A 10 year surveillance for antimicrobial susceptibility of *Escherichia coli* and *Klebsiella pneumoniae* in community- and hospital-associated intra-abdominal infections in China

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Abbreviations: ATCC, American Type Culture Collection; CA, community-associated; CLSI, Clinical and Laboratory Standards Institute; ESBL, extended-spectrum beta-lactamase; HA, hospital-associated; IAI, intra-abdominal infection; MIC, minimal inhibitory concentration; QC, quality control; SMART, The Study for Monitoring Antimicrobial Resistance Trends.
INTRODUCTION

A number of surveillance programmes exist to monitor the susceptibility of clinically important pathogens on a national or international scale. The Study for Monitoring Antimicrobial Resistance Trends (SMART) is a global surveillance programme initiated in 2002 and designed to monitor the susceptibility of aerobic and facultative Gram-negative bacilli isolated from patients with intra-abdominal infections (IAIs). E. coli and K. pneumoniae are the most common pathogens causing community-associated (CA) and hospital-associated (HA) IAIs. Although there have been other reports from the SMART programme describing susceptibility levels observed globally (Baquero et al., 2009; Hawser et al., 2009a; Hoban et al., 2010; Ko & Hseuh, 2009; Rossi et al., 2006), this report is the first to provide an overview specifically of the antimicrobial susceptibility of CA and HA E. coli and K. pneumoniae in China from 2002 to 2011.

METHODS

Clinical isolates. Over the study period (2002–2011), a total of 3074 E. coli and 1025 K. pneumoniae were isolated consecutively from IAIs from 23 centres located in 16 cities (Beijing, Shanghai, Hangzhou, Wuhan, Guangzhou, Chongqing, Changchun, Changsha, Harbin, Haikou, Jinan, Nanchang, Nanjing, Shenyang, Tianjin and Zhengzhou) in China. Isolates were cultured from intra-abdominal body sites. The majority of intra-abdominal specimens were obtained during surgery, though some paracentesis specimens were also accepted. By protocol, duplicate isolates (the same genus and species from the same patient) were excluded. Isolates obtained from abdominal drains or drainage bottles, stool, superficial wounds, blood, urine, or perirectal abscesses were excluded. Bacteria were identified by standard methods used in the participating clinical microbiology laboratories. All organisms were deemed clinically significant by local participant criteria. Isolates were considered to be CA if they were recovered from a specimen taken less than 48 h after the patient was admitted to the hospital, or HA if the specimen was taken 48 or more hours after hospital admission, as described previously (Hawser et al., 2009b).

Antimicrobial susceptibility test method. Minimum inhibitory concentrations (MICs) were determined using custom dehydrated MicroScan broth microdilution (Siemens Medical Solutions Diagnostics) by following Clinical and Laboratory Standards Institute (CLSI) guidelines (CLSI, 2012). Susceptibility interpretations were based on CLSI clinical breakpoints (CLSI, 2013). Twelve antimicrobial agents commonly used to treat IAIs were tested although some of them were not tested over the whole study period because of the changes in protocols, which included cefotaxime (2005–2011), ampicillin-sulbactam (2002, 2005–2011) and levofloxacin (2003–2011). Reference strains E. coli ATCC (American Type Culture Collection) 25922, Pseudomonas aeruginosa ATCC 27853 and K. pneumoniae ATCC 700603 (positive ESBL control) were used as quality control (QC) strains for each batch of MIC tests. Results were included in the analysis only when corresponding QC isolates tested within the acceptable range according to CLSI guidelines.

Extended-spectrum β-lactamases (ESBLs) detection. Phenotypic identification of ESBL production among E. coli and K. pneumoniae was detected by the method recommended by CLSI (CLSI, 2013). If the ceftaxime or ceftazidime MIC was ≥2 µg ml⁻¹, then the MIC of cefotaxime or ceftazidime was compared to the MIC of cefotaxime + clavulanic acid (4 µg ml⁻¹) or ceftazidime + clavulanic acid (4 µg ml⁻¹). A positive test for ESBL production was defined as a ≥eightfold (i.e. three doubling dilution) decrease in the MIC for cefotaxime or ceftazidime when tested in combination with clavulanic acid versus their MICs when either drug was tested alone.

Statistical analysis. The study period (2002–2011) was segmented into five 2-year periods. Statistical methods were used to compare the susceptibility rates of CA and HA isolates to different antimicrobial...
agents. Fisher’s exact test (two tailed) and the Pearson chi-squared test (two tailed) were used to determine significance. A $P$-value of $<0.05$ was considered to represent statistical significance.

**RESULTS**

**In vitro susceptibility of HA and CA E. coli isolates**

Against HA E. coli isolates from IAI s, ertapenem, imipenem, amikacin and piperacillin-tazobactam retained the highest and most stable activity, with susceptibility rates of 94.9–98.7 %, 98.6–100 %, 87.6–93.1 % and 89.3–92.2 %, respectively. Cefoxitin showed moderate activity against this species and showed little difference in susceptibility rates among years (69.2–76.2 %). For the third- and fourth-generation cephalosporins, dramatic decreases were found in the susceptibility rates, with susceptibility rates of most of the tested cephalosporins decreasing by 20 % during the 10 year study period (cefepine: from 55.1 % in 2002–2003 to 34.7 % in 2010–2011; ceftazidime: from 77.5 % to 54.3 %; ceftiraxone: from 48.6 % to 26.7 %; cefotaxime was not tested in 2002–2004, however, the susceptibility rate was only 26.9 % in 2010–2011). Two tested fluoroquinolones (ciprofloxacin 2002–2011, levofloxacin 2005–2011) exhibited stable but low activity, with susceptibility rates of 20.4–30.4 % during the 10 years. Ampicillin-sulbactam was the least active antimicrobial agent against E. coli isolates.

Against CA E. coli isolates, ertapenem, imipenem, amikacin and piperacillin-tazobactam also retained the highest and most stable activity, and the susceptibility rates of these four antimicrobial agents showed no significant differences when compared to those of HA E. coli isolates except for some occasional study periods (Table 1). The susceptibility rates of CA isolates to other antimicrobial agents were mostly higher than those of HA isolates ($P<0.05$). Cefoxitin susceptibility rates were 73.9–89.6 %. The susceptibility rates of CA isolates to the cephalosporins exhibited greater decreases than those of HA isolates during the 10 year study period (cefepine: from 85.5 % in 2002–2003 to 46.1 % in 2010–2011; ceftazidime: from 92.4 % to 63.9 %; ceftiraxone: from 80.9 % to 37.1 %; cefotaxime was not tested in 2002, however, the susceptibility rate was 36.5 % in 2010–2011).

**In vitro susceptibility of HA and CA K. pneumoniae isolates**

Against HA K. pneumoniae isolates from IAI s, ertapenem, imipenem, amikacin and piperacillin-tazobactam retained the highest and most stable activity, with susceptibility rates of 90.1–96.5 %, 94.2–100 %, 81.0–94.4 % and 75.0–89.0 %, respectively. Cefoxitin susceptibility rates were 68.0–81.3 %. For the third- and fourth-generation cephalosporins, the susceptibility rates ranged from 43.8 % to 75.4 % (cefepine, 52.1–71.9 %; ceftazidime, 64.5–75.4 %; cefotaxime, 44.4–59.8 % and ceftriaxone, 43.8–64.9 %), while only the isolates from 2004–2005 had relatively lower susceptibility. Ciprofloxacin and levofloxacin showed stable and higher activity against K. pneumoniae than against E. coli, with susceptibility rates of 59.5–75.0 % during the 10 years. Ampicillin-sulbactam was the least active antimicrobial agent against K. pneumoniae isolates.

Against CA K. pneumoniae isolates, ertapenem, imipenem, amikacin and piperacillin-tazobactam also retained the highest and most stable activity. Cefoxitin susceptibility rates were 77.0–92.7 %. Ciprofloxacin and levofloxacin showed moderate activity with susceptibility rates of 62.2–83.7 % and 70.3–90.7 %, respectively. During most of the study period (except 2006–2007), the susceptibility rates of CA K. pneumoniae isolates to ertapenem, imipenem, amikacin, piperacillin-tazobactam, cefoxitin, ciprofloxacin and levofloxacin showed no significant differences compared to those of HA K. pneumoniae ($P>0.05$) (Table 1). In contrast, the susceptibility rates of CA isolates to cephalosporins and ampicillin-sulbactam were always higher than those of HA isolates during most of the periods ($P<0.05$).

**ESBL production in HA and CA E. coli and K. pneumoniae**

During the 10 year study period, the ESBL-positive rates for E. coli from IAI s nearly doubled from 36.1 % in 2002–2003 to 68.1 % in 2010–2011 ($P<0.001$). While the ESBL-positive rates increased from 52.2 % in 2002–2003 to 70.0 % in 2010–2011 in HA isolates ($P=0.001$), and rates among CA isolates more than tripled from 19.1 % in 2002–2003 to 61.6 % in 2010–2011 in CA isolates ($P<0.001$) (Fig. 1). Trends in ESBL prevalence in K. pneumoniae were quite different from E. coli. The ESBL-positive rate remained at 30.1–39.3 % of the total isolates during the 10 years with no significant difference. Even though there was some fluctuation in the ESBL rates during the periods for HA and CA isolates, differences were not statistically significant (Fig. 2).

**DISCUSSION**

IAIs are commonly encountered in clinical practice. These infections include a variety of conditions including peritonitis, appendicitis, intra-abdominal abscesses, and intra-hepatic infection (Guembe et al., 2008). Although many species of pathogens are known to cause IAI s, E. coli and K. pneumoniae have been reported to be the most common causative agents (Nicoletti et al., 2009). Thus, the development of antibiotic resistance among these two species, especially strains that produce ESBL, severely limits the choices of appropriate empirical antibiotics. ESBLs have been widely reported among HA Enterobacteriaceae. However, some recent studies showed that this resistance determinant has also been found in CA isolates (Dias et al., 2012; Park et al., 2012). Because E. coli and K. pneumoniae
Table 1. Susceptibility rates of E. coli and K. pneumoniae isolates from IAIs by isolate source (HA versus CA) in 2002–2011 in China

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<td>72.0</td>
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ND, Not determined.  
P-values <0.05 are shown in bold.
comprise the major aerobic and facultative anaerobic pathogens associated with IAIs, knowledge of their resistance patterns and ESBL prevalence in HA and CA settings is critical.

ESBL production is the predominant resistance determinant of *E. coli* and *K. pneumoniae* to cephalosporins. In this study, the susceptibility rates of HA *E. coli* strains to all tested third- and fourth-generation cephalosporins declined by more than 20% over the 10 year study period, with susceptibility of 26.7%, 26.9%, 54.3% and 34.7% for ceftriaxone, cefotaxime, ceftazidime and cefepime, respectively, in 2010–2011. Against CA *E. coli*, the susceptibility to cephalosporins decreased even more severely, with drops of 28.5–43.8% in susceptibility rates during the 10 years. These results indicate that the third- and fourth-generation cephalosporins should no longer be considered first line choices for the empirical therapy of IAIs in China, even for CA settings. We also found that no statistically significant

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**Fig. 1.** Occurrence of ESBL-producing *E. coli* (%) in 2002–2011 from IAIs in China. ESBL rate (%) is compared by using Fisher’s exact test (two tailed).

**Fig. 2.** Occurrence of ESBL-producing *K. pneumoniae* (%) in 2002–2011 from IAIs in China. ESBL rate (%) is compared by using Fisher’s exact test (two tailed).
difference was seen for the ESBL rates in HA *E. coli* during the years after 2003 (*P*>0.05), which indicates that ESBL prevalence in HA *E. coli* remained stable during the years 2004–2011 (64.7–70.0%). However, the significant differences in the ESBL rates among CA *E. coli* during the study period indicate fast-growing ESBL prevalence (19.1% in 2002–2003 to 61.6% in 2010–2011, an increase of over 300%). We believe that the cephalosporin resistance development in *E. coli* overall during the years 2004–2011 was driven largely by the fast-growing ESBL prevalence in CA isolates. In contrast, the susceptibility of *K. pneumoniae* to cephalosporins was stable with no significant differences during the 10 years. In 2010–2011, the susceptibility of HA and CA *K. pneumoniae* to cefepime, ceftazidime, cefotaxime and ceftriaxone were 69.7% (HA) and 81.9% (CA), 75.1% (HA) and 88.9% (CA), 59.8% (HA) and 80.6% (CA) and 58.7% (HA) and 76.4% (CA), respectively. The relatively stable susceptibility can be explained by the mostly unchanged and relatively lower ESBL rates (compared with that of *E. coli*) among HA and CA *K. pneumoniae* (HA was 36.8% in 2002–2003 to 39.4% in 2010–2011; CA was 23.2% in 2002–2003 and 22.2% in 2010–2011). We also observed some fluctuation of ESBL rates in *K. pneumoniae* and susceptibility to some antimicrobial agents in some time periods, which may have resulted from the somewhat limited number of isolates in early stages of this study. Researchers in China have previously determined that the ESBL genotypes in Beijing, Guangdong and Hangzhou were mainly CTX-M types (Chanawong et al., 2002; Wang et al., 2003), which preferentially hydrolyse cefotaxime and ceftriaxone over ceftazidime. This may explain why ceftazidime always showed the highest susceptibility rates among cephalosporins against ESBL-producing *E. coli* and *K. pneumoniae*. We also noticed a decline of ceftazidime activity against ESBL-producing *E. coli* and *K. pneumoniae*. This may have resulted from increases in both ESBL prevalence and other *β*-lactamase types among the two species, especially SHV-type ESBLs and AmpC cephalosporinases.

Fluoroquinolone-resistant *E. coli* is a very big problem in China. The susceptibility to ciprofloxacin of HA *E. coli* decreased from 29.7% in 2002–2003 to 26.6% in 2010–2011 (*P*<0.075), and from 56.5% in 2002–2003 to 32.6% in 2010–2011 against CA strains (*P*<0.001). Wang et al. (2001) found that ciprofloxacin-resistant *E. coli* had multiple substitutions in the gyrA and parC genes. In light of the poor activity of fluoroquinolones against *E. coli*, ciprofloxacin and levofloxacin should not remain first line choices for empirical therapy of complicated IAIIs. We also found that susceptibility to ciprofloxacin among ESBL-producing *E. coli* and *K. pneumoniae* was significantly lower than that of ESBL-non-producing isolates, as has been reported by other investigators (Ben-Ami et al., 2009). Ben-Ami et al. (2009) and Pitout et al. (2005) reported that isolates producing CTX-M-type ESBLs were significantly more resistant to fluoroquinolones than the isolates producing other types of ESBLs. This may partly explain the dramatic development of resistance to fluoroquinolones among CA *E. coli*, given the fast-growing CTX-M type ESBL prevalence in CA *E. coli* reported in China (Sun et al., 2010; Tian et al., 2011).

Carbapenems have always been considered a good treatment option for severe infections and the empiric therapy alternative of choice for infections with high suspicion of being caused by ESBL-producing or AmpC derepressed *Enterobacteriaceae* (Essack, 2000; Livermore et al., 2001; Paterson, 2000). In this study, carbapenems, including ertapenem and imipenem, demonstrated high and stable activity against *E. coli* and *K. pneumoniae* isolates, regardless of ESBL production and isolate background (HA or CA). However, carbapenem-resistant *Enterobacteriaceae* have emerged. Based upon our analysis of the resistance mechanisms of ertapenem-non-susceptible isolates, nearly one-third of isolates produced carbapenemases (mainly KPC-2 and IMP-4), while two-thirds of isolates showed resistance due to loss of porins (OmpK35/36 for *K. pneumoniae* and OmpF/C for other *Enterobacteriaceae*) combined with hyper-production of ESBLs or AmpC (data not shown).

In conclusion, the SMART programme is a specific resistance surveillance study focused on IAIIs. During 2002–2011, the carbapenems retained the highest activity against both HA and CA *E. coli* and *K. pneumoniae*, followed by amikacin and piperacillin-tazobactam. ESBL-positive rates showed stable and high prevalence in HA *E. coli* and a dramatic increase in CA *E. coli* during the past 10 years, which complicates the treatment of IAIIs in both HA and CA settings. Dramatic decreases in the susceptibility to cephalosporins and fluoroquinolones suggest that those drugs are no longer suitable as first line choices for empirical therapy of IAIIs in China.

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Susceptibility of E. coli and K. pneumoniae in IAIs


