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Risk factors for antimicrobial resistance in paediatric burn infections: Insights from a retrospective cohort study

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ABSTRACT

Aim: To define the microbiome, antimicrobial resistance profiles and associated risk factors among paediatric patients with infected burns.
Methods: A retrospective cohort study was conducted among paediatric patients with infected burns admitted to a tertiary burns service between January 2011 to December 2023. Basic demographic data and burn-related clinical information were extracted from the Burns Unit database and linked with microbiological data.
Result: Among a total of 3679 paediatric burn patients admitted, 183 (5 % of overall admitted) were identified as clinically having infected burns. Of the 173 (4.7 % of overall admitted) patients with documented cultures, 152 (87.9 % of suspected clinical infections) had culture-positive burn wound infections (BWIs) and 15 (8.7 % of overall admitted) had developed blood stream infections. The most common microorganisms identified in BWI were Gram-positive bacteria (245 isolates, 63.1 %), with *Staphylococcus aureus* being the most prevalent (32 %) followed by *Streptococcus* species (11.9 %). Gram-negative bacteria were identified in 32.5 % of cases, with *Pseudomonas aeruginosa* being the most common organism (5.7 %). Nineteen (5 %) methicillin-resistant *Staphylococcus aureus* isolates were detected from 17 (9.8 %) paediatric patients with burns. The highest resistance was reported against ampicillin (100 %) followed by penicillin (91.7 %), and amoxicillin (88.6 %) against *S. aureus* isolates. *P. aeruginosa* isolates showed resistance in 58.8 % of cases to ceftazidime, followed by 47 % to piperacillin-tazobactam, and 2 isolates were resistant to imipenem, a carbapenem antibiotic considered a last-resort option. Multivariate logistic regression analysis revealed that burns to the head and neck regions (AOR = 5.2, 95 %CI: 2.20–12.31; $p < 0.001$), admission to the paediatric intensive care unit (PICU) (AOR = 8.2, 95 % CI: 1.03–64.86; $p = 0.047$) and previous medical history (AOR = 2.4, 95 %CI: 1.07–5.55; $p = 0.033$) were independent risk factors associated with antimicrobial-resistant (AMR) burn infections
Conclusions: AMR in paediatric patients with infected burns is common and therefore early culture confirmation could improve treatment outcomes especially for patients with high risk factors.

1. Introduction

Burn-associated injuries are a major global public health problem and remain the leading cause of disability, imposing profound psychological and economic burden on both patients and the healthcare system [1]. According to the World Health Organisation (WHO), burns account for an estimated 180,000 deaths annually, while over 11 million people require medical attention due to burn-associated injuries each year worldwide [2]. In Australia, burn injuries are a significant public health issue, with over 200,000 cases reported each year, costing Australian's healthcare system over $150 million annually [3]. Due to children's curiosity, risk-taking behaviour, and innate physical characteristics, burns disproportionately affect the paediatric population [1,4,5]. Burn injuries result in a breakdown of the protective skin barrier, facilitating translocation of pathogens and the development of infection. Additionally, the innate and adaptive immune systems are compromised in patients with burns, further increasing host susceptibility to infection, along with a heightened metabolic demand during tissue repair [6,7]. Children have a relatively thin dermis compared with adults, resulting in deeper burns with less thermal insult compared to adults [8], providing

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a more suitable environment for microbial colonization and infection [9]. In addition to the depth of burn injury, other risk factors including the affected total body surface area (TBSA) [9–11], intensive care unit (ICU) admission, extended hospital length of stay [11], burns to the head or neck [12], inhalation injuries and flame burns [9,10,13] all increase the likelihood of infections. Infection is recognised as a clinical challenge in the management of burn injuries, contributing to up to 75 % of all deaths in burn patients [14,15].

Burn wound infections (BWIs) are a major concern in paediatric burn patients, as infected burns can rapidly progress into more severe complications including bloodstream infections (BSIs), which are a leading cause of sepsis [6]. Bacterial infections are the most common cause of BWIs [14]. The most common pathogenic microorganisms associated with paediatric burn wound infection include *Staphylococcus aureus*, *Pseudomonas aeruginosa*, *Streptococcus pyogenes, coagulase negative Staphylococcus* (CoNS), *Serratia marcescens, Acinetobacter baumannii, Enterococcus faecalis, Enterobacter cloacae* and *Candida albicans* [10, 16]. The spectrum of pathogens and their antimicrobial susceptibility patterns have been shown to vary across different settings and change over time [16–18]. For example, a study in the USA reported *S. aureus* (25 %) as the most predominant clinical burn isolate in paediatric burn patients, followed by *P. aeruginosa* (13 %) [16]. Additionally, trends of increasing emergence of methicillin resistant *S. aureus* (MRSA) rose from 20 % in 2004 to 45 % in the period of 2009–2011 [16]. A study in Australia among patients with severe burn injury (> 20 %TBSA) reported a 16 % rate of MRSA [19] and a recent retrospective study in the Australia and New Zealand burn registry shows the significance of MRSA in paediatric burns, identifying it as the most commonly isolated multidrug resistant pathogen [17].

Despite the significant advances in burn care over the last several decades, microbial wound infection remains a critical concern and are one of the substantial contributors to BSIs in burn patients. The use of invasive diagnostic and therapeutic indwelling devices, such as endotracheal intubation, central venous access catheter, arterial catheter and urinary catheters, are crucial to the effective management of severe burns in children (> 10 % TBSA), all of which have been shown to increase the risk of acquiring antimicrobial resistant (AMR) pathogens [20–22]. Burn wounds infected with AMR pathogens have been shown to result in prolonged hospital stays [22], delayed skin grafting and increased financial burden on both patients and the health care system [21]. Furthermore, due to the global emergence of AMR, burn patients are at an increased risk of infections from AMR organisms, and the use of preoperative broad-spectrum antibiotic prophylaxis in burn patients is indeed a common practice in Australia [23]. However, these further drives resistance by sustained selective pressure [24] and complicates future treatment and worsened patient outcomes [19]. Understanding the current microbial epidemiology of burn wounds and changing trends in antimicrobial resistance patterns enables burn unit clinicians to make informed decisions regarding empirical antimicrobial therapy whilst facilitating evaluation of alternative infection prevention strategies to combat AMR [25–27].

Given the difference in microbial landscapes and the ever-changing nature of AMR profiles across geographic locations, it is crucial to perform regular AMR assessment tailored to the local settings. This allows clinicians to better understand the specific pathogens causing infections, developing resistance patterns, and how those patterns shift over time [28]. As of to date, there is a lack of studies linking AMR infection and associated risk factors in paediatric patients at the Women's and Children's Hospital (WCH) Burn Unit in Adelaide, Australia. Conducting such studies at the WCH Burn Unit will help to inform best evidence-based practice and optimize the use of antimicrobial agents and antimicrobial stewardship program.

2. Materials and methods

2.1. Study design and setting

This single-centre retrospective cohort study was conducted at the Women's and Children's Hospital (WCH) Burn Unit in Adelaide, Australia from January 2011 to December 2023. The WCH Burn Unit serves as a main referral centre for children from birth to 16 years old with burn injuries in South Australia, Northern Territory, and the Western part of New South Wales and Victoria. During the period of 2011–2023 the WCH Burn Unit provided services to an average of 283 burn inpatient admission per year.

2.2. Data extraction

Demographic and clinical data were retrieved from the burns unit database. The medical record was reviewed to complete any missing data where necessary. Patient information was de-identified, and the study received ethics approval from both the local Ethics Review Committee (ID number: 2022/HRE00187) and the Human Research Ethics Committee at the University of South Australia (ID number: 205564). The trends in prevalence of burn wound infections (BWIs) were calculated using clinically suspected patients, while the analysis of risk factors for AMR infection and BSI was performed only on patients with documented culture results.

2.3. Microbiological data acquisition

Records of all bacterial and fungal isolates were retrieved from the medical record. Identified microorganisms were classified as Gram-positive bacteria, Gram-negative bacteria, or fungi. Duplicates of the same causative microorganism culture were excluded if they were identified from the same body location within a 14-day period. This ensured that repeat cultures for the same BWI would be accounted for. However, if different types of microorganisms or the same microorganism with different antimicrobial resistance profiles were isolated, each isolate was included in the analysis [29].

2.4. Definitions

According to the Australian New Zealand Burn Association (ANZBA), a severe burn in a paediatric patient is defined as a burn affecting ≥ 10 % of the TBSA or less if it involves critical areas such as the face, hands, feet or genitalia [30]. Burns are classified into three depths: superficial, partial-thickness and full-thickness burns. In cases of mixed burn depth and pathophysiology, the maximal burn depth was considered. In this study, burn wound infection (BWI) was defined based on the presence of clinical signs (including erythema, swelling or tenderness, purulent discharge, offensive smell, increased pain, or fever) along with a positive microbiological culture from the burn wound [31]. Additionally, polymicrobial infection is defined as isolation of more than one pathogen in a sample.

2.5. Statistical analysis

Data was extracted from the database, cleaned, and analysed using Statistical Package for social Sciences (SPSS), v26.0 software (IBM SPSS statistics, Armonk, NY). Pearson's chi-square analysis and Fisher's exact test were used to compare categorical variables. Continuous variables were described as the mean or median and interquartile range (IQR), with differences assessed using Student *t*-test or Mann-Whitney *U* test. Binary logistic regression models were also applied in the statistical analysis. AMR infection was used as a dependent variable and the following parameters were considered as predictor variables: age, sex, year, TBSA, burn depth, cause of burn, ways of admission, length of stay in the PICU, total length of stay in the hospital, previous medical history,

invasive procedure, co-morbidity, antibiotic use prior/on the time of wound swab collection, skin grafting and dermal substitutes. To integrate independent variables in the multivariate model, the selection criteria was the *p*-value of each variable being less than 0.2 in the bivariate model. For all variables a two tailed *p*-value of ≤ 0.05 was considered to indicate statistical significance.

3. Results

3.1. Demographic and clinical data of paediatric burn patients with AMR pathogen infections

During the study period from January 2011 to December 2023, a total of 3679 paediatric patients with burns were admitted to the WCH Burn Unit. The incidence of clinically suspected BWI requiring treatment was 183 (5 % of overall admitted). The trends in the prevalence of burn wound infection (BWI) across the years from 2011 to 2023 are shown in Supplementary Fig. 1. Of the 183 patients with suspected clinical infection, wound swab samples were not received for 10 (5.4 % of suspected clinical infection) patients, leaving 173 (94.6 %) of patients (4.7 % of overall admitted) who had a documented culture result included for analysis. Of these, 152 (87.9 %) were culture-positive, 126 (72.8 %) tested positive for one or more AMR bacteria and 69 (39.9 %) showed polymicrobial growth. A flowchart summarizing the number of paediatric burn patients admitted during the study period and key microbiological outcomes is depicted in Supplementary Fig. 2. To assess risk factors for multidrug resistance (MDR), defined as resistance to at least one agent in three or more antimicrobial categories [32], the number of patients with MDR isolates was small. Therefore, we classified patients into AMR (resistant to at least one antimicrobial agent) and non-AMR. Table 1 summarises the characteristics of patients infected with AMR pathogen (n = 126) vs. those with the antimicrobial sensitive pathogens and includes the basic demographic data for patient population focused on patients with BWI. Earlier studies focused on comparison between BWI and non-BWI patients however this was not the focus of this study.

BWI with AMR pathogens were significantly younger, with a median age of 2 years, compared to those infected with antimicrobial-sensitive pathogens, who had a median age of 5 years ($p < 0.001$). Additionally, patients infected with AMR pathogens had significantly higher median TBSA burned (5.5 % [IQR 2–12 %]) compared to 2.3 % [IQR 1–4.8 %]; $p < 0.001$). Patients infected with AMR pathogens more frequently required admissions to the PICU (20.6 % vs. 2.1 %), spent a longer time in PICU with an average length of stay of 15.4 days (ranging from 1 to 89 days), underwent more invasive procedures ($p = 0.05$) and had longer overall hospital length of stay (LOS) (25.6 vs. 10.8 days $p < 0.001$). A significantly higher percentage of patients with burns to the upper limbs ($p = 026$), trunk ($p = 0.009$) as well as head and neck ($p = 0.001$) were infected with AMR pathogens compared to those with burns to the lower limbs ($p = 0.036$), where more sensitive pathogens were identified.

Adverse effects on patients with BWI who developed additional infection complications during study period included viral and respiratory tract infections, sepsis, toxic shock syndrome (TSS), urinary tract infections (UTI) and others (Supplementary Fig. 3), and these patients were significantly more likely to be infected with AMR pathogens compared to their counterparts. Furthermore, patients who received dermal substitute were also significantly more likely to be infected with AMR pathogens ($p = 0.032$), with Biobrane being the most commonly used dermal substitute (6.4 %). The types and frequency of dermal substitute usage are summarised in the Supplementary Fig. 4. Although antibiotic use prior to or at the time of initial swabbing, was not significantly associated with AMR infections, a total of 72 patients (41.9 %) received some form of antibiotics. Importantly, antibiotics were used only, if a positive wound culture or clinical infection was detected and not routinely used as prophylaxis. In addition to systemic antibiotics, all patients with BWI received at least one topical antimicrobial dressing, with Acticoat being the most used (92.5 %) as summarised in the Supplementary Fig. 5. Nearly half of patients with BWI (46.2 %) also received skin grafts (Table 1). Of these, only two patients underwent full-thickness skin grafts, while the rest received split-thickness skin graft on multiple sites.

Table 1
Demographic and clinical data of paediatric burn patients infected with AMR pathogens.

	All infected burn patients (n = 173)	AMR positive (n = 126)	Non-AMR (n = 47)	*p*-value
Median age (years)	3 (IQR 1.4–9)	2 (1.3–6)	5 (2–11)	**< 0.001**
Sex (male: female)	95(54.9):78 (41.5)	72(57.1):54 (42.8)	23(48.9):24 (51.1)	0.335
Burn mechanism				
Scald	98 (57)	73(57.9)	25(54.3)	0.582
Contact	37(21.5)	25 (19.8)	12(26.1)	
Flame	26(15.1)	2116.7)	5(10.9)	
Others*	11(6.4 %)	7(5.6)	4(8.7)	
Median TBSA	5(IQR 1.5–9)	5.5 (2–12)	2.3(1–4.8)	**0.001**
Depth of burn**				
Superficial	2(1.2)	1(0.8)	1(2.2)	0.346
Partial thickness	117(71.3)	82(68.9)	35(77.8)	
Full thickness	45(27.4)	36(30.)	9 (20)	
Regions of the body burned				
Upper limb	101(58.4)	80(63.5)	21(44.7)	**0.026**
Lower limb	77(44.5)	50(39.7)	27(57.4)	**0.036**
Trunk	64 (37)	54(42.9)	10(21.3)	**0.009**
Head and neck	80(46.2)	71(56.3)	9(19.1)	**0.001**
Referred from another health institution				
No	90 (52)	64(50.68)	26(55.3)	0.596
Yes	83 (48)	62(49.2)	21(44.7)	
PMHx				
No	125 (72.3)	98(77.8)	27(57.4)	**0.008**
Yes	48(27.7)	28(22.2)	20 (42.6)	
Admission to PICU				
No	146(84.4)	100(79.4)	46(97.9)	**0.003**
Yes	27(15.6)	26(20.6)	1(2.1)	
Mean LOS		25.6 ± 4.2	10.8 ± 1.2	**0.001**
Other infection				
No	105(60.7)	67(53.2)	38(80.9)	**< 0.001**
Yes	68(39.3)	59(46.8)	9(19.1)	
Invasive procedures				
No	138 (79.8)	96(76.2)	42(89.4)	0.055
Yes	35(20.2)	30(23.8)	5(10.6)	
Antibiotic use***				
No	100(58.1)	71(56.8)	29(61.7)	0.561
Yes	72(41.9)	54(43.2)	18(38.3)	
Skin graft				
No	93(53.8)	69(54.8)	24(51.1)	0.664
Yes	80(46.2)	57(45.2)	23(48.9)	
Dermal substitute				
No	150(86.7)	105(83.3)	45(95.7)	**0.032**
Yes	23(13.3)	21(16.7)	2(4.3)	

TBSA, total burn surface area; PICU, paediatric intensive care unit; LOS: length of stay *p-value* was determined by an independent-sample *t*-test, Wilcoxon-rank sum or Chi-squared test where applicable.

* Others: cold (1), friction (5), sun burn (4), thermal (1) and unknown (1).

** 10 patients data missed.

*** Antibiotics used prior to first swab collection or antibiotics they were on when swabbed.

3.2. Common risk factors associated with AMR burn wound infections

Binary logistic regression analysis was carried out to assess the

predictors of AMR infection in paediatric burn patients. Using the univariable analysis various risk factors were found to be strongly associated with AMR burn wound infection. However, the forward conditional multivariable logistic regression analysis revealed only three significant independent risk factors including burns to the neck and head (AOR = 5.2, 95 %CI: 2.20–12.31; $p < 0.001$), admission to the PICU (AOR = 8.2, 95 %CI: 1.03–64.86; $p = 0.047$) and previous medical history (AOR = 2.4, 95 %CI: 1.07–5.55; $p = 0.033$) (Table 2).

3.3. Pathogen distribution in paediatric burn wound infections

In this study, 445 wound swab samples were cultured from 173 infected patients resulting in the recovery of 728 microorganisms (Supplementary Table 1). Of these, 388 non-duplicate isolates were included for calculation of isolation rates and antimicrobial resistance (Table 3). The predominant organisms included *S. aureus* (124/388; 32 %), *P. aeruginosa* (22/388; 5.7 %) and *C. albicans* (6/388; 1.5 %), representing primary Gram-positive bacteria, Gram-negative bacteria, and fungi, respectively (Table 3). Among the 124 *S. aureus* strains identified, 5 % (19/388) were MRSA. Overall, *S. aureus* (124;32 %) was

Table 2
Logistic regression analysis risk factors associated with burn wound infection caused by AMR pathogens.

	Univariable analysis		Multivariable analysis	
	OR (95 %CI)	*p*-value	OR (95 %CI)	*p*-value
Age	**0.91 (0.85–0.98)**	**0.008**		
Sex	1.39 (0.71–2.72)	0.335		
TBSA	**1.12 (1.03–1.21)**	**0.007**		
Depth				
Partial thickness	0.59 (0.25–1.34)	0.207		
Full thickness	1 (reference)			
Mechanism				
Scald	1.67 (0.45–6.18)	0.444		
Contact	1.19 (0.29–4.87)	0.808		
Flam	2.4 (0.50–11.52)	0.274		
Others	1 (reference)			
Regions of the body burned				
Upper limb	**2.15 (1.09–4.25)**	**0.027**		
Lower limb	**0.48 (0.24–0.96)**	**0.038**		
Trunk	**2.77 (1.27–6.07)**	**0.011**		
Head and neck	**5.5 (2.43–12.22)**	**< 0.001**	**5.2 (2.20–12.31)**	**< 0.001**
Refereed from other health institution	1.19 (0.61–2.35)	0.596		
PMHx	0.49 (0.25–1.00)	0.051	**2.4 (1.07–5.55)**	**0.033**
Admissions to PICU	**11.9 (1.58–90.8)**	**0.016**	**8.2 (1.03–64.86)**	**0.047**
LOS	**1.03 (1.00–1.06)**	**0.05**		
Other infections	**3.72 (1.66–8.32)**	**0.001**		
Invasive procedures	2.63 (0.95–7.23)	0.062		
Dermal substitute	**4.5 (1.01–20.00)**	**0.048**		

OR: odds ration; 95 %CI: 95 % confidence interval; TBSA, total burn surface area; * Others: cold (1), friction (5), sun burn (4), thermal (1) and unknown (1); PICU, paediatric intensive care unit; PMHx: previous medical history; LOS: length of stay.

Table 3
Bacterial and fungal isolates recovered from 445 burn wound swab cultures at the WCH Adelaide, Australia from 2011 to 2023.

Variables	Wound swab cultures n = 445 Number of pathogens after removing duplicates (n = 388) (%)
Gram-positive bacteria	**245 (63.1)**
S. aureus	124 (32)
MRSA	19 (5)
S. pyogenes	26 (6.7)
Other *Streptococcus spp*	20 (5.2)
Coagulase negative *Staphylococci*	28 (7.2)
Enterococcus species	17 (4.4)
Micrococcus Luteus	1 (0.3)
Dermabacter hominis	1 (0.3)
Corynebacterium species	1 (0.3)
Bacillus species	4 (1)
Arcanobacterium haemolyticum	2 (0.5)
Aerococcus viridans	1 (0.3)
Diphtheroid	1 (0.3)
Gram-negative bacteria	**126 (32.5)**
P. aeruginosa	22 (5.7)
Other *Pseudomonas spp*	19 (5)
Enterobacter species	21(5.4)
Acinetobacter species	14 (3.6)
Serratia spp	10 (2.6)
Stenotrophomonas maltophilia	11 (2.8)
Chryseobacterium sp.	1 (0.3)
Aeromonas species	1 (0.3)
Citrobacter spp	3 (0.8)
Elizabethkingia species	3 (0.8)
Escherichia coli	3 (0.8)
Haemophilus species	1 (0.3)
Hafnia alvei	1 (0.3)
Klebsiella species	9 (2.3)
Moraxella Catarrhalis	1 (0.3)
Morganella morganii	1 (0.3)
Neisseria spp	2 (0.5)
Proteus spp	3 (0.8)
Fungi	**17 (4.4)**
Candida albicans	6 (1.5)

(*continued on next page*)

Table 3 (*continued*)

Variables	Wound swab cultures n = 445 Number of pathogens after removing duplicates (n = 388) (%)
Candida parapsilosis complex	5 (1.3)
Candida metapsilosis	1 (0.3)
Clavispora lusitaniae	1 (0.3)
Fusarium incarnatum-equiseti complex	1 (0.3)
Lichtheimia corymbifera	1 (0.3)
Dematiaceous hyphomycete	1 (0.3)
Trichosporon asahii	1 (0.3)

the most common pathogen, followed *CoNS* (28; 7.2 %), *S. pyogenes* (26; 6.7 %), *P. aeruginosa* (22; 5.7 %) and *Enterobacter* species (21; 5.4 %) (Table 3**).** This study also highlights the identification of eight different fungal pathogens in 11 (6.4 %) burn patients, emphasizing the significant concern of their coexistence with bacterial pathogens, leading to polymicrobial infections. *C. albicans* was the most frequently isolated fungal pathogen identified, accounting for 1.5 % of the overall pathogens isolated. Moreover, the isolation of *Fusarium incarnatum-equiseti complex* and *Dematiaceous hyphomycete,* raises alarms due to their potential antifungal drug-resistance **(**Table 3**).**

The type of microorganisms identified from paediatric BWIs were associated TBSA, LOS in the hospital and wound healing status [22]. In this study, the median %TBSA of burn in patients with fungal infections (i.e. with at least 3 bacterial isolates) was 27 % (IQR 12.5–37.25 %), and for those with Gram-negative bacterial infection (i.e. with or without Gram-positive isolates), 8.25 % (IQR 2–15.5 %). These values were significantly higher as compared to patients infected with only Gram-positive bacteria, who had a median TBSA of 4 % (IQR

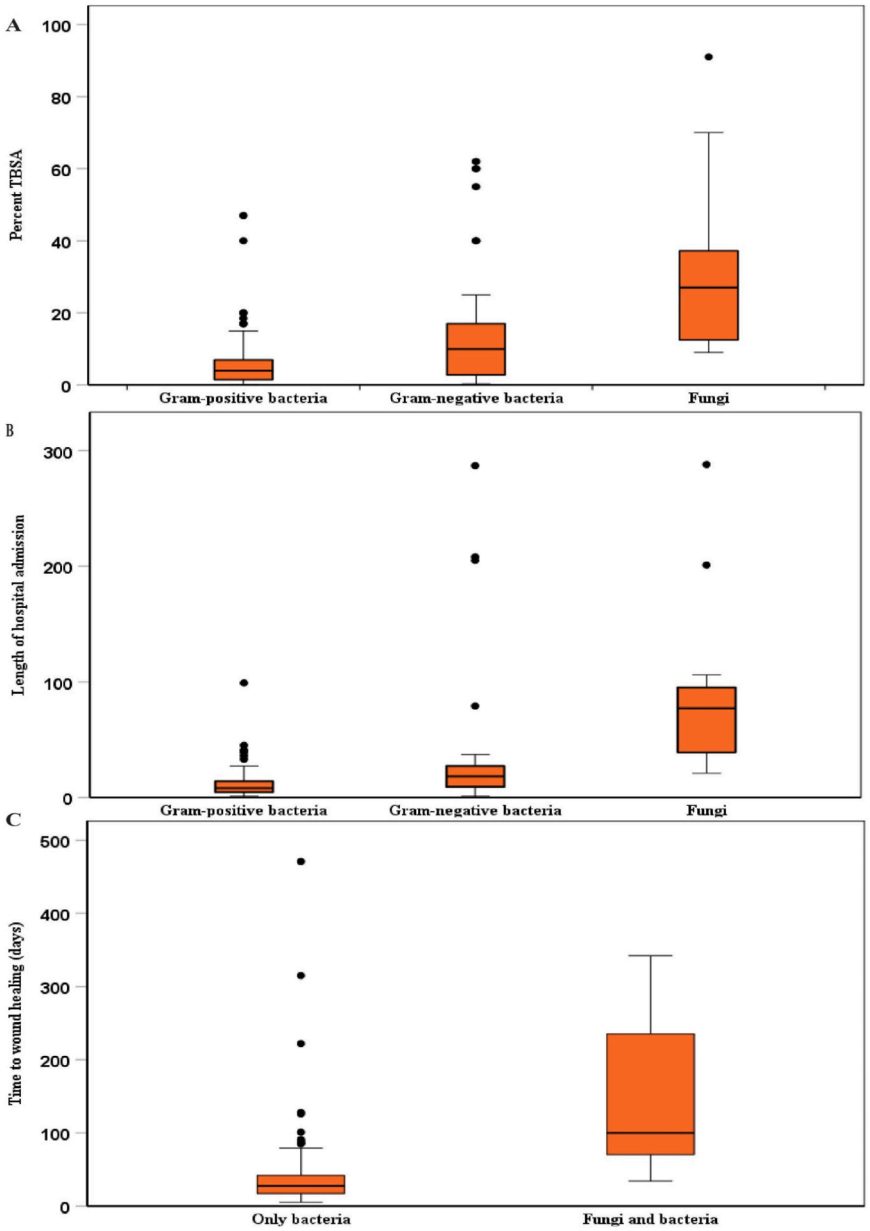

Fig. 1. Box plot chart showing the relation of the type of microorganisms in paediatric burn injuries to (A) the length of stay (LOS) in hospital (B) percent total body surface area burn (%TBSA), and (C) wound healing time.

1.5–7.25 %); p < 0.001). Additionally, patients infected with fungi and Gram-negative bacteria had a significantly prolonged LOS in the hospital 77 days (IQR 39–95 days) and 15.5 days (IQR 8–26 days), respectively, compared to those with only Gram-positive bacterial infections, who had a median LOS of 8 days (IQR 5–15 days); $p < 0.001$). Patients with fungal infections also had longer healing time for burn wounds, with a median of 100 days (IQR 70.5–235.5 days), compared to 27.5 days (IQR 17–42 days) for those who developed only bacterial BWIs ($p < 0.001$), regardless of the type of wound dressing applied (Fig. 1**A–C**).

3.4. Antimicrobial resistance profile

To investigate the antimicrobial resistance profile, a single representative isolate with a distinct resistance pattern was selected from each patient. Among the 201 *S. aureus* isolates collected at different time points and from different body locations, 143 were selected for antimicrobial resistance analysis (Supplementary Table 1). These *S. aureus* isolates showed resistance to ampicillin (100 %), penicillin (91.7 %), and amoxicillin (88.6 %). Every *Staphylococcus* species observed in this study was sensitive to vancomycin. However, 3 (21.4 %) *Enterococcus* species, including 2 *Enterococcus gallinarum* and 1 *Enterococcus casseliflavus*, were found to have vancomycin resistance (VRE).

Nearly all selected *S. pyogenes* isolates 24 (88.5 %) were widely susceptible to antimicrobial agents, with only 3 isolates (11.6 %) exhibiting resistance to erythromycin and 2 (7.6 %) to clindamycin (Table 4). Among the 55 (7.6 %) MRSA isolates, 19 strains from 17 (9.8 %) paediatric patients, including those from two patients which harboured different resistance patterns within the same isolate at different time points, were selected for further resistance analysis. The majority (88.2 %) of MRSA-positive patients were referred from other hospitals. Additionally, one highly virulent *S. aureus* strain that produces Panton-Valentine leucocidin (PVL) (0.7 %), which is associated with severe skin infections and necrotizing pneumoniae [33], was identified (Table 4). Among the *P. aeruginosa* isolates tested, 58.8 % (10/17) were resistant to the third-generation cephalosporin, ceftazidime, followed by 47 % (8/17) resistant to the β-lactamase inhibitor, piperacillin-tazobactam, and 40 % (2/5) resistant to imipenem, a carbapenem antibiotic class that is considered one of the last-resort options (Table 5). Although, *Stenotrophomonas maltophilia* is intrinsically resistant to carbapenems (100 %), it exhibited sensitivity to trimethoprim-sulfamethoxazole (100 %), which remains the current drug of choice for this pathogen (Table 5). All the tested *Enterobacter*, *Acinetobacter* and *Serratia* species were resistant to amoxicillin (100 %) and amoxicillin-clavulanic acid (100 %). Of these, 3 *Enterobacter cloacae* isolates were confirmed as extended -spectrum β-lactamase (ESBL) producers (Tables 4–5). Although there are no internationally recognised interpretive criteria for most fungal pathogens, resistance to 5-fluorocytosine, posaconazole, itraconazole and amphotericin B was reported in *C. albicans* in this study. In addition, the *Fusarium incarnatum-equiseti* complex has shown resistance to itraconazole, fluconazole, voriconazole, posaconazole, while *Dematiaceous hyphomycetes* exhibited resistance to amphotericin B and fluconazole (Tables 4–5).

Table 4
Antimicrobial resistance pattern of gram-positive bacteria from paediatric burns wound infection at WCH, Adelaide, Australia from 2011 to 2023.

Antimicrobials	*S. aureus* (N = 143) n* (% resistant)	CoNS (N = 28) n*(% resistant)	*S. pyogenes* (N = 26) n*(% resistant)	Enterococci spp. (N = 17) n*(% resistant)
Penicillin	121/132 (91.7)	3/3(100)	0/26(0)	0/6 (0)
Cefazolin	11/134 (8.2)	2/3(66.7)	0/21(0)	6/6(100)
Flucloxacillin	12/134 (9.0)	2/3(66.7)	0/1(0)	
Clindamycin	25/139 (18)	0/1(0)	2/26(7.6)	0/1(0)
Erythromycin	14/76 (18.4)	1/1(100)	3/26(11.6)	
Ampicillin	53/53 (100)	1/1(100)	0/1(0)	1/10 (10)
Amoxicillin	39/44 (88.6)	½ (50)	0/10 (0)	2/12(16.7)
AMC	3/45 (6.7)	1/1(100)	0/8 (0)	½ (50)
SXT	3/19 (15.8)	1/1(100)	ND	0/1(0)
Roxithromycin	5/32 (15.6)	1/1(100)	1/8(12.5)	ND
Vancomycin	0/17 (0)	0/1(0)	0/1(0)	3/14(21.4)

N: total number of *S. aureus* selected for antimicrobial susceptibility study, n: total number of *S. aureus* resistant to the tested antibiotic divided by total tested, PEN: penicillin, CZO: cefazolin, FLU, flucloxacillin, CLI: clindamycin ERY: erythromycin, AMP: ampicillin, AMO: amoxicillin, AMC: amoxicillin-clavulanic acid, SXT: trimethoprim-sulfamethoxazole, ROX: roxithromycin, VAN: vancomycin, * 2VRE *Enterococcus gallinarum* and 1 *Enterococcus casseliflavus*. *CONS*: Coagulase negative staphylococci, Spp: Species, ND: not done.

3.5. Characteristics of paediatric patients who develop a BSI

Among paediatric patients with burns admitted to the burn unit between 2011 and 2023, 0.4 % (15/3679) developed BSIs, which accounts for 8.7 % (15/173) of the patients with BWI. Compared to patients without BSI these patients had a significantly higher median TBSA (34.5 %) and are more likely to have sustained a flame burn (26.9 %). Additionally, patients who developed a BSI were more frequently admitted to the PICU (33.3 %) and required a central venous catheter (CVC) (31.4 %), endotracheal tube (ETT) (53.8 %), mechanical ventilation (53.8 %), arterial catheter (61.5 %) or total parenteral nutrition (TPN) (75 %) support. Previous medical history and other infection complications have been associated with BSI in 9.3 % and 19.1 % of patients, respectively (Table 6). Moreover, patients who developed BSI had a significantly prolonged admission (number of days) in PICU and experienced a longer duration of hospitalisation overall, with a median stay of 36 days (Supplementary Fig. 6–7). The type of microorganisms isolated from patients who developed BSI are summarised in the Supplementary Table 2.

4. Discussion

The main findings of this study on paediatric patients with burns include microbiologically confirmed burn wound infections (BWIs) identified in 4.1 % of overall admitted patients throughout the study period (2011–2023), with no significant change in annual incidence. Among patients who had a documented culture result, 72.8 % were positive for at least one AMR pathogen, 9.8 % exhibited MRSA positivity, 39.9 % showed polymicrobial growth (6.4 % of which co-existed with fungi) and 8.7 % developed BSIs. Burn to the head and neck, previous medical history and admission to PICU were identified as key independent predictors of AMR burn wound infection. Gram-positive bacteria followed by Gram-negative bacteria and fungi were the most common pathogens. Fungal pathogens were shown to co-exist with bacteria and were associated with severe burn injuries (≥ 10 % TBSA), prolonged hospital stays and delayed wound healing. While infection prevention guidelines (including routine MRSA screening upon admission and weekly thereafter), cleaning protocols, strict hand hygiene (for both staff and visitors), the use of appropriate personal protective equipment and isolation measures in positive pressure rooms for patients with multidrug-resistant infections have been implemented in local WCH Burn Unit, an active and consistent antimicrobial stewardship program remains essential to protect this vulnerable population from the acquisition of AMR pathogens [25,31]. Moreover, if AMR is suspected, close clinical monitoring with early infectious disease support is crucial.

In the present study, no mortality was documented during the study period even with patients who had a TBSA of 91 %. This finding was supported by a previous study in the same hospital reporting the declining trend of mortality among paediatric patients between 1960 and 2017 [34]. Although several studies have indicated a declining trend in mortality [35,36], a prolonged LOS in the hospital increases the risk of acquiring AMR Gram-negative bacteria and fungi, primarily due

Table 5
Antimicrobial resistance pattern of gram-negative bacteria from paediatric burns wound infection at WCH, Adelaide, Australia from 2011 to 2023.

Bacteria	Isolates (n) resistance to antimicrobial agents												
	CZO (45)	**AMP** (39)	**AMO (49)**	**AMC (55)**	**PIT (51)**	**CIP (72)**	**GEN (100)**	**CZA (56)**	**CRO (49)**	**SXT** (22)	**FEP** (20)	**IMP** (11)	**MER (53)**
P. aeruginosa (22)	ND	ND	ND	ND	17	11	17	17	ND	ND	11	5	7
Resistance					8	0	0	10			2	2	0
Resistance (%)					47			58.8			18.2	40	
Enterobacter spp (21)	18	17	19	19	5	16	20	1	19	2	1	ND	13
Resistance	18	17	19	19	2	2	3	0	15	0	0		0
Resistance %	100	100	100	100	40	11.8	15	0	78.9	0	0		0
Acinetobacter spp (14)	5	6	5	7	5	9	17	7	4	4	4	3	12
Resistance	4	5	5	7	0	0	1	1	100	0	0	0	0
Resistance %	80	83.3	100	100	0	0	7.7	14.3	100	0	0	0	0
Stenotrophomonas maltophilia (11)	ND	ND	ND	ND	1	ND	2	9		10	ND	ND	2
Resistance					1		2	2		0			2
Resistance %					100		100	22.2		0			100
Serratia spp (10)	9	ND	8	8	ND	8	8	ND	8	1	ND	ND	8
Resistance	9		8	8		3	0		2	0			0
Resistance %	100		100	100			0			0			0
Klebsiella spp (9)	5	6	7	7	3	5	7	ND	6	ND	ND	ND	1
Resistance	0	6	7	0	0	0	0		0				0
Resistance %	0	100	100	0	0	0	0		0				0

*CZO: cefazolin, AMP: ampicillin, AMO: amoxicillin, AMC: amoxicillin-clavulanic acid, PIT: Piperacillin/Tazobactam, CIP: Ciprofloxacin, GEN: Gentamicin, CZA: Ceftazidime-avibactam, CRO: Ceftriaxone, SXT: trimethoprim-sulfamethoxazole, FEP: Cefepime, IMP: Imipenem, MER: Meropenem. ND: not done.

Table 6
Characteristics of blood stream infections among burn paediatric patients.

	Blood stream infections (BSIs)		
Risk factors	**Negative n (%)**	**Positive n = 15 (8.7 %)**	***p-value***
Median age (years)	3 (IQR 1.5–9)	2(1.2–4.5)	0.193
Sex			
Female	74(94.9)	4(5.1)	0.134
Male	84(88.4)	11(11.6)	
Median TBSA	4(IQR 1.5–9)	34.5 (9–60)	**< 0.001**
Depth of burn **			0.086
Partial thickness	109(93.2)	8(6.8)	
Full thickness	38(84.4)	7(15.6)	
Burn mechanisms			
Scald	91 (92)	7(7.1)	**0.002**
Contact	37(100)	0	
Flame	19(73.1)	7(26.9)	
Others*	10(90.9)	1(9.1)	
PICU admission			
No	140(95.9)	6(4.1)	**< 0.001**
Yes	18(66.7)	9(33.3)	
PMHx	49(90.7)	5(9.3)	0.853
Other infections	55(80.9)	13(19.1)	**< 0.001**
Invasive procedures			**< 0.001**
CVC	24 (68.6)	11 (31.4)	
ETT	6 (46.2)	7 (53.8)	
Ventilation	6 (46.2)	7 (53.8)	
Arterial catheter	5 (38.5)	8 (61.5)	
TPN	1 (25)	3 (75)	

TBSA: total burn surface area, IQR: inter quartile range, Others: cold (1), friction (5), sun burn(4), thermal (1) and unknown (1)**: 10 missed data and 2 superficial burn; PICU, paediatric intensive care unit; LOS: length of stay; CVC: central venous catheter, ETT: endotracheal tubes, TPN: total parenteral nutrition; *p-value* was determined by an independent-sample *t*-test, Wilcoxon-rank sum or Chi-squared test where applicable.

to the use of invasive devices [14,22,37]. This was also observed in the present study, where prolonged LOS was significantly associated with Gram-negative bacterial infections (median of 15.5 days) and fungal infections (median of 77 days). These findings are also consistent with a recent retrospective study from Istanbul, Turkey which reported a similar observation [38]. Furthermore, patients co-infected with fungal infections experienced delayed wound healing compared to those with BWIs caused by bacteria alone. These findings are concerning, as resistance to the most common fungal isolates including *C. albicans*, *Fusarium incarnatum-equiseti complex and Dematiaceous hyphomycete* was documented in our study. Similarly, recent studies have shown the emergence of resistant fungal infections among burn patients [39]. Moreover, additional studies have also highlighted the predominance of MDR Gram-negative bacteria and fungi, particularly *Candida* species that are the common cause of fungal BSI [38,40]. These trends suggest that antimicrobial stewardship, particularly with regard to fungicidal agents, may be an increasingly important focus for burn units.

In this study, 8.7 % of paediatric patients with BWI developed a BSI, representing 0.4 % of the total patients admitted during the study period. This rate is considerably lower than a recent retrospective study using data from the Australia and New Zealand burns registry (BRANZ) for the years 2016–2021, which reported a BSI prevalence of 4.7 % in the paediatric burn patients. A study conducted on South African paediatric burn patients reported an even higher prevalence of BSIs (18.7 %) [41]. Previous studies have shown that BSIs in paediatric burn patients result from an accumulation of various associated risk factors, including increased TBSA burns, flame burns and other infection-related complications. These factors are linked to systemic immune dysfunction and an increased risk of hospital-acquired infections [9, 17]. Although the low number of patients with BSI limits the ability to draw statistical inferences about the independent predictors of BSIs, this study found that significantly higher number of patients who developed a BSI were using central venous catheters, endotracheal tubes, mechanical ventilation, arterial catheters or total parenteral nutrition support. All of these factors significantly increase patients' potential exposure to AMR pathogens, which contribute to prolonged stays in the PICU, and an overall extended length of hospital stay, placing a significant burden on both the patient and the healthcare system. This aligns with our study, where admissions to the PICU, a history of previous medical conditions, and burns to the head and neck were found to be key independent risk factors for AMR burn wound infection development. These factors could be linked to the use of invasive devices in the PICU and reduced immune status of the patients due to comorbidity and proximity of MRSA nasal carriage to the site of head and neck burn injuries [42]. Moreover, the overall increase AMR infections may be related to the large catchment area of the study setting, which can contribute to transfer delays.

A retrospective analysis of the microbial profile among the paediatric patients with BWI revealed that Gram-positive bacteria are the predominant pathogen, followed by Gram-negative bacteria and fungi [14]. Common pathogens identified include *S. aureus,* CoNS, *S. pyogenes, P. aeruginosa*, *Enterobacter species*, MRSA and *Enterococcus species*. The

incidence of *S. aureus* among burn wound infections is high (32 %) which is comparable with other studies in USA (25 %) [16]. Previous studies in Australia have primarily focused on MRSA isolates [17,19], however, a recent molecular epidemiological study in China has shown that methicillin-sensitive *S. aureus* (MSSA) isolates are as equally important as MRSA isolates [40]. The study reported that MSSA are genetically diverse with several sequence type stains being linked to burn patients. Additionally, these strains have been shown to be highly virulent with most strains carrying the PVL gene and having the ability to form biofilms. Therefore, future research should consider molecular characterisation of all *S. aureus* strains in Australia.

This study highlights the persistent challenge of managing MRSA infections in the Burn Units despite the implementation of strict screening and standard-of-care practices as evident in the WCH Burn Unit. Among patients whose culture results were documented, 9.8 % exhibited an MRSA positive strain. This finding aligns with a previous BRANZ retrospective study, which reported a 12.1 % BSI rate in paediatric burn patients [17]. However, this figure is lower than the 16 % prevalence seen in a recent study conducted in Sydney, Australia, among the general burn population [19]. A notable observation in the present study is that most of the burn patients (82.4 %) who were infected with MRSA had been referred from other healthcare institutions. This suggests that MRSA might be spreading between facilities or is acquired from the community, potentially indicating challenges in the initial management of these infections or a lack of effective containment measures at referring institutions. The findings underscore the ongoing difficulty in controlling MRSA transmission and infection in burn patients, emphasizing the need for early diagnosis upon admission and perhaps the need for enhanced infection prevention strategies within and across healthcare systems to effectively manage MRSA infection in the burn care settings.

A recent study on the epidemiological profile of hospitalized paediatric burn patients reported that rural residency was a significant risk factor for infection with *Streptococcus* species. Particularly, First Nation (Aboriginal and Torres Strait Islander) children had four times higher odds of developing *Streptococcus* infections compared to other Australian children [13]. In this study, *Streptococcus* species were the second most common isolate, with more than half of *Streptococcus* isolates being identified as *S. pyogenes,* a major cause of graft failure and systemic infection in burn patients [43]. This demographic data was outside the scope of this study; however, the catchment of our burn's unit includes many indigenous communities and could explain the higher incidence of *Streptococcus* species in this study. Although all the *S. pyogenes* strains exhibited sensitivity to the first-line antibiotic penicillin [44], resistance to alternative antibiotics for patients who are allergic to β-lactams including erythromycin and clindamycin were also observed. This is concerning, as previous studies have shown a growing relationship between virulence and macrolide resistance in *S. pyogenes* [45]. A recent study conducted in the Northern Territory, Australia, has reported an increasing trend of clindamycin and erythromycin resistance in *Group A Streptococcus* among rural residents [46]. Although CoNS are normal component of the skin flora and is generally considered a low-virulence organism, recent studies have reported the evolution of CoNS from commensal organisms into invasive, resistant pathogens due to increased application of invasive surgical procedures[47]. This pathogen has been associated with significant complications, including BSIs in burn patients. In this study, CoNS-associated BSIs were identified in three patients.

Nevertheless, this study has several limitations which need to be considered when interpreting this data. Although the WCH hospital is the main paediatric referral Burn Unit in South Australia, the results are generated using data from a single hospital; therefore, extrapolation to other hospital Burn Units is limited. Key burns unit concerns, for example graft failure rate, the effect on LOS, degree of scarring or burns contracture, was beyond the scope of this study but would provide insight into the material consequences of BWI. Therefore, this paper demonstrates the need for further prospective study investigating the association between inadequate perioperative prophylactic antibiotic cover against early Gram-negative colonisers and complication rates in paediatric burn patients across multiple hospital sites.

5. Conclusion

Despite a high proportion of paediatric burn patients developing AMR polymicrobial infections, which impede wound healing and contribute to other infection complications including BSI, no mortality was recorded during the study period. Early identification and treatment of BWIs by closely monitoring patients with previous medical history, burns to the head and neck, those referred from other healthcare institutions, and those admitted to the PICU may help improve care for paediatric burn patients. Proactive antimicrobial stewardship should be implemented to empirically target the most likely pathogens based on up-to-date, locally relevant microbiological data as suggested by this study. Timely consultation with a multidisciplinary team, particularly for final cultures and unusual pathogens (e.g. fungal infection) is crucial. Further research is needed to assess the clinical effect of BWIs and their treatments on the short- and long-term complications of paediatric burns.

Abbreviations

AMR: antimicrobial resistance, BRANZ: Australia and New Zealand burns registry, BSI: blood stream infection, BWI: burn wound infection, CoNS: Coagulase negative *staphylococcus*, LOS: length of stay, MRSA: methicillin resistant *Staphylococcus aureus*, PICU: paediatric intensive care unit, TBSA: total body surface area

Author contributions

All authors have made substantial contributions to the manuscript and have approved the final version to be submitted. Anteneh A contributed to the study design, data analysis and interpretation and drafting of the manuscript. Anton A and SH made significant contributions to data collection. AM assisted in ethics acquisition, study protocol design and manuscript editing, Anna A assisted in manuscript drafting. LQ and BC provided clinical interpretation. ZK conceptualized and designed the study. All authors participated in the manuscript preparation and critical revisions.

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Declaration of Competing Interest

All authors declared no conflict of interest.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.burns.2025.107584.

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