: Clin, clindamycin; Ery, erythromycin; Tet, tetracycline; Virg, virginiamycin.
well as reservoirs of erythromycin-resistant genes (Brysikier 2002), passing on clindamycin resistance determinants to more pathogenic species as described above.

Furthermore, exposure to virginiamycin-, erythromycin-, clindamycin-, and tetracycline-resistant Enterococcus, coagulase-negative staphylococci, and viridans group streptococci through the inhalation of contaminated air could lead to the colonization of these multidrug-resistant organisms in both the nasal passages (Aubry-Damon 2004) and the lungs of swine CAFO workers, potentially making the workers themselves reservoirs of antibiotic-resistant organisms. Coexposures to other aerosols and gases in the swine environment such as organic dusts, molds, and ammonia have been shown to induce symptoms associated with chronic bronchitis, including a persistent cough characterized by expectoration (Mackiewicz 1998). The presence of this type of cough can increase the potential for secondary spread of antibiotic-resistant organisms into the community, where additional individuals could serve as reservoirs of multidrug-resistant bacteria.

Moreover, the tunnel-ventilated design of swine CAFOs, which moves air outside of the facilities at a high flow rate, could create a situation where neighbors living downwind of the ventilation fans also could be directly exposed to airborne multidrug-resistant bacteria. An epidemiologic study by Wing and Wolf (2000) indicated that people who live in the vicinity of swine CAFOs experience elevated rates of headaches, runny noses, sore throats, excessive coughing, and diarrhea compared with people living in communities that are not situated near livestock operations. The findings of airborne multidrug-resistant bacteria in a swine CAFO in our study raise the question as to whether airborne bacteria also could travel beyond the confines of the swine CAFO on ventilation fan air currents, directly contacting nearby neighbors and potentially contributing to health effects such as those observed in the Wing and Wolf study. Because populations living in areas where swine CAFOs are built already may experience higher rates of certain diseases because of lack of access to appropriate health care (Weber et al. 1989), investigating airborne exposures to multidrug-resistant bacteria among these at-risk populations is an important area for future research.

In addition to potential airborne exposures occurring among individuals living near swine CAFOs, the results of this study could have broader public health implications. Specifically, one may question whether airborne exposures to multidrug-resistant bacteria could be occurring and contributing to health problems around other environmental sources of animal or human waste, including land application areas for animal waste and human sludge, and human wastewater treatment facilities. Endotoxins, exotoxins, and other chemical components in dusts associated with animal waste and human sludge have been linked to hypersensitivity reactions among individuals living near land application areas (Lewis and Gattie 2002). These reactions have been shown to result in increased susceptibility to serious respiratory infections, including those caused by S. aureus (Lewis and Gattie 2002). Thus, the presence of high concentrations of multidrug-resistant staphylococci and other bacterial pathogens amidst endotoxin-containing dust from animal and human waste could pose unique health concerns to people living near land application areas.

Conclusions

In summation, the findings of this study suggest that the inhalation of air from swine CAFOs may serve as an additional environmental exposure pathway for the transfer of multidrug-resistant bacterial pathogens from swine to humans. Given the growing interest in reservoirs of antibiotic resistance genes associated with large-scale livestock operations (Nandi et al. 2004), our findings in this investigation emphasize the importance of studying multiple genera of bacteria in different environmental media as sources of human exposure to antibiotic resistance genes.

References

Aarestrup FM, Agerso Y, Gerner-Smidt P, Madsen J, Jensen LB. 2000a. Comparison of antimicrobial resistance phenotypes and resistance genes in Enterococcus faecalis and Enterococcus faecium from humans in the community, broilers, and pigs in Denmark. Diagn Microbiol Infect Dis 37:127–137.

Aarestrup FM, Kruse H, Tast E, Hammerum AM, Jensen LB. 2000b. Associations between the use of antimicrobial agents for growth promotion and the occurrence of resistance among Enterococcus faecalis from broilers and pigs in Denmark, Finland, and Norway. Microb Drug Resist 6:63–70.

Aubry-Damon H, Grenet K, Saïl-Nélaya P, Che D, Cordeiro E, Bougnoux ME, et al. 2004. Antibiotic resistance in communal flora of pig farmers. Emerg Infect Dis 10:873–879.

Bager F, Madsen M, Christensen J, Aarestrup FM. 1997. Avoparcin used as a growth promoter is associated with the occurrence of vancomycin-resistant Enterococcus faecium on Danish poultry and pig farms. Prev Med 31:95–112.

Brysikier A. 2002. Viridans group streptococci: a reservoir of resistant bacteria in oral cavities. Clin Microbiol Infect 8:65–69.

Campanella ER, Johnson KR, Karpati A, Rubin CS, Dolpin DW, Meyer MT, et al. 2002. Antimicrobial residues in animal waste and water resources proximal to large-scale swine and poultry feeding operations. Sci Total Environ 299:89–95.

Chee-Sanford JC, Aminov RI, Krupac IJ, Garrigues-Jeannin N, Mackie RI. 2001. Occurrence and diversity of tetracycline resistance genes in lagoons and groundwater underlying two swine production facilities. Appl Environ Microbiol 67:1494–1502.

Clark S, Rylander R, Larsson L. 1983. Airborne bacteria, endotoxin and fungi in poultry and swine confinement buildings. Am Ind Hyg Assoc J 44:537–541.

Cohen ML, Taube RV. 1986. Drug-resistant Salmonella in the United States: an epidemiologic perspective. Science 232:694–698.

Cormier Y, Tremblay G, Meriaux A, Brochu G, Laviole J. 1990. Airborne microbial content in two types of swine confinement buildings. Can J Ind Hyg Assoc J 35:304–309.

Crook B, Robertson JF, Glass SA, Botheroyd EM, Lacey J, Topping MD. 1991. Airborne dust, ammonia, microorganisms, and antigens in pig confinement houses and the respiratory health of exposed farm workers. Am Ind Hyg Assoc J 52:271–279.

Donabedian SM, Thai LA, Hershberger E, Periby MB, Chow JW, Barrett P, et al. 2003. Occurrence of gentamicin-resistant Enterococcus in the United States: evidence of spread from animals to humans through food. J Clin Microbiol 41:1109–1113.

Environmental Defense. 1997. Animal Waste Summary. New York:Environmental Defense. Available at: http://www.hogwatch.org/maps/index [accessed 15 June 2004].

Food and Drug Administration. 2004. FDA Approved Animal Drug Products. Blacksburg, VA:Center for Veterinary Laboratory, Virginia/Maryland Regional College of Veterinary Medicine.

Gambardello K, Plooy MC, Dupron F, Giangibbe M, Denis F. 2001. Occurrence of vancomycin-resistant enterococci in pork and poultry products from a cattle-rearing area of France. J Clin Microbiol 39:2354–2355.

Gorbach SL. 2001. Antimicrobial use in animal feed—time to stop. N Engl J Med 345:1202–1203.

Hamscher G, Pawlickt HT, Szcesny S, Nau H, Hartung J. 2003. Antibiotics in dust originating from a pig-fattening farm: a new source of health hazard for farmers? Environ Health Perspect 111:1590–1594.

Hayes JR, English LL, Carter PJ, Proescholdt T, Lee KY, Wagner DD, et al. 2003. Prevalence and antimicrobial resistance of enterococcus species isolated from retail meats. Appl Environ Microbiol 69:3330–3333.

Institute of Medicine. 1998. Antimicrobial Resistance: Issues and Options, Workshop Report, Forum on Emerging Infections. Washington, DC:National Academy Press.

Jensen LB, Hammerum AM, Aarestrup FM, van den Bossche AE, Stobergh EE. 1998. Occurrence of aadA and vgb genes in streptogramin-resistant Enterococcus faecium isolates of animal and human origins in the Netherlands. Antimicrob Agents Chemother 42:3330–3332.

Jensen LB, Hammerum AM, Bager F, Aarestrup FM. 2002. Streptogramin resistance among Enterococcus faecium isolated from production animals in Denmark in 1997. Microb Drug Resist 8:369–374.

Johnson AP, Livermore DM. 1999. Quinupristin/dalfopristin, a new addition to the antimicrobial arsenal. Lancet 354:2012–2013.

Lewis DL, Gattie DK. 2002. Pathogen risks from applying sewage sludge to land. Environ Sci Technol 36:280A–292A.

Lin X, Willeke K, Ulivcious V, Grinshpun S. 1997. Effect of sampling time on the collection efficiency of all-glass impingers. Am Ind Hyg Assoc J 58:460–488.

Mackiewicz B. 1998. Study on exposure of pig farm workers to bioaerosols, immunologic reactivity and health effects. Ann Agric Environ Med 5:169–175.

Marcinak JF, Frank AL. 2003. Treatment of community-acquired methicillin-resistant Staphylococcus aureus in children. Curr Opin Infect Dis 16:265–269.

Mascini EM, Janzeca M, Schouls LB, Verhoef J, Van Dijk H. 2001. Penicillin and clindamycin differentially inhibit the production of pyrogenic exotoxins A and B by group A streptococci. Int J Antimicrob Agents 18:395–398.

Mellon M, Benbrook C, Benbrook KL. 2001. Hogging It: Estimates of Antimicrobial Abuse in Livestock. Cambridge, MA:Union of Concerned Scientists Publications.

Murray PR, Baron EJ, Jorgensen JH, Pfaller MA, Yolken RH. 2003. Manual of Clinical Microbiology. 8th ed. Washington, DC:American Society for Microbiology Press.

Nandi S, Mauer JJ, Hofacra C, Summers AD. 2004. Gram-positive bacteria are a major reservoir of class 1 antibiotic resistance integrons in poultry litter. Proc Natl Acad Sci USA 101:7118–7122.

National Research Council. 1999. The Use of Drugs in Food Animals: Benefits and Risks. Washington, DC:National Academy Press.

NCCCLS. 2002. Performance Standards for Antimicrobial Disk and Dilution Susceptibility Tests for Bacteria Isolates from Animals; Approved Standard. 2nd ed. M31-A2. Wayne, PA:National Committee for Clinical Laboratory Standards.

NNIS. 2001. National Nosocomial Infections Surveillance (NNIS) system report, data summary from January 1992–June 2001. Am J Infect Control 29:404–421.

Predicza ZB, Urban JE, Maghirang RG, Jerez SB, Goodband RD. 2002. Assessment of bioaerosols in swine barns by filtration and impaction. Curr Microbiol 44:136–140.
Sorensen TL, Blom M, Monnet DL, Frimodt-Moller N, Poulsen RL, Espersen F. 2001. Transient intestinal carriage after ingestion of antibiotic-resistant Enterococcus faecium from chicken and pork. N Engl J Med 345:1161–1166. 

U.S. EPA. 2000. Improved Enumeration Methods for the Recreational Water Quality Indicators: Enterococci, and Escherichia coli. EPA/821/R-97/004. Washington, DC: U.S. Environmental Protection Agency. 

van den Boogard AE, Stobberingh EE. 1999. Antibiotic usage in animals: impact on bacterial resistance and public health. Drugs 58:589–607. 

Weber D, Rutala W, Samsa G, Sarubbi F, King L. 1989. Epidemiology of tuberculosis in North Carolina, 1966 to 1986: analysis of demographic features, geographic variation, AIDS, migrant workers, and site of infection. South Med J 92:1204–1214. 

Wegener HC. 2003. Antibiotics in animal feed and their role in resistance development. Curr Opin Microbiol 6:439–445. 

Wegener HC, Aarestrup FM, Jensen LB, Hammerum AM, Bager F. 1999. Use of antimicrobial growth promoters in food animals and Enterococcus faecium resistance to therapeutic antimicrobial drugs in Europe. Emerg Infect Dis 5:329–335. 

White DG, Zhao S, Sudler R, Ayers S, Friedman S, Chen S, et al. 2001. The isolation of antibiotic-resistant salmonella from retail ground meats. N Engl J Med 345:1147–1154. 

Wing S, Wolf S. 2000. Intensive livestock operations, health, and quality of life among eastern North Carolina residents. Environ Health Perspect 108:233–238. 

Zahn JA, Anhalt J, Boyd E. 2001. Evidence for transfer of tylosin and tylosin-resistant bacteria in air from swine production facilities using sub-therapeutic concentrations of tylan in feed [Abstract]. J Anim Sci 79:189.