Linezolid vs Glycopeptide Antibiotics for the Treatment of Suspected Methicillin-Resistant \textit{Staphylococcus aureus} Nosocomial Pneumonia: A Meta-analysis of Randomized Controlled Trials

Allan J. Walkey, Max R. O'Donnell and Renda Soylemez Wiener

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Methicillin-resistant *Staphylococcus aureus* (MRSA) represents the most common pathogen associated with nosocomial pneumonia and is an increasing cause of severe community-acquired pneumonia. MRSA pneumonia is associated with increased morbidity and use of health-care resources compared with methicillin-sensitive *S aureus* (MSSA) strains. Although glycopeptide antibiotics (eg, vancomycin and teicoplanin) have long been the standard treatment of MRSA pneumonia, recent American Thoracic Society/Infectious Disease Society of America guidelines have suggested that the oxazolidinone antibiotic linezolid (Zyvox) may be preferred over glycopeptides for MRSA pneumonia. This recommendation is based on a post hoc analysis of data from a randomized controlled trial that demonstrated a survival advantage in the subgroup of subjects with documented MRSA nosocomial pneumonia treated with linezolid compared with those treated with vancomycin. This retrospective analysis has been criticized on methodologic and statistical grounds.

In light of this controversy, further investigation of the comparative efficacy of linezolid is important.
especially given the approximately tenfold increase in cost per dose\textsuperscript{12} and increased risk of thrombocytopenia\textsuperscript{13,14} for linezolid compared with vancomycin. Two recent meta-analyses have demonstrated superior efficacy for linezolid in the treatment of skin and soft tissue infections.\textsuperscript{13,14} However, neither of these reviews focused specifically on pneumonia, resulting in the omission of relevant studies as well as important pneumonia-specific mortality, adverse events, and MRSA subgroup analyses. The purpose of this systematic review and meta-analysis was to investigate the efficacy and adverse event profile of linezolid compared with glycopeptide antibiotics in nosocomial pneumonia.

**Materials and Methods**

**Data Sources**

A "highly sensitive search method"\textsuperscript{15,16} was used to search MEDLINE and the Cochrane Central Register of Controlled Trials (CENTRAL). The highly sensitive search strategy is a previously validated search method, with a reported sensitivity of 98\% for method identifying relevant articles against a gold standard database.\textsuperscript{16} The search was conducted November 11, 2009, with the following terms designed to identify published randomized controlled trials investigating linezolid: "Randomized Controlled Trial" [Publication Type] OR "Controlled Clinical Trial" [Publication Type] OR randomized [tiab] OR placebo [tiab] OR drug therapy [sh] OR randomly [tiab] OR trial [tiab] OR groups [tiab] AND "linezolid" [Substance Name]. In addition, we searched published abstracts from major international conferences (CHEST 2003-2009, American Thoracic Society 2008-2009, and Infectious Diseases Society of North America 2001, 2003-2006) and the ClinicalTrials.gov registry to identify unpublished trials.

**Study Selection**

Two investigators (A. J. W. and M. R. O.) independently reviewed results of the search to identify randomized controlled trials comparing linezolid to a glycopeptide antibiotic in subjects diagnosed with pneumonia. Potentially eligible trials were excluded if they were not written in English and study details were not available from the abstract, did not assess clinical success as an end point, studied strictly immunocompromised subjects, or enrolled only subjects <12 years of age.

**Validity Assessment**

All studies meeting entry criteria were included in this meta-analysis. Jadad scores,\textsuperscript{17} a simple instrument with high interrater reliability used to assess randomized controlled trial quality, were calculated for each study.

**Data Abstraction**

Data were abstracted independently in duplicate (A. J. W. and M. R. O.). All corresponding authors of the included studies were contacted via e-mail and asked to provide unpublished summary data pertinent to the outcomes of interest. Specifically, we requested unpublished summary data regarding outcomes (eg, test-of-cure [TOC] and end-of-treatment [EOT] outcomes, adverse events) and prespecified subject subgroups (eg, MRSA and non-MRSA pneumonia) related to subjects with pneumonia.

The primary outcome assessed in this analysis was clinical success at the TOC study follow-up evaluation in clinically evaluable subjects. This end point was chosen for its clinical relevance. Two studies (Wilcox et al\textsuperscript{18} and Wunderink et al\textsuperscript{19}) did not record TOC results; results from the EOT outcome assessment were analyzed for these studies. TOC visits ranged from 5 to 28 days after antibiotic course completion in the studies included in this analysis. Clinical success in these studies was defined as resolution of clinical signs and symptoms of pneumonia compared with baseline. The intention-to-treat (ITT) population was defined as subjects who were randomized and received at least one dose of the study medication; clinical success in the ITT population was analyzed as a secondary outcome. Other secondary outcomes included clinical success at EOT in the clinically evaluable subjects, microbiologic success (sputum pathogen eradication), all-cause mortality during the study period in the ITT sample, and drug-related adverse events (total adverse events, as well as thrombocytopenia and acute renal failure) in the ITT sample.

A prespecified subgroup analysis was performed investigating the primary outcome in subjects with culture-proven MRSA as compared with non-MRSA pneumonia. Data regarding subjects with non-MRSA pneumonia were unavailable from four studies (Wilcox et al,\textsuperscript{18} Wunderink et al,\textsuperscript{19} Kohno et al,\textsuperscript{20} and Lin et al\textsuperscript{21}) but could be inferred from information given regarding total subjects and subjects with MRSA pneumonia in three studies (Rubinstein et al,\textsuperscript{22} Wunderink et al,\textsuperscript{19} and Stevens et al\textsuperscript{23}) and were supplied directly upon request in one study (Cepeda et al\textsuperscript{24}).

Additional data were collected regarding study design, methods of blinding and randomization, study population, criteria for diagnosis of pneumonia, criteria for assessment of treatment success, and antibiotic dosing, duration, and monitoring procedures. Sensitivity analyses were also performed based on differences in blinding (unblinded vs blinded) and type of glycopeptide comparator (vancomycin vs teicoplanin).

**Statistical Analysis**

In order to reach 90\% power to demonstrate a relative 15\% difference between linezolid and vancomycin clinical success rates (75\% vs 65\%), 450 subjects were necessary in each of the primary analysis intervention groups. Pooled relative risks (RRs) and 95\% CIs of outcome comparisons between glycopeptide antibiotics and linezolid were calculated using the Mantel-Haenszel random effects method. Random effects models were chosen for primary statistical analysis due to their more conservative CIs and underlying
assumptions that allow for greater generalizability of the study findings. As a sensitivity analysis, all models were also run using fixed-effects methods, without any significant change in effect estimates or statistical significance. All results reported herein are from random-effects models. Heterogeneity was assessed with $\chi^2$ testing and $I^2$ statistics. Interaction between subgroups (eg, MRSA and MSSA pneumonia) was calculated using the method of Bland and Altman. Visual inspection of funnel plots was used to assess the potential for publication bias. Review Manager, Version 5.0 (The Nordic Cochrane Centre, The Cochrane Collaboration; Copenhagen, Denmark) was used for all statistical analyses. An $\alpha$ level of 0.05 was selected for all analyses.

RESULTS

The flow diagram for selection of the relevant trials of ITT subjects included in this analysis is shown in Figure 1. One study (Cepeda et al) supplied requested data regarding unpublished pneumonia outcomes. No additional data from unpublished abstracts were identified.

Of 762 articles retrieved with the search strategy, eight trials enrolling a total of 1,641 subjects met entry criteria and were selected for this meta-analysis. Table 1 summarizes the trial characteristics. All trials were multicenter, and four of eight were double-blind, with an average Jadad score of 3 ± 0.93. Studies that received a Jadad score of 2 did so because they were not double-blind and did not describe the method of randomization.

All subjects were hospitalized; two studies included only critically ill or mechanically ventilated patients. Two studies investigated teicoplanin as the comparator medication; the remaining studied vancomycin. In no study were vancomycin or teicoplanin drug levels assessed as part of a study protocol. All studies used linezolid doses of 600 mg IV every 12 h and allowed use of concomitant antibiotics with gram-negative, but not MRSA, activity. The mean duration of therapy in the four studies reporting these data were 10.5 ± 1.18 days for linezolid and 9.96 ± 1.13 days for glycopeptide ($P = .56$). The proportion of the ITT subjects who had outcome assessments was not different between the two treatments; 493/841 (58.6%) subjects who received linezolid and 476/800 (59.5%, $P = .72$) subjects who received a glycopeptide antibiotic were evaluable for the primary outcome of clinical success at TOC follow-up.

Our primary outcome of clinical success at TOC was not different between the two antibiotic classes (pooled RR of treatment success for linezolid compared with glycopeptide, 1.04; 95% CI, 0.97-1.11; $P = .28$) (Fig 2A). This effect estimate was not different for meta-analyses of the EOT end point (1.04; 95% CI, 0.98-1.11) or the TOC end point in entire ITT population (1.02; 95% CI, 0.93-1.12) (Fig 2B). Sensitivity analyses of primary outcome stratifying by allocation concealment type (double-blinded RR, 1.04; 95% CI, 0.93-1.16; open-label RR, 1.04; 95% CI, 0.95-1.13) or type of glycopeptide comparator (vancomycin RR, 1.05; 95% CI, 0.94-1.17; teicoplanin RR, 1.03; 95% CI, 0.95-1.13) also did not result in outcome differences.

Clinical success for subjects with culture-confirmed MRSA pneumonia was not different from those without MRSA. The RR of clinical success for linezolid compared with glycopeptide in those with MRSA (1.23; 95% CI, 0.97-1.57) (Fig 3A) was not different from those without MRSA (0.95; 95% CI, 0.83-1.09; $P$ for interaction 0.07) (Fig 3B). Microbiologic eradication (Fig 4A), mortality (Fig 4B), and total adverse events (Fig 4C) were also similar in linezolid and glycopeptide groups.

Risk for thrombocytopenia was a nonstatistically significant 2.97 times higher for linezolid (95% CI, 0.81-10.94; $P = .10$) in three studies reporting these data. The risk of renal impairment was not significantly different comparing linezolid and glycopeptides (RR, 1.09; 95% CI, 0.35-3.38; $P = .89$).

A funnel plot of effect size vs SE in the primary analysis of clinical success was used to evaluate for publication bias (Fig 5). This plot shows a slight imbalance of effects toward linezolid.

DISCUSSION

This meta-analysis of randomized controlled trials comparing linezolid to glycopeptide antibiotics for suspected MRSA nosocomial pneumonia does not support the assertion that linezolid is a more efficacious antibiotic. Specifically, clinical and microbiologic outcomes in subjects randomized to linezolid
Table 1—Characteristics of Included Studies

<table>
<thead>
<tr>
<th>Study/Year</th>
<th>Design</th>
<th>Population</th>
<th>Comparator</th>
<th>ITT, No.</th>
<th>% ITT Subjects Evaluable for Outcome</th>
<th>Jadad Study Quality Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rubinstein et al</td>
<td>Multicenter</td>
<td>Age &gt; 18 y Nosocomial pneumonia</td>
<td>V</td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Stevens et al</td>
<td>Multicenter</td>
<td>Age &gt; 13 y Hospitalized, presumed</td>
<td>MRSA pneumonia, cSSTI, UTI, bacteremia</td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Wunderink et al</td>
<td>Multicenter</td>
<td>Age &gt; 18 y Nosocomial pneumonia</td>
<td>V</td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Wunderink et al</td>
<td>Multicenter</td>
<td>Age &gt; 18 y Nosocomial pneumonia</td>
<td>V</td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Cepeda et al</td>
<td>Two centers</td>
<td>Age &gt; 16 y Critically ill, suspected</td>
<td>T</td>
<td></td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>Kohno et al</td>
<td>Multicenter</td>
<td>Age &gt; 20 y MRSA only, nosocomial pneumonia and cSSTI</td>
<td>V</td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Lin et al</td>
<td>Multicenter</td>
<td>Age 18-75 y Nosocomial pneumonia and cSSTI</td>
<td>V</td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Wunderink et al</td>
<td>Multicenter</td>
<td>Age &gt; 18 y MRSA only, ventilator-associated pneumonia; BAL at 0, 72 h</td>
<td>V</td>
<td></td>
<td></td>
<td>3</td>
</tr>
</tbody>
</table>

+ = positive; cSSTI = complicated skin and soft tissue infection; ITT = intention to treat; L = linezolid; MRSA = methicillin-resistant Staphylococcus aureus; T = teicoplanin; UTI = urinary tract infection; V = vancomycin.

were not superior to subjects randomized to glycopeptides, regardless of the confirmed presence of MRSA. In addition, adverse events were not significantly different between the two antibiotics. These results are consistent with other meta-analyses that have compared linezolid against glycopeptides for the treatment of multiple sources of infection. Although complicated skin and soft tissue infections have shown to have improved outcomes with linezolid, none of the prior meta-analyses observed significant differences between linezolid and comparators for pneumonia outcomes. Similar to our results for pneumonia, the prior meta-analyses that pooled infectious source showed no difference in total adverse events between treatments. However, Beibei et al found an increased odds of nephrotoxicity for vancomycin, and Falagas et al demonstrated increased thrombocytopenia with linezolid. Neither of these adverse events was reported with high incidence in the in the patients with pneumonia included in our meta-analysis. This may be because of the shorter courses of antibiotics typically prescribed for pneumonia compared with other infections, such as MRSA bacteremia.

Reports suggesting linezolid as superior for MRSA pneumonia hypothesize superior drug concentrations in the lung as a potential mechanism of benefit. This is supported by a study of lung epithelial lining fluid levels after one dose of vancomycin in subjects without pneumonia that showed levels below S aureus minimal inhibitory concentration (MIC) after 3 h in many subjects. In contrast, evidence from studies of humans and animals with pneumonia did not show subtherapeutic lung concentrations of glycopeptides. Additionally, Lamer et al demonstrated higher epithelial lining fluid concentrations of vancomycin with increasing degrees of lung inflammation, which may weaken the validity of drug penetration studies in subjects without pneumonia. Last, when comparing two studies of subjects with nosocomial pneumonia, the proportion of subjects demonstrating trough drug concentrations above the MRSA MIC cited in each study was greater with vancomycin (79% > MIC 2.0 mg/mL) than linezolid (31% > MIC 4 mg/mL). Because no single study in humans has compared pulmonary concentrations of these drugs in patients with pneumonia, it is currently not known if subtherapeutic pulmonary drug levels are more common in patients with pneumonia with glycopeptides compared with linezolid.

Other studies suggest that inhibition of protein synthesis and bacterial toxin production, particularly

Multiple studies have investigated the cost-effectiveness of linezolid for MRSA pneumonia, using pooled data from Rubinstein et al and Wunderink et al. These studies conclude that, despite linezolid costs approximately 10 times that of glycopeptides, the Panton-Valentine Leukocidin (PVL) toxin associated with necrotizing pneumonias is the mechanism of putative superiority for linezolid. Importantly, the studies included in our meta-analysis focused on nosocomial MRSA pathogens, which are less likely to produce the PVL toxin, as compared with emerging community-acquired MRSA. Thus, our results showing no significant difference in efficacy between linezolid and glycopeptides in nosocomial pneumonia should not be generalized to community-acquired MRSA pneumonias or MRSA pneumonia with characteristics of a PVL toxin-producing strain (eg, necrosis, parapneumonic effusion).

Figure 2. Forest plots for clinical success outcomes. A, Clinical success at test-of-cure (TOC) follow-up in clinically evaluable subjects. B, Clinical success at TOC follow-up in the intention-to-treat population.

Figure 3. A, Forest plot for clinical success in subjects with culture-positive MRSA pneumonia. B, Forest plot for clinical success in subjects without culture-positive MRSA pneumonia. A also includes the data from Rubinstein et al 2001. MRSA = methicillin-resistant Staphylococcus aureus.
of vancomycin, linezolid is cost-effective given the assumption of improved outcomes. These analyses should be reassessed given our findings of no significant difference in clinical success or mortality between these antibiotics.

Our findings argue against widespread routine use of linezolid for suspected MRSA nosocomial pneumonia based on the presumption of superior efficacy. Targeted use of linezolid may be of greater importance given the recent outbreak of linezolid-resistant *S aureus*, directly correlating with linezolid use in a Spanish ICU. This outbreak highlights the importance of thoughtful antibiotic stewardship, especially given the paucity of effective treatments for MRSA pneumonia.

Our study has limitations. The proportion of ITT subjects who were evaluated for clinical outcomes was low across all studies. Whether certain characteristics of the study medications differentially affected loss to follow-up is unknown; however, the proportion of subjects lost to follow-up was not different between interventions. Although this study was adequately powered to detect differences in clinical success between the two antibiotics, it was not powered for subgroup analysis or for detecting interaction between MRSA and non-MRSA groups. Ongoing randomized controlled trials (NCT00084266) comparing these antibiotics for MRSA ventilator-associated pneumonia may provide further information regarding the comparative efficacy of these antibiotics. The funnel plot used to investigate publication bias suggests the possibility of publication bias in favor of linezolid. This weak suggestion is not supported by our findings.

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<table>
<thead>
<tr>
<th>Study or Subgroup</th>
<th>Linezolid</th>
<th>Glycopeptide</th>
<th>Risk Ratio (95% CI)</th>
<th>Random Effect, Risk ratio (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rubinstein et al. 2001</td>
<td>36/203</td>
<td>49/193</td>
<td>0.70 (0.48, 1.02)</td>
<td></td>
</tr>
<tr>
<td>Wunderink et al. 2003</td>
<td>64/321</td>
<td>61/302</td>
<td>0.99 (0.72, 1.35)</td>
<td></td>
</tr>
<tr>
<td>Capdevila et al. 2004</td>
<td>17/47</td>
<td>16/57</td>
<td>1.29 (0.73, 2.26)</td>
<td></td>
</tr>
<tr>
<td>Wunderink et al. 2008</td>
<td>41/74</td>
<td>6/72</td>
<td>0.65 (0.19, 2.20)</td>
<td></td>
</tr>
<tr>
<td>Total, Mortality</td>
<td>121/645</td>
<td>132/624</td>
<td>0.91 (0.69, 1.16)</td>
<td></td>
</tr>
</tbody>
</table>

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**B** Microbiological success

<table>
<thead>
<tr>
<th>Study or Subgroup</th>
<th>Linezolid</th>
<th>Glycopeptide</th>
<th>Risk Ratio (95% CI)</th>
<th>Random Effect, Risk ratio (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rubinstein et al. 2001</td>
<td>36/50</td>
<td>28/39</td>
<td>1.00 (0.77, 1.30)</td>
<td></td>
</tr>
<tr>
<td>Wunderink et al. 2003</td>
<td>47/76</td>
<td>42/79</td>
<td>1.16 (0.89, 1.53)</td>
<td></td>
</tr>
<tr>
<td>Capdevila et al. 2004</td>
<td>17/27</td>
<td>19/33</td>
<td>1.09 (0.72, 1.65)</td>
<td></td>
</tr>
<tr>
<td>Kohno et al. 2007</td>
<td>12/35</td>
<td>7/19</td>
<td>1.01 (0.49, 2.09)</td>
<td></td>
</tr>
<tr>
<td>Wunderink et al. 2008</td>
<td>13/23</td>
<td>9/19</td>
<td>1.19 (0.86, 2.16)</td>
<td></td>
</tr>
<tr>
<td>Lin et al. 2008</td>
<td>17/22</td>
<td>15/28</td>
<td>1.64 (0.95, 2.96)</td>
<td></td>
</tr>
<tr>
<td>Total, Microbiological success</td>
<td>143/233</td>
<td>120/217</td>
<td>1.13 (0.97, 1.31)</td>
<td></td>
</tr>
</tbody>
</table>

---

**C** Adverse events

<table>
<thead>
<tr>
<th>Study or Subgroup</th>
<th>Linezolid</th>
<th>Glycopeptide</th>
<th>Risk Ratio (95% CI)</th>
<th>Random Effect, Risk ratio (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rubinstein et al. 2001</td>
<td>143/203</td>
<td>143/193</td>
<td>0.96 (0.84, 1.07)</td>
<td></td>
</tr>
<tr>
<td>Wunderink et al. 2003</td>
<td>45/321</td>
<td>42/302</td>
<td>1.01 (0.88, 1.19)</td>
<td></td>
</tr>
<tr>
<td>Capdevila et al. 2004</td>
<td>18/36</td>
<td>12/32</td>
<td>1.33 (0.77, 2.32)</td>
<td></td>
</tr>
<tr>
<td>Wunderink et al. 2008</td>
<td>18/74</td>
<td>23/72</td>
<td>0.86 (0.46, 1.64)</td>
<td></td>
</tr>
<tr>
<td>Total, Adverse events</td>
<td>225/634</td>
<td>220/599</td>
<td>0.96 (0.86, 1.07)</td>
<td></td>
</tr>
</tbody>
</table>

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review of unpublished abstract or clinical trial registry data. In addition, subgroup comparisons of MRSA vs non-MRSA-related outcomes were not performed in the studies in this meta-analysis; thus, it would be difficult to argue for publication bias against null findings in this subgroup. Importantly, this meta-analysis does not investigate the efficacy of linezolid as a treatment of community-acquired MRSA; in vitro data, animal studies, and case reports suggest that linezolid may be of benefit for these toxin-producing strains.3,24,42,43

In conclusion, this meta-analysis does not show superiority of linezolid as compared with glycopeptide antibiotics for the treatment of nosocomial pneumonia. We recommend that decisions between linezolid or glycopeptide antibiotics for empirical or MRSA-directed therapy of nosocomial pneumonia depend on local availability, antibiotic resistance patterns, preferred routes of delivery, and cost, rather than presumed difference in efficacy.

Acknowledgments

Author contributions: Dr Walkey had full access to the data and takes responsibility for the accuracy of the data and analyses. Dr Walkey: contributed to conception, design, data analysis and interpretation, manuscript draft, and critical revision. Dr O'Donnell: contributed to conception, design, data interpretation, manuscript revision for critical intellectual content, and supervision of the study.

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Role of sponsors: The funding organizations had no role in the design and conduct of the study; in the collection, management, analysis, and interpretation of the data; or in the preparation, review, or approval of the manuscript. The views expressed herein do not necessarily represent the views of the National Cancer Institute, the Department of Veterans Affairs, or the United States government.

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