International Journal of One Health
Available at www.onehealthjournal.org/Vol.8/No.2/8.pdf

REVIEW ARTICLE
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Review of pork and pork products as a source for transmission of methicillin-resistant *Staphylococcus aureus*

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Received: 26-04-2022, **Accepted:** 13-10-2022, **Published online:** 12-12-2022

doi: www.doi.org/10.14202/IJOH.2022.167-177 **How to cite this article:** Khairullah AR, Sudjarwo SA, Effendi MH, Ramandinianto SC, Gelolodo MA, Widodo A, Riwu KHP, and Kurniawati DA (2022) Review of pork and pork products as a source for transmission of methicillin-resistant *Staphylococcus aureus*, *Int. J. One Health*, 8(2): 167-177.

Abstract

Methicillin-resistant *Staphylococcus aureus* (MRSA) is an opportunistic bacterium that can cause infection in animals and humans. Recently, MRSA from food-producing or farm animals has been identified as livestock-associated MRSA (LA-MRSA). The spread of LA-MRSA is particularly found in pork and pork products because LA-MRSA has been widely known to infect pigs. The most common type of LA-MRSA identified in pork and pork products is the clonal complex LA-MRSA 398 (LA-MRSA CC398). The MRSA strains on the surface of pork carcasses can be spread during the handling and processing of pork and pork products through human hands, cutting tools, and any surface that comes into direct contact with pork. Food infection is the main risk of MRSA in pork and pork products consumed by humans. Antibiotics to treat food infection cases due to MRSA infection include vancomycin and tigecycline. The spread of MRSA in pork and pork products is preventable by appropriately cooking and cooling the pork and pork products at temperatures above 60°C and below 5°C, respectively. It is also necessary to take other preventive measures, such as having a clean meat processing area and disinfecting the equipment used for processing pork and pork products. This review aimed to explain epidemiology, transmission, risk factors, diagnosis, public health consequences, treatment of food poisoning, and preventing the spread of MRSA in pork and pork products.

Keywords: antibiotics, livestock, methicillin-resistant *Staphylococcus aureus*, pork products, public health.

Introduction

Methicillin-resistant *Staphylococcus aureus* (MRSA) is an opportunistic pathogenic bacterium capable of causing infection in animals and humans [1]. Methicillin resistance occurs due to the activity of the penicillin-binding protein encoded by the *mec*A and *mec*C genes located on the staphylococcal cassette chromosome *mec* (SCC*mec*) [2]. Different epidemiological MRSA groups have been identified, such as hospital-associated MRSA known as hospital-acquired MRSA (HA-MRSA) and community-associated MRSA known as community-acquired MRSA (CA-MRSA). Recently, MRSA from food-producing or farm animals has been identified as livestock-associated MRSA (LA-MRSA). The spread of LA-MRSA is particularly found in pork and pork products, categorized as unprocessed meat products because LA-MRSA has been widely known to infect pigs [3, 4].

One of the most widely identified types of LA-MRSA in pig farming is clonal complex 398 (CC398), which has been widespread in pig farms worldwide [5, 6]. Then, LA-MRSA began to be identified in other livestock, including cattle [7], poultry [8], and meats, including beef, lamb, poultry, and pork [6, 9–11].

Although LA-MRSA is mainly associated with pigs, there are an increasing number of cases in which humans are infected and colonized by LA-MRSA, even in humans with no history of contact with pigs [12, 13]. If pigs infected with MRSA are slaughtered, the MRSA can spread to pig carcasses, slaughterhouse workers, meat-processing industry employees, and the surrounding environment. In addition, if pork and pork products are contaminated with MRSA, the MRSA strain can infect humans when humans consume them [14]. Several studies have demonstrated MRSA contamination in foodstuffs of animal origin, particularly pork and pork products, highlighting the potential risk of MRSA through food handling and consumption [10, 15–19]. This raises concerns about MRSA transmission, which has not received much attention between pigs and humans through the food production chain. However, it remains to be determined to what extent pork and pork products may contribute to this MRSA [6].

Routine inspection of MRSA isolation is common in the human and animal health sector. However, information is still scarce in the field of foodstuffs of animal origin, which are also reservoirs of MRSA transmission [20]. So far, the pork and pork product consumption rate is quite high globally, but there are still limited reports on the MRSA characteristics and transmission in pork and pork products [21].

This review will explain MRSA in general, MRSA in the meat of animal origin, MRSA in pork, MRSA epidemiology in pork and pork products, MRSA transmission in pork and pork products, risk factors for MRSA transmission in pork and pork products, MRSA diagnosis and identification in pork and pork products, public health consequences, treatment of food poisoning due to MRSA from pork and pork products, and preventing the spread of MRSA in pork and pork products.

Methicillin-resistant *S. aureus*

Soon after penicillin antibiotics were introduced and widely used, around 1945, most *S. aureus* became resistant to penicillin by producing β-lactamase, an enzyme that acts in hydrolyzing penicillin. In the late 1950s, methicillin was introduced and widely used in medicine against *S. aureus* penicillin-resistant. However, not long after methicillin was introduced, *S. aureus* isolates resistant to methicillin were also known as MRSA [22].

The resistance of *S. aureus* to methicillin is due to acquiring the genes encoding *mec*A and *mec*C. These genes encode an alternative penicillin-binding protein, PBP2a, and have a low affinity for β-lactam antibiotics [23, 24]. The genes encoding *mec*A and *mec*C are part of a cellular genetic element known as the SCC*mec*. Staphylococcal cassette chromosome *mec* can be integrated at specific sites in the *S. aureus* sensitive [25]. SCC*mec* carries a set of cassette chromosome recombinase genes (*ccr*A, *ccr*B, or *ccr*C) for integration and excision into the host chromosome. Based on the *mec*A, *mec*C, and *ccr* combination identified in the bacterial genome, molecular typing of the MRSA strain has shown that there are 11 types of *mec,* and several composite subtypes of two or more SCC elements have been found worldwide [26]. Other than the complex differences in this gene, various elements of SCC*mec* also differ from each other in markers of the ability of *S. aureus* to resist antibiotics other than β-lactam antibiotics [25].

Methicillin-resistant *S. aureus* in the Meat of Animal Origin

Methicillin-resistant *S. aureus* from food of animal origin has been widely reported in several studies in different countries [27]. For example, in the Netherlands, 267 MRSA isolates (11.9%) were found from 2217 samples of raw meat obtained from market traders: Turkey (35.3%), chicken (16.0%), veal (15.2%), pork (10.7%), beef (10.6%), and lamb and mutton (6.2%); most of these MRSA isolates were included in LA-MRSA CC398 [10]. A recent study conducted in Brazil found MRSA isolates in samples of pork (37.5%), fish meat (30%), chicken (23.3%), and beef (23.3%) [28]. In another study conducted in Tunisia, two MRSA isolates from pork samples were found and included in LA-MRSA CC398 [29]. The MRSA strains have also been found in fish meat, albeit rarely reported [30].

Foods of animal origin are often contaminated with LA-MRSA CC398, particularly in meat, which presumptively implies that LA-MRSA isolates found in live animals may also be found in meat and items made from processed meat [10]. In addition, HA-MRSA and CA-MRSA may be detected in meat, indicating that humans can be a source of contamination for MRSA transmission during slaughter and meat processing. In the United States, 22 MRSA isolates (18.3%) were detected in 120 retail pork samples and 30 pork product samples [31]. In Canada, 31 MRSA isolates (7.7%) were identified among 402 retail pork samples, and most were LA-MRSA CC398 [32]. Although meat can be contaminated with MRSA, there is currently no strong evidence that eating meat can increase the risk of transmitting MRSA to humans.

Ogata *et al.* [33] demonstrated that commercially distributed meat may play a role in spreading CA-MRSA in the community. The European Food Safety Authorities have issued policies regarding the importance of public health regarding the spread of MRSA in animals and food. The European Food Safety Authority's Panel on Biological Hazards (BIOHAZ) stated that there is currently no evidence that consuming or processing meat contaminated with MRSA increases the risk of humans becoming infected with MRSA or becoming MRSA carriers [34]. Panel on Biological Hazards also stated that where the MRSA prevalence is high in food-producing livestock that comes into contact with other livestock, breeders, veterinarians, and family farmers are at greater risk than the general public. In addition, based on the BIOHAZ data, there is no evidence that humans can be infected with LA-MRSA CC398 from MRSA-contaminated meat and no strong evidence that the LA-MRSA CC398 strain can cause food poisoning [34].

Epidemiology of MRSA in Pork and Pork Products

The MRSA strain began to emerge as a healthcare-associated infection in the 1960s, and in the late 1990s, it became known as community-associated MRSA (CA-MRSA) [35]. In 2004, an MRSA strain was identified in the Netherlands that is resistant to digestion by restricting the *sma*1 endonuclease by typing with PFGE and is associated with contact with pigs [36]. This MRSA strain belongs to the CC398. The MRSA CC398 strain is usually resistant to methicillin and other β-lactam antibiotics. The LA-MRSA CC398 strain has been referred to as a livestock-associated strain, especially in pigs, and has been found in several carcasses after livestock slaughter. Since the discovery of MRSA strains in pig herds in the Netherlands, many studies on MRSA in pork and pork products have been reported globally [3, 6, 19, 32, 36–38].

The LA-MRSA CC398 strain and other MRSA strains have been found in pork globally [6, 10, 14, 17]. Public health agencies in Europe and the United States have yet to find evidence that pork contaminated with MRSA contributes to an increased risk of MRSA transmission [39]. Heikinheimo *et al.* [6] quantified the number of bacterial colonies in MRSA-positive pork samples purchased at retail stores across Canada and confirmed that a 37% prevalence of MRSA-positive pork samples was below the detection threshold for quantification <100 CFU/g found in most of the pork samples. Methicillin-resistant *S. aureus* has also been identified in various farm animals, especially pigs [40]. Kalupahana *et al.* [41] described the association of pig farming with an increased risk of MRSA exposure in pork and pork products that can infect humans.

Methicillin-resistant *Staphylococcus aureus* testing has been documented for various meat products, especially pork products because pork is the most consumed meat product in the world, especially in Algeria [42]. The consumption rate of pork in the United States is approximately 51 pounds per person annually [43]. Recent study has evaluated various pork products globally to determine MRSA prevalence in pork products [19]. Wu *et al.* [31] reported a 5.6% MRSA-positive prevalence rate in 90 samples of pork products in a Louisiana retail store. A similar study conducted in the Netherlands reported that there was a 2.5% MRSA-positive prevalence rate in 64 samples of pork products [17]. In a recent study, O'Brien *et al.* [44] revealed a 6.6% MRSA-positive prevalence rate in 395 samples of pork products in Iowa, New Jersey, and Minnesota retail stores. Most of the literature shows that the MRSA contamination level in pork products is still very low, <100 CFU/g.

Although several studies have been conducted in Europe and the United States showing that there are MRSA strains in pork products on the market, it is estimated that MRSA transmission is still rare from meat products contaminated with MRSA. Panel on Biological Hazards revealed no evidence to date that consuming or handling meat products contaminated with MRSA will cause MRSA infection in humans [16]. When MRSA strains are found in pig populations, it is likely that these MRSA strains will still be found in pig carcasses after slaughter in abattoirs. As a commensal, MRSA can infect pigs without showing clinical symptoms. Microbiological screening tests are necessary to detect positive and negative MRSA in pork [3].

Various survey studies have been conducted to evaluate the extent to which MRSA has spread through live pigs infected with MRSA to pig carcasses after slaughter. Samples were obtained from pigs in abattoirs and pig carcasses were cut into pieces. However, the data obtained at the beginning of the slaughtering process cannot be directly used to reveal MRSA prevalence in the primary production sector because of the possibility of cross-contamination during transportation or in abattoir cages, which can increase the frequency of MRSA detection in pork [3].

Several studies were conducted in Europe, including the Netherlands [45–47], Denmark [19], Switzerland [48, 49], Germany [50–52], Spain [53, 54], and Italy [55], and have reported MRSA in pork ranging from 1.3%–64.7%. Methicillin-resistant *S. aureus* findings were also derived from pork in other studies conducted in Tenerife [56] and Asia [57–59].

Most MRSA strains found in pigs during slaughter in European abattoirs belonged to *spa* strains t011, t034, and t108. The results of investigations conducted in Spain and the Netherlands accounted for 11% [53, 54] and 37.5% [47] of all MRSA isolates belonging to the *spa* t108. Meanwhile, in Italian slaughterhouses, 49% of the MRSA isolates found in pork were *spa* t899 and 47% of the MRSA isolates found in pork carried strains other than MRSA CC398, such as MRSA CC1, MRSA CC9, and MRSA CC97 [55]. In a study conducted in Spain, the MRSA prevalence rate in pork on the island of Tenerife was 85% [56]; most of these MRSA strains belonged to the MRSA CC398 strain.

In studies conducted in Asia, MRSA strains were reported to be found in pork in China [58], Japan [57], and Korea [59], with prevalence rates still quite low, 0.9%–7%. Korea was the only country that reported the MRSA CC398 strain as the dominant strain in the pig population, and 81% of the examined pork contained the MRSA CC398 strain. In the results of a study conducted in China reporting *spa* t899, CC9 multilocus was the most dominant type of sequence found in pork [58]. Meanwhile, a study conducted in Japan reported a type of MRSA CC5 in one sample of pork in a Japanese slaughterhouse [57].

When MRSA strains are found in pork, they are likely to be found in processed pork products. In studies conducted in Europe, MRSA-positive pork products were reported in the Netherlands [10, 60], Germany [50, 51, 61, 62], Spain [63], and Denmark [19], with prevalence rates of 1.8%–15%. Combining the level of MRSA identification from pork and various pork products, pork products are twice as likely to be MRSA-positive than fresh pork. This difference may be due to MRSA contamination factors during the processing of pork into pork products [61, 62]. In minced pork, the MRSA possibility of entry is quite large because, in minced pork, there is an increase in the surface area of the meat, which can increase the growth of *S. aureus*.

Based on the regional distribution of *spa* types in primary meat production and abattoirs, most MRSA isolates in pork and pork products belonged to *spa* t011 and t034. Meanwhile, *spa* t108 can only be found among samples of pork products in the Netherlands. Methicillin-resistant *S. aureus*-positive isolates from samples of pork products imported to Denmark indicated the presence of MRSA in other European countries, including France and Poland [19]. In Canada [6, 32] and the United States [6, 11, 31, 32, 44, 64], a 3.6%–9.6% prevalence rate of MRSA was found in pork products. Most MRSA strains found in pork products in the United States belong to sequence type 5 (ST5) and sequence type 8 (ST8), the most common CA-MRSA strains found in the United States. The investigation results from the United States indicate that MRSA transmission in pork products may result from human contamination during the processing of pork [11, 31, 64]. No significant differences in MRSA prevalence rates were observed when comparing samples of pork products with pigs raised on alternative farms without antibiotics and conventional farms [44].

In a study conducted in Canada, two main MRSA clones were found in pork product samples: MRSA ST2 and MRSA ST5, which are community-associated strains (CA-MRSA) in Canada; only a small number of isolates were identified as *spa* t034 [6, 32]. Based on the quantitative MRSA analysis results, it was revealed that 60% of the pork product samples were MRSA positive and had *S. aureus* of 1.3 log CFU/g. This is in contrast to the findings in Europe, where pork samples in Canada were twice as likely to be more MRSA-positive than samples of pork products [6]. In studies conducted in Asia, MRSA isolates were found in pork products in Hong Kong and Korea, with prevalence rates of 21.5% and 7.1%, respectively [65, 66]. In a study conducted in China, samples of pork products from the market were included in the MRSA *spa* t899 and in the sequence type 9 (ST9) [66]. In a study conducted in Korea, ST72 MRSA was found in pork products [65] because ST72 is the most common type of CA-MRSA found among humans in Korea [67], it is possible that industrial employees contaminated ST72 MRSA during handling and pork processing. In Korea, MRSA CC398 is the most common type of MRSA found in the pig population on farms [59].

Transmission of MRSA on Pork and Pork Products

After pork carcasses leave the refrigerated slaughterhouse, MRSA strains on the surface of pork carcasses can be spread during pork handling and processing through human hands, cutting tools, and any surface that comes into direct contact with pork. Increased manual handling of pork during processing may also cause the introduction of human-sourced MRSA strains into pork processing production units. A pork processing plant in Switzerland reported prevalence of *S. aureus* contamination of 22.7% in pork obtained from 18 suppliers in Europe, with bacterial counts ranging from 0.1 CFU/g to 2 log CFU/g [68]. Pork contaminated with MRSA was traced back to several abattoirs, which then concluded that the slaughter process caused MRSA contamination in pork. There was a significant reduction in the amount of MRSA in pork due to the removal of the surface of the pork tissue during the carcass slaughtering process [69]. Kastrup [51] investigated a pork processing unit in Germany, where there was an MRSA detection frequency of 6% in pork slaughter, 5% in industrial employees, and 2% in pork processing equipment.

Beneke *et al.* [50] reported a prevalence rate of 4.2% positive for MRSA in pork samples and obtained a similar prevalence rate of 4.2% in abattoir processing areas in Germany. The factory environment and abattoirs are also sources of MRSA transmission in pork, while MRSA is rare for pork processing equipment. In general, *S. aureus* can survive on stainless steel surfaces, possibly leading to recontamination in the long term. In experimental studies, *S. aureus* at contamination levels of 5 log CFU/100 cm^2–7 log CFU/100 cm^2 was detected on dry stainless steel surfaces for at least 96 h. Even at a low contamination level of 3 log CFU/100 cm^2, *S. aureus* can still be found within 48 h [70]. In a study in Colombia, Gutierrez *et al.* [71] found MRSA in three pork processing facilities and two institutional kitchens. Methicillin-resistant *S. aureus* was not found in the nose and hands of humans, but there were 31 people (33%) who carried methicillin-sensitive *S. aureus* (MSSA). Five pork samples (14.3%) were positive for MRSA contamination, two of which were included in the MRSA *spa* t011. *Staphylococcus aureus* is usually non-invasive when eaten, except in rare circumstances [14]. Accidental MRSA contamination when handling and processing pork is the most important consideration. Pork and pork products can also serve as a source of MRSA transmission if the organism has not been destroyed by cooking. An epidemiologist at the University of Rotterdam Hospital, Dijkzigt, the Netherlands, believes that MRSA transmission originates from health workers who transmit MRSA through food given to patients [45]. Then, Sergelidis and Angelidis [46] linked diseases originating from the food consumed by the community with meat products, a report proving that MRSA can cause food poisoning because it can produce enterotoxins in food.

Risk Factor of MRSA on Pork and Pork Products

Methicillin-resistant *Staphylococcus aureus* found in pork and pork products poses potential risks to human health. Food poisoning is the main risk arising from MRSA in pork and pork products. However, MRSA is an irrelevant factor in enterotoxin production, and food poisoning is not a disease that is treatable with antibiotics. Therefore, MRSA should not pose a greater risk of food poisoning than MSSA. In fact, MRSA CC398 is rarely found with the toxin gene [72].

A second risk is the development of invasive disease after ingesting pork and pork products contaminated with MRSA, but this is still a rare event and has only been reported once in the context of an MRSA outbreak in a patient with food poisoning at the Erasmus Medical Center, Rotterdam, the Netherlands [73]. In this outbreak, patients became infected with MRSA after consuming meat and pork products contaminated with MRSA, resulting in severe sepsis that can cause mortality. The patient was severely immune and then received antibiotics and antacids. Therefore, under these conditions, an invasive infection may occur after consuming pork and pork products contaminated with MRSA. However, it is not necessarily a health risk for most people.

A third potential risk is the possibility of MRSA colonization during the processing or consumption of pork and pork products. If pork and pork products are cooked properly, the potential risk of MRSA infection in humans may not occur when consumed. The risk is highly dependent on hygienic measures, the amount of MRSA present, and the ability of the MRSA strain to infect the host. Here, note that, based on the results of several previous studies, the amount of MRSA present in the samples of pork and pork products is still very low [14].

Diagnostic and Identification of MRSA in Pork and Pork Products

Methicillin-resistant *Staphylococcus aureus* infection is diagnosed by culturing the organism from the affected site. In contrast, in cases of food poisoning, MRSA is diagnosed by examining MRSA's food and toxin production [74]. Samples of pork or pork products were collected using a sterile cotton swab moistened with sterile phosphate buffer solution; then, the samples were stored and collected in a place free from other contamination [75].

There are various tests available to identify MRSA, but there is no universal standard for detecting MRSA and the cost-effectiveness of most of the methods is unknown [76]. In simple terms, *S. aureus* can be detected directly using a Gram stain. *Staphylococcus aureus*, including MRSA, is visible under the microscope as clustered, purple colonies [77]. Using Gram stain alone, MRSA is still indistinguishable from *S. aureus*. Previously, BBL CHROM agar for MRSA was shown to be a highly specific and sensitive medium for detecting MRSA [78]. The confirmation of MRSA is tested for the presence of PBP2 with the MRSA latex agglutination test (Oxoid Ltd., Hants, UK) [79].

Molecular methods used to examine MRSA have been widely used in several places [80, 81]. The standard method used to detect human MRSA (CA-MRSA) is gel electrophoresis [82]. However, this is not usually compatible with LA-MRSA molecular typing due to the presence of a unique methylase [83]. It is necessary to perform *pvl* doubling and *spa* sequencing to identify each MRSA isolate. The *pvl* gene is frequently associated with CA-MRSA and severe disease cases, although its pathogenic role remains unclear [84]. Most current LA-MRSA do not carry the *pvl* [23]. Molecular *spa* typing is a very common first-line typing tool that utilizes *S. aureus* variable repeat region [5]. The following are several types of *spa* associated with LA-MRSA CC398. including t011, t034, t108, t567, t571, t779, t898, t943, t1197, t1250, t1254, t1255, t1451, t1456, t1457, t2346, t2970,83 t3015, t3119, t4208, t4872, t337, t899, and t1939 [23]. Finally, it is necessary to test for susceptibility to antibiotics using the broth dilution method [85].

Public Health Importance

The results of several survey studies have revealed that the presence of LA-MRSA in pork and pork products is a substantial health risk for consumers [86, 87]. Several investigators have reported that LA-MRSA CC398 can cause severe cases of diseases, such as pneumonia, endocarditis, and infections of the urinary tract, soft tissues, and wounds [88–91]. The incidence of MRSA CC398 detection in hospitalized patients and the proportion of MRSA infections caused by the LA-MRSA genetic type appear to correlate with MRSA contamination in pork and pork products [60, 92]. In Germany, the proportion of LA-MRSA isolated from humans is steadily increasing [93].

The widespread of LA-MRSA through pork and pork products has been demonstrated, but the public health relevance of MRSA-contaminated pork and pork products remains unclear. Methicillin-resistant *S. aureus* colonization through handling or consumption of pork and pork products contaminated with MRSA remains very rare, but that does not mean that MRSA colonization is impossible. Only two cases of clinical MRSA were thought to have originated from the consumption of pork contaminated with MRSA, but both cases were not associated with the CC398 strain of MRSA. In the first case, the patient was severely immunocompromised due to septicemia after consuming pork contaminated with MRSA; the MRSA strain was then transmitted to several other patients through a nurse who was colonized with MRSA [73]. The second case was food poisoning caused by pork contaminated with the toxin-producing strain of MRSA [46]. Investigations among professional pork handlers in the Netherlands revealed that even high-frequency exposure to MRSA resulted in a low MRSA colonization rate of ≤3% [71]. Pork and pork products contaminated with MRSA can be a source of LA-MRSA transmission to the community, but this is avoidable by following standard recommendations for hygienic handling and adequate heating of pork and pork products.

The number of LA-MRSA strains in pork and pork products may be another reason for the rate of MRSA transmission. There is still no reliable quantitative data available regarding LA-MRSA in pork and pork products. However, some evidence of MRSA in pork and pork products has been found, although the number of MRSA strains in pork and pork products is still low. In a quantitative study conducted in Canada regarding MRSA contamination in retail pork, researchers found a low level of MRSA epidemic in pork, with 37% of pork samples still below the detection threshold [6]; most of the pork samples accounted for *S. aureus* as much as <2 log CFU/g. In a quantitative study conducted in the Netherlands, the isolation of MRSA from pork products was only possible if a color-sensitive enrichment protocol was used [17]. However, permanent MRSA colonization or infectious disease can occur by handling or consuming pork and pork products contaminated with MRSA and the number of MRSA doses when infecting humans. Another reason for the discrepancy between the small number of infectious disease cases attributable to MRSA and the high detection frequency of MRSA CC398 is the lack of clinically important virulence factors [72, 94].

Although cases of infectious diseases associated with LA-MRSA remain low, continuous monitoring is important because the MRSA CC398 pathogenicity can continue to develop by inserting additional genes. In China, five MRSA CC398-positive isolates were associated with wound and lung infections in hospitalized patients [95]. A study conducted in Germany reported that two MRSA CC398 isolates were associated with recurrent cases of furunculosis in hospitalized patients [96].

Treatment of Food-borne Infection due to MRSA from Pork and Pork Products

Antibiotic therapy should be based on testing the susceptibility of bacteria to antibiotics, but all MRSA strains are considered resistant to cephalosporins, penicillin, and several other β-lactam antibiotics, including ampicillin-sulbactam, carbapenems, piperacillin-tazobactam, ticarcillin-clavulanic acid, and amoxicillin-clavulanic acid [97, 98].

Several antibiotics for treating MRSA infection have been used, including vancomycin and tigecycline antibiotics. However, the antibiotics, vancomycin and tigecycline, remain controversial in their use in animals and can only be used in humans [40]. Meanwhile, patients who are allergic to the antibiotic vancomycin can use other antibiotics in case of MRSA infection, such as tetracycline (minocycline), lincosamide (clindamycin), and fluoroquinolones (ciprofloxacin) [99, 100]. Antibiotics, such as ciprofloxacin, can also be used, but their use is limited due to the rapid development of resistance during the treatment process [99, 100]. MRSA infections can also be treated with oral medications, such as doxycycline, linezolid, cotrimoxazole, pristinamycin, clindamycin, and rifampicin-fusidic acid [101]. Mupirocin (Bactroban) can also be used in MRSA infection [102]. A new antibiotic called platensimycin has also been shown to be effective against MRSA [103].

Prevention of the Spread of MRSA in Pork and Pork Products

The spread of MRSA in pork and pork products can be prevented [104]. What must be considered is that consumers need to be aware of the potential for MRSA contamination in pork and pork products during cooking in the kitchen. It is important to thoroughly cook pork and pork products, but preventing cross-contamination and maintaining tipping points are the most effective ways to prevent the spread of MRSA. In addition, public health interventions should be designed to prevent MRSA before and after slaughter in pork processing facilities. Public awareness of the safe handling and processing of pork will help prevent MRSA cross-contamination [6], as well as the potential for MRSA colonization through handling pork products contaminated with MRSA. Other public health interventions, including customized and personalized food safety education programs targeting sociodemographically diverse people, can help prevent the spread of MRSA in pork and pork products [104].

The permissive temperature that supports the growth and production of *S. aureus* and MRSA toxins is between 6°C and 46°C. Thus, the ideal cooking and refrigerating temperatures for pork and pork products should be above 60°C and below 5°C, respectively. A study evaluating the performance of household refrigerators worldwide reported that many refrigerators were operating above the recommended temperature [105]. Another study conducted in Portugal revealed that more than 80% of people clean their refrigerators only once monthly [106]. The results of this study indicate the need for public awareness in maintaining food safety and taking other preventive measures, such as the practice of serving food quickly when stored at, wearing gloves, wearing a mouth mask, tying hair during handling and processing pork and pork products, diligently washing hands, and maintaining personal hygiene [107, 108].

Keeping pork and pork products refrigerated are essential to prevent MRSA growth [109]. Other preventive measures include proper handling, control, and processing of pork and pork products, including maintaining the cleanliness of meat processing sites and disinfection of equipment used in pork processing [6, 110]. In addition, strict application of food safety guidelines, such as Good Manufacturing Practice, Hazard Analysis and Critical Control Points, and Good Hygienic Practices, developed by the United States Food and Drug Administration and the Health Organization needs to be adhered. Worldwide, it helps prevent the spread of MRSA in pork and pork products and other animal products [111–114]. This potential concern warrants further study. However, standard recommendations for handling and cooking raw pork should be observed to reduce, if not eliminate, the risk of MRSA transmission. It is also like cooking; proper food handling should reduce or eliminate the risk of enterotoxin-associated gastroenteritis. It also makes sense that MRSA from pork could directly contaminate vulnerable places, such as wounds, which can be of particular concern to humans who work in the food preparation industry and may be prone to knife stab wounds on their hands [32, 115]. Hence, further studies on the potential role of pork in MRSA transmission in the community are needed, including measures such as inquiring about food contact history in LA-MRSA studies.

Conclusion

This review could not conclude that pork or pork products are the sources of human MRSA infection. However, the discovery of MRSA in pork, including strains implicated in human infection, raises concerns and the possibility that pork and pork products play a role in the spread of MRSA in the community. Further studies are needed to elucidate this possible role better and determine whether appropriate mitigation strategies exist. The type of MRSA commonly found in pork and pork products is LA-MRSA CC398. It remains rare to report cases of food poisoning originating from pork and pork products, but that does not mean that such cases of food poisoning will not occur. Proper handling and processing of pork and pork products are necessary to prevent the spread of MRSA. It is also necessary to cook pork and pork products at appropriate temperatures to destroy MRSA contamination and inhibit MRSA growth.

Authors' Contributions

ARK: Drafted the manuscript. SAS and MHE: Revised and edited the manuscript. SCR, MAG, AW, and KHPR: Retrieved references. DAK: Edited the references. All authors have read and approved the final manuscript.

Acknowledgments

This article was supported in part by the Penelitian Pasca Sarjana - Penelitian Disertasi Doktor funding from PENELITIAN DRTPM KEMENDIKBUDRISTEK TAHUN 2022, with grant number from Universitas Airlangga, Indonesia: 904/UN3.15/PT/2022.

Competing Interests

The authors declare that they have no competing interests.

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