Ultrasound Guidance Facilitates Radial Artery Catheterization
A Meta-analysis With Trial Sequential Analysis of Randomized Controlled Trials

Wan-Jie Gu, MD; Xiang-Dong Wu, MSc; Fei Wang, MD, PhD; Zheng-Liang Ma, MD, PhD; and Xiao-Ping Gu, MD, PhD

BACKGROUND: Potential benefits and possible risks associated with ultrasound guidance compared with traditional palpation for radial artery catheterization are not fully understood.

METHODS: We searched PubMed, Embase, and the Cochrane Library through July 2015 to identify randomized controlled trials that evaluated ultrasound guidance compared with traditional palpation for radial artery catheterization. Primary outcome was first-attempt failure. Secondary outcomes included mean attempts to success, mean time to success, and hematoma complications. A random-effects model was used to estimate relative risks (RRs) with 95% CIs.

RESULTS: Twelve trials used dynamic two-dimensional (2-D) ultrasound guidance (N = 1,992) and two used Doppler ultrasound guidance (N = 666). Compared with traditional palpation, dynamic 2-D ultrasound guidance was associated with a reduced first-attempt failure (RR, 0.68; 95% CI, 0.52-0.87). Trial sequential analysis showed that the cumulative z curve crossed the trial sequential monitoring boundary for benefit establishing sufficient and conclusive evidence. Dynamic 2-D ultrasound guidance further reduced mean attempts to success, mean time to success, and hematoma complications. No evidence of publication bias was detected. Compared with traditional palpation, Doppler ultrasound guidance had no benefit on first-attempt failure (RR, 1.00; 95% CI, 0.87-1.15), which was confirmed by trial sequential analysis as the cumulative z curve entered the futility area.

CONCLUSIONS: The use of dynamic 2-D ultrasound guidance for radial artery catheterization decreases first-attempt failure, mean attempts to success, mean time to success, and the occurrence of hematoma complications. Dynamic 2-D ultrasound guidance is recommended as an adjunct to aid radial arterial catheterization.

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KEY WORDS: catheterizations; meta-analysis; ultrasound

ABBREVIATIONS: 2-D = two-dimensional; GRADE = Grading of Recommendations Assessment, Development, and Evaluation; MD = mean difference; MeSH = Medical Subject Headings; PRISMA = Preferred Reporting Items for Systematic Reviews and Meta-analyses; RCT = randomized controlled trial; RR = relative risk; TSA = trial sequential analysis

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Arterial catheterization is a common invasive procedure in many clinical settings including the operating room, ICU, and ED.\(^1\)\(^,\)\(^2\) It allows continuous arterial pressure monitoring and repeated arterial blood sampling.\(^2\)\(^,\)\(^3\) The radial artery is the most commonly used site and the preferred access for arterial catheterization because of its superficial accessibility and low incidence of complications.\(^4\)\(^,\)\(^5\) Traditionally, radial artery catheterization has been guided by using anatomic knowledge and pulse palpation. However, the technique often can be technically challenging in infants, small children, and patients who are hypotensive or obese, even for experienced operators.\(^1\)\(^,\)\(^4\) The first unsuccessful attempt and next multiple attempts increase patient discomfort and may lead to local hematoma, arterial spasm, or other complications.\(^1\)\(^,\)\(^3\)\(^,\)\(^4\)\(^,\)\(^6\)\(^,\)\(^7\)

To overcome this issue, ultrasound has been introduced as an adjunct to aid radial artery catheterization, because it allows easy visualization of the targeted vessel.\(^8\) However, potential benefits and possible risks associated with ultrasound guidance compared with traditional palpation for radial artery catheterization are not fully understood. Evidence from randomized controlled trials (RCTs) reported inconsistent results\(^9\)\(^-\)\(^17\) and consecutive meta-analyses were underpowered to reach determinate conclusions.\(^18\)\(^-\)\(^20\) Moreover, four recent trials with adequate power have been published and involve new evidence.\(^21\)\(^-\)\(^24\) Thus, we undertook a meta-analysis of the latest and most convincing evidence to evaluate the efficacy and safety of ultrasound guidance compared with traditional palpation for radial artery catheterization, and we further applied trial sequential analysis (TSA) to determine whether the currently available evidence was sufficient and conclusive.

Materials and Methods

The current meta-analysis was performed according to the recommendations of the Cochrane Handbook for Systematic Reviews of Interventions\(^2\)\(^5\) and was reported in compliance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement guidelines (e-Appendix).\(^2\)\(^6\) There was no registered protocol.

Literature Search

We performed a systematic electronic search in PubMed, Embase, and the Cochrane Library from inception through May 2015. We conducted electronic searches using exploded Medical Subject Headings (MeSH) terms and corresponding key words. The search terms used were (MeSH exp “Ultrasonography,” “Ultrasound,” and key words “ultrasonography”, “ultrasonic,” and “ultrasound”), and (MeSH exp “Radial Artery” and key words “radial artery” and “radial arterial”). No language restriction was applied. To ensure literature saturation, we reran the searches on July 20, 2015. We also searched ClinicalTrials.gov registry (www.clinicaltrials.gov) and manually checked the bibliographies of previous reviews and included trials to identify other potentially eligible trials.

Selection Criteria

Two authors (W.-J. G. and X.-D. W.) independently carried out the initial search, deleted duplicate records, screened the titles and abstracts for relevance, and identified records as included, excluded or uncertain. In case of uncertainty, the full-text article was acquired to identify eligibility. Any discrepancy was resolved by discussion and consensus.

Published RCTs meeting the following criteria were included: (1) population: children or adults requiring radial artery catheterization regardless of clinical settings; (2) intervention: dynamic two-dimensional (2-D) or Doppler ultrasound guidance technique; (3) comparison: traditional palpation technique; and (4) \(\geq 1\) of the following outcomes: first-attempt failure, mean attempts to success, mean time to success, and hematoma complications.

Data Extraction

Data extraction was performed by W.-J. G. and confirmed independently by other authors (X.-D. W. and F. W.). Collected data included the following: first author, year of publication, country, number of patients, clinical setting, ultrasound type, ultrasound machine (type, device, and approach), operator experience, and outcomes data. Extracted data were entered into a standardized Excel (Microsoft Corporation) file. We also sought supplementary appendices of included trials or contacted corresponding authors to verify extracted data and request the missing data. Discrepancies were resolved by discussion with coauthors. Predefined primary outcome was first-attempt failure. Secondary outcomes included mean attempts to success, mean time to success, and hematoma complications.

Risk of Bias Assessment

Two authors (W.-J. G. and F. W.) independently assessed risk of bias using the Cochrane risk-of-bias tool.\(^2\)\(^7\) We reviewed each trial and scored as high, low, or unclear risk of bias to the following criteria: random sequence generation; allocation concealment; blinding of participants and personnel to the study protocol; blinding of outcome assessment; incomplete outcome data; selective reporting; and other bias. Blinding of patients and clinicians to the study protocol was extremely difficult and generally not feasible in these trials, and we judged that the primary outcome (that is, first-attempt failure) was less prone to be influenced by lack of blinding. Thus, trials with high risk of bias for \(\geq 1\) key domains except blinding were considered to be at high risk of bias whereas trials with low risk of bias for all key domains except blinding were considered to be at low risk of bias; otherwise they were considered to be at unclear risk of bias.

Grading Quality of Evidence

Two authors (W.-J. G. and Z.-L. M.) independently evaluated the quality of evidence for primary and secondary outcomes according to Grading of Recommendations Assessment, Development, and Evaluation (GRADE)\(^2\)\(^8\) methodology for risk of bias, inconsistency, indirectness, imprecision, and publication bias, classified as very low, low, moderate, or high. Summary tables were constructed using the GRADE Profiler (version 3.6, GRADEpro).

Statistical Analysis

We calculated relative risks (RRs) with 95% CIs for dichotomous outcomes and mean differences (MDs) with 95% CIs for continuous
outcomes. Heterogeneity across studies was quantified using the $I^2$ statistic; $I^2 > 50\%$ indicated significant heterogeneity.\textsuperscript{29} We pooled outcome data using a random-effects model accounting for clinical heterogeneity. To check the influence of various factors on first-attempt failure of dynamic 2-D ultrasound, we further performed post hoc subgroup analyses according to clinical setting (operating room vs ED), patient population (children vs adults), operator experience (experienced vs inexperienced), ultrasound guidance approach (short axis out-of-plane vs long axis in-plane), and risk of bias (low vs unclear/high). Only subgroup analyses showing a statistically significant test of interaction ($P < .05$) were considered statistically significant, except where otherwise specified. Publication bias was assessed by visually inspecting a funnel plot, and also evaluated using the tests of Begg and Mazumdar\textsuperscript{30} and Egger et al.\textsuperscript{31} All statistical analyses were performed using Stata 12.0 (StataCorp LP) and RevMan 5.3 (Nordic Cochrane Centre).

**Trial Sequential Analysis**

In a single trial, interim analyses increase the risk of type I error (false-positive results). To avoid this, monitoring boundaries can be used to decide whether a single randomized trial could be terminated early because the $P$ value was sufficiently small to show the anticipated effect or for futility. Similarly, in a meta-analysis, random errors because of sparse data and repetitive testing of accumulating data increase the risk of type I error.\textsuperscript{32,33} Because no reason exists why the standards for a meta-analysis should be less rigorous than those for a single trial, analogous trial sequential monitoring boundaries can be applied to meta-analysis; these are called trial sequential monitoring boundaries.\textsuperscript{32,34} This method for meta-analysis that aims to correct for the increased risk of random errors is called TSA, and can determine whether the evidence in a meta-analysis is reliable and conclusive. When the cumulative $z$ curve crosses the trial sequential monitoring boundary or enters the futility area, a sufficient level of evidence for the anticipated intervention effect may have been reached and no further trials are needed. If the $z$ curve crosses none of the boundaries and the required information size has not been reached, there is insufficient evidence to reach a conclusion.

We used TSA to calculate a diversity-adjusted required information size for meta-analysis. Similar to a sample size calculation for a single trial, estimating the required information size involves a calculation that includes type I error, type II error, the control event proportion, and the effect size. For our TSAs, we estimated the required information size using $\alpha = .05$ (two-sided), $\beta = .20$ (power of 80%), the control event proportions calculated from the traditional palpation group, and an RR reduction of 20% in first-attempt failure. We used software TSA version 0.9 beta (http://www.ctu.dk/tsa) for these analyses.\textsuperscript{35}

**Results**

**Trial Selection**

The PRISMA statement flowchart shows the process of literature screening, study selection, and reasons for exclusion (Fig 1). Our initial search yielded 493 records. After removing duplicates and screening the titles and abstracts, 26 articles were thought to be potentially eligible for inclusion. After reviewing the full text,
## TABLE 1  Characteristics of Included Randomized Controlled Trials Comparing Ultrasound Guidance With Traditional Palpation for Radial Artery Catheterization

<table>
<thead>
<tr>
<th>Study/Year</th>
<th>Country</th>
<th>Population</th>
<th>No. Patients</th>
<th>Clinical Setting</th>
<th>Ultrasound Type</th>
<th>Ultrasound Device</th>
<th>Ultrasound Approach</th>
<th>Operator Experience</th>
<th>Main Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Levin et al(^9)/2003</td>
<td>Israel</td>
<td>Adults</td>
<td>69</td>
<td>Operating room undergoing abdominal, cardiothoracic, and vascular surgery and neurosurgery</td>
<td>Dynamic 2-D ultrasound</td>
<td>Site Rite II (Dymax Corporation, Pittsburgh, PA)</td>
<td>Short axis out-of-plane</td>
<td>Anesthetists with experience of ultrasound-guided central venous catheterization but no experience of ultrasound-guided arterial catheterization</td>
<td>Favors dynamic 2-D ultrasound</td>
</tr>
<tr>
<td>Tada et al(^10)/2003</td>
<td>Japan</td>
<td>Adults</td>
<td>166</td>
<td>Operating room undergoing routine surgical cases</td>
<td>Doppler ultrasound</td>
<td>HD-307 (Nihon Koden, Tokyo, Japan)</td>
<td>Not reported</td>
<td>Board-certified anesthetists who had been trained in ultrasound technique in 20 patients before current study</td>
<td>No difference</td>
</tr>
<tr>
<td>Shiver et al(^12)/2006</td>
<td>Georgia</td>
<td>Adults</td>
<td>60</td>
<td>ED requiring arterial line</td>
<td>Dynamic 2-D ultrasound</td>
<td>SonoSite Ilook 25 (SonoSite, Bothell, WA)</td>
<td>Long axis in-plane</td>
<td>Anesthetists with experience of ultrasound-guided central venous catheterization but not of ultrasound-guided arterial catheterization</td>
<td>Favors dynamic 2-D ultrasound</td>
</tr>
<tr>
<td>Ganesh et al(^13)/2009</td>
<td>United States</td>
<td>Children</td>
<td>152</td>
<td>Operating room undergoing abdominal, craniofacial, orthopedic, and thoracic surgery and neurosurgery</td>
<td>Dynamic 2-D ultrasound</td>
<td>SonoSite 180plus (SonoSite)</td>
<td>Short axis out-of-plane</td>
<td>Anesthetists with experience of &gt;20 ultrasound-guided arterial catheterization</td>
<td>No difference</td>
</tr>
</tbody>
</table>

(Continued)
<table>
<thead>
<tr>
<th>Study/Year</th>
<th>Country</th>
<th>Population</th>
<th>No. Patients</th>
<th>Clinical Setting</th>
<th>Ultrasound Type</th>
<th>Ultrasound Device</th>
<th>Ultrasound Approach</th>
<th>Operator Experience</th>
<th>Main Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bobbia et al14/2013</td>
<td>France</td>
<td>Adults</td>
<td>72</td>
<td>ED for blood gas analysis</td>
<td>Dynamic 2-D ultrasound</td>
<td>GE Vivid S6 machine (General Electric Company, Fairfield, CT)</td>
<td>Not reported</td>
<td>Physicians with 3 h simulator training but not of ultrasound-guided arterial catheterization</td>
<td>Favors traditional palpation</td>
</tr>
<tr>
<td>Ishii et al15/2013</td>
<td>Japan</td>
<td>Small children and infants</td>
<td>59†</td>
<td>Operating room undergoing cardiac surgery</td>
<td>Dynamic 2-D ultrasound</td>
<td>SonoSite 180 (SonoSite)</td>
<td>Short axis out-of-plane</td>
<td>Anesthetists with experience of ultrasound-guided central venous catheterization but not of ultrasound-guided arterial catheterization</td>
<td>Favors dynamic 2-D ultrasound</td>
</tr>
<tr>
<td>Zaremski et al16/2013</td>
<td>United States</td>
<td>Adults</td>
<td>183</td>
<td>Operating room undergoing cardiac catheterization or PCI</td>
<td>Dynamic 2-D ultrasound</td>
<td>MTurbo (SonoSite)</td>
<td>Short axis out-of-plane</td>
<td>Cardiac operators with experience of &gt;200 transradial procedures/y</td>
<td>No difference</td>
</tr>
<tr>
<td>Hansen et al17/2014</td>
<td>Denmark</td>
<td>Adults</td>
<td>40†</td>
<td>Operating room undergoing cardiac surgery</td>
<td>Dynamic 2-D ultrasound</td>
<td>Flex-Focus 400 anesthesia ultrasonography system (BK-Medical, Herlev, Denmark)</td>
<td>Short axis out-of-plane</td>
<td>Anesthetists with 20 y experience in transesophageal and transthoracic ultrasonography, 1 year experience with ultrasonography dynamic needle tip positioning, and no experience with ultrasound-guided nerve blocks</td>
<td>Favors dynamic 2-D ultrasound</td>
</tr>
<tr>
<td>Study/Year</td>
<td>Country</td>
<td>Population</td>
<td>No. Patients</td>
<td>Clinical Setting</td>
<td>Ultrasound Type</td>
<td>Ultrasound Device</td>
<td>Ultrasound Approach</td>
<td>Operator Experience</td>
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<tr>
<td>Laursen et al 21/2015</td>
<td>Denmark</td>
<td>Adults</td>
<td>224</td>
<td>ED for blood gas analysis</td>
<td>Dynamic 2-D ultrasound</td>
<td>Not reported</td>
<td>Short axis out-of-plane</td>
<td>Not reported</td>
<td>No difference</td>
</tr>
<tr>
<td>Peters et al 22/2015</td>
<td>Canada</td>
<td>Adults</td>
<td>125</td>
<td>Operating room undergoing cardiac surgery</td>
<td>Dynamic 2-D ultrasound</td>
<td>SonoSite iLook (SonoSite)</td>
<td>Short axis out-of-plane</td>
<td>Anesthetists with a minimum of 10 y ultrasound-guided arterial catheterization</td>
<td>No difference</td>
</tr>
<tr>
<td>Seto et al 23/2015</td>
<td>United States</td>
<td>Adults</td>
<td>473</td>
<td>Operating room undergoing cardiac catheterization</td>
<td>Dynamic 2-D ultrasound</td>
<td>M-Turbo (SonoSite)/Site-Rite Vision (Bard Access, Salt Lake City, UT)/IU22 Xmatrix (Philips, Andover, MA)</td>
<td>Long axis in-plane</td>
<td>Operators experienced in transradial catheterization, with a minimum of 100 previous radial artery catheterization procedures, with at least 15 ultrasound-guided procedures</td>
<td>Favors dynamic 2-D ultrasound</td>
</tr>
<tr>
<td>Ueda et al 24/2015</td>
<td>United States</td>
<td>Adults</td>
<td>749</td>
<td>Operating room requiring continuous arterial pressure monitoring</td>
<td>Dynamic 2-D ultrasound and Doppler ultrasound</td>
<td>NanoMaxx (SonoSite)/915 BL Doppler (Ultrasound, Parks, Las Vegas, NV)</td>
<td>Long axis in-plane</td>
<td>Anesthetists with 1-4 y training gave voluntary verbal consent, using Doppler and ultrasound less than times for radial arterial cannulation</td>
<td>Favors dynamic 2-D ultrasound but not Doppler ultrasound</td>
</tr>
</tbody>
</table>

2-D = two-dimensional; PCI = percutaneous coronary intervention.

*aMatched data (radial arteries are matched as they belong to the same patient).*
13 RCTs\textsuperscript{9-17,21-24} were finally included in the meta-analysis. Data on first-attempt failure were obtained by contacting authors in one trial.\textsuperscript{14}

**Trials Characteristics**

The main characteristics of the included trials are summarized in Table 1. These trials were published from 2003 to 2015. Population sizes ranged from 30 to 749, with a total of 2,402 patients. Among the included trials, 11 of 13 trials compared dynamic 2-D ultrasound with traditional palpation,\textsuperscript{9,11-17,21-23} one compared Doppler ultrasound with traditional palpation,\textsuperscript{10} and one compared both dynamic 2-D ultrasound and Doppler ultrasound with traditional palpation.\textsuperscript{24} Eight of 11 dynamic 2-D ultrasound trials used transverse (out-of-plane) visualization\textsuperscript{9,11,13,15-17,21,22} and the remaining 3 used longitudinal (in-plane) visualization.\textsuperscript{12,23,24} Three trials enrolled infants and small children,\textsuperscript{11,13,15} and the remaining 10 trials included adults.\textsuperscript{9,10,12,14,16,17,21-24} The operator experience and study settings were also different among trials.

**Risk of Bias Assessment**

e-Figures 1 and 2 summarize details of risk of bias. Overall, four trials were categorized as being at low risk of bias,\textsuperscript{12,22-24} eight as being unclear,\textsuperscript{9-11,13,15-17,21} and one as being at high risk of bias.\textsuperscript{14} An adequate randomized sequence was generated in nine trials\textsuperscript{9,12,13,15-17,22-24} and appropriate allocation concealment was reported in four.\textsuperscript{12,22-24} Blinding of outcome assessments was unclear or seldom reported in these trials, but the primary outcome was less prone to be influenced by lack of blinding.

**Dynamic 2-D Ultrasound vs Traditional Palpation**

**Primary Outcome: First-Attempt Failure:** Twelve trials totaling 1,992 patients provided data on first-attempt failure.\textsuperscript{9,11-17,21-24} Compared with traditional palpation, dynamic 2-D ultrasound significantly reduced first-attempt failure (RR, 0.68; 95% CI, 0.52-0.87; \(P = .003\)) (Fig 2), with significant heterogeneity (\(I^2 = 72\%\)). TSA showed that the cumulative \(z\) curve crossed both the conventional boundary for benefit and the

\[
\text{Figure 2 – Effect of ultrasound guidance vs traditional palpation for radial artery catheterization on first-attempt failure. M-H = Mantel-Haenszel. See Figure 1 legend for expansion of other abbreviation.}\]
trial sequential monitoring boundary for benefit and entered the area of benefit, which established sufficient and conclusive evidence. Thus, further trials were not required and were unlikely to alter the conclusions (Fig 3 and e-Fig 3). Table 2 presents the results of subgroup analyses. The findings of decreased first-attempt failure were consistent in all subgroup analyses except for the ED, inexperienced operator, and unclear/high risk of bias subgroups.

**Secondary Outcomes:** Compared with traditional palpation, dynamic 2-D ultrasound guidance for radial artery catheterization further reduced mean attempts to success (MD, −1.26 times; 95% CI, −1.58 to −0.94 times; \( P < .00001 \)) (Fig 4), mean time to success (MD, −43.18 s; 95% CI, −80.22 to −6.13 s; \( P = .02 \)) (Fig 5), and hematoma complications (RR, 0.39; 95% CI, 0.16-0.95; \( P = .04 \)) (Fig 6).

**Doppler Ultrasound vs Traditional Palpation**

Two trials totaling 666 patients provided data on first-attempt failure.\(^{10,24} \) Compared with traditional palpation, Doppler ultrasound had no benefit on first-attempt failure (RR, 1.00; 95% CI, 0.87-1.15; \( P = .98 \)) (Fig 2), with no heterogeneity (\( I^2 = 0\% \)). TSA showed that the cumulative \( z \) curve crossed the futility boundary and entered the futility area, establishing sufficient and conclusive evidence and suggesting that further trials were not required (Fig 7 and e-Fig 4).

**GRADE Profile Evidence and Publication Bias**

GRADE evidence profiles for the primary and secondary outcomes are shown in e-Table 1. The GRADE Working Group grades level of evidence is moderate for first-attempt failure (dynamic 2-D ultrasound vs traditional palpation), low for first-attempt failure (Doppler ultrasound vs traditional palpation), mean attempts to success, and hematoma complications; and very low for mean time to success.

For the meta-analysis of dynamic 2-D ultrasound on first-attempt failure, there was no evidence of...
publication bias by inspection of the funnel plot and formal statistical tests (Egger test, \( P = .69 \); Begg test, \( P = .73 \)) (Fig 8).

Discussion

Main Findings

Our meta-analysis comprehensively and systematically reviewed the current available literature and found that (1) dynamic 2-D ultrasound compared with traditional palpation significantly reduced first-attempt failure for radial artery catheterization. The evidence of benefit was consistent in most subgroup analyses and was confirmed by TSA; (2) dynamic 2-D ultrasound further reduced mean attempts to success, mean time to success, and hematoma complications; (3) Doppler ultrasound had no benefit on first-attempt failure compared with traditional palpation, which was confirmed by TSA, although this evidence came from only two trials.

Comparison With Other Meta-analyses

Several meta-analyses on the topic have been published, as shown in Table 3.18-20 Although the main finding of our meta-analysis was consistent with previous meta-analyses, differences between ours and the previous ones should be noted. First, these previous meta-analyses included no more than seven trials and 482 patients. In comparison, our current meta-analysis included 13 trials totaling

<table>
<thead>
<tr>
<th>Study or Subgroup</th>
<th>Dynamic 2-D Ultrasound</th>
<th>Traditional Palpation</th>
<th>Mean Difference IV, Random, 95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Levin 2003</td>
<td>1.6 1.0 34</td>
<td>3.1 2.4 35</td>
<td>-1.50 [-2.36 to -0.64]</td>
</tr>
<tr>
<td>Schwemmer 2006</td>
<td>1.3 0.5 15</td>
<td>2.3 0.9 15</td>
<td>-1.00 [-1.52 to -0.48]</td>
</tr>
<tr>
<td>Seto 2015</td>
<td>1.65 1.2 236</td>
<td>3.05 3.4 237</td>
<td>-1.40 [-1.86 to -0.94]</td>
</tr>
</tbody>
</table>

Total (95% CI) 285  100.0%  -1.26 [-1.58 to -0.94]

Figure 4 – Effect of dynamic 2-D ultrasound guidance on mean attempts to success compared with traditional palpation. IV = inverse variance. See Figure 1 legend for expansion of other abbreviation.
2,402 patients. With added statistical power of at least 1,900 cases, our current meta-analysis was the latest and the most comprehensive one, which generally concurs and further reinforces earlier results of previous meta-analyses. Second, we further applied TSA to provide a more conservative estimate. TSA suggested that evidence of the effect from previous meta-analyses was insufficient and potentially spurious (e-Fig 3); our current meta-analysis established sufficient and conclusive evidence. Third, we also evaluated the effect of Doppler ultrasound on first-attempt failure for radial artery catheterization compared with traditional palpation. Finally, we evaluated the quality of evidence for outcomes using GRADE to help health-care professionals make clinical decisions.

Implications for Clinical Practice

Our meta-analysis showed that the benefit existed only in dynamic 2-D ultrasound but not Doppler ultrasound compared with traditional palpation. A previous trial found that dynamic 2-D ultrasound guidance for radial arterial catheterization provided a greater first-attempt success than Doppler-assisted technique. Therefore, dynamic 2-D ultrasound might be the best guide for radial artery catheterization. There are two basic approaches in needling techniques for radial artery catheterization: short-axis out-of-plane and long-axis in-plane. Previous trials comparing long-axis in-plane with short-axis out-of-plane approaches for radial artery catheterization have shown inconsistent results. Our subgroup analyses found that both short-axis out-of-plane and long-axis in-plane approaches efficiently decreased the first-attempt failure, with no statistically significant test of interaction between subgroups. It is difficult to clarify which approach is more efficient since the current evidence is limited and further trials are warranted.

Furthermore, operator experience and learning curve are equally considerable factors. The operators varied from inexperienced to briefly trained and fairly experienced, which not only contributed to heterogeneity but also influenced first-attempt failure. Subgroup analyses suggested that the first-attempt success involved only in dynamic 2-D ultrasound but not Doppler ultrasound compared with traditional palpation. With added statistical power of at least 1,900 cases, our current meta-analysis was the latest and the most comprehensive one, which generally concurs and further reinforces earlier results of previous meta-analyses. Second, we further applied TSA to provide a more conservative estimate. TSA suggested that evidence of the effect from previous meta-analyses was insufficient and potentially spurious (e-Fig 3); our current meta-analysis established sufficient and conclusive evidence. Third, we also evaluated the effect of Doppler ultrasound on first-attempt failure for radial artery catheterization compared with traditional palpation. Finally, we evaluated the quality of evidence for outcomes using GRADE to help health-care professionals make clinical decisions.

**Implications for Clinical Practice**

Our meta-analysis showed that the benefit existed only in dynamic 2-D ultrasound but not Doppler ultrasound compared with traditional palpation. A previous trial found that dynamic 2-D ultrasound guidance for radial arterial catheterization provided a greater first-attempt success than Doppler-assisted technique. Therefore, dynamic 2-D ultrasound might be the best guide for radial artery catheterization. There are two basic approaches in needling techniques for radial artery catheterization: short-axis out-of-plane and long-axis in-plane. Previous trials comparing long-axis in-plane with short-axis out-of-plane approaches for radial artery catheterization have shown inconsistent results. Our subgroup analyses found that both short-axis out-of-plane and long-axis in-plane approaches efficiently decreased the first-attempt failure, with no statistically significant test of interaction between subgroups. It is difficult to clarify which approach is more efficient since the current evidence is limited and further trials are warranted.

Furthermore, operator experience and learning curve are equally considerable factors. The operators varied from inexperienced to briefly trained and fairly experienced, which not only contributed to heterogeneity but also influenced first-attempt failure. Subgroup analyses suggested that the first-attempt success involved only in dynamic 2-D ultrasound but not Doppler ultrasound compared with traditional palpation. With added statistical power of at least 1,900 cases, our current meta-analysis was the latest and the most comprehensive one, which generally concurs and further reinforces earlier results of previous meta-analyses. Second, we further applied TSA to provide a more conservative estimate. TSA suggested that evidence of the effect from previous meta-analyses was insufficient and potentially spurious (e-Fig 3); our current meta-analysis established sufficient and conclusive evidence. Third, we also evaluated the effect of Doppler ultrasound on first-attempt failure for radial artery catheterization compared with traditional palpation. Finally, we evaluated the quality of evidence for outcomes using GRADE to help health-care professionals make clinical decisions.

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failure rate was significantly decreased only in experienced but not inexperienced operators, although there was no statistically significant test of interaction between subgroups. The learning curve of ultrasound technique in radial artery catheterization may also influence the clinical outcomes, since ultrasound technique is a relatively new procedure and more technically challenging, especially for inexperienced operators.

Our meta-analysis showed the benefit of dynamic 2-D ultrasound in an unselected population. Theoretically speaking, in a difficult catheterization population, dynamic 2-D ultrasound may greatly facilitate radial artery catheterization. Evidence from case reports has shown the benefit in patients with anatomic variation and those who are critically injured, edematous and pulseless, or hypotensive.

Because of the growing use of ultrasound for a variety of indications in clinical settings, it is essential to delineate the role of ultrasound guidance for radial artery catheterization. The Council of the American Society of Echocardiography and the Society of Cardiovascular Anesthesiologists do not recommend routine use of dynamic ultrasound guidance for arterial catheterization in general. However, for radial artery catheterization, there is category A, level 1 support for the use of ultrasound to improve first-attempt success. The results of our meta-analysis provide the latest and most convincing references for updates of the current guidelines.
Strengths and Limitations

A major strength of this meta-analysis was compliance with the PRISMA guidelines and the recommendations of the Cochrane Collaboration, although our study was not registered with protocol. To increase the robustness of this meta-analysis, we applied TSA to assess the impact of random error and repetitive testing.

Our meta-analysis also had limitations. The included trials in our meta-analysis were conducted in various patient groups and clinical settings, and different ultrasound device and operator experience. Thus, the risk of introducing potentially significant heterogeneity is imminent. Nearly all included trials were not blinded to the study protocol, which may have resulted in performance and detection bias.

### TABLE 3: Comparison With Other Previous Meta-analyses

<table>
<thead>
<tr>
<th>Author/Year</th>
<th>Shiloh et al 18/2011</th>
<th>Gu and Liu 19/2014</th>
<th>Tang et al 20/2014</th>
<th>Current Meta-analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of randomized controlled trials</td>
<td>4</td>
<td>5</td>
<td>7</td>
<td>12 (Dynamic 2-D ultrasound) 2 (Doppler ultrasound)</td>
</tr>
<tr>
<td>No. of participants</td>
<td>311</td>
<td>370</td>
<td>482</td>
<td>1,992 (Dynamic 2-D ultrasound) 666 (Doppler ultrasound)</td>
</tr>
<tr>
<td>Search strategy until, y</td>
<td>2010</td>
<td>2013</td>
<td>2014</td>
<td>2015</td>
</tr>
<tr>
<td>Type of ultrasound</td>
<td>Dynamic 2-D ultrasound</td>
<td>Dynamic 2-D ultrasound</td>
<td>Dynamic 2-D ultrasound</td>
<td>Dynamic 2-D ultrasound Doppler ultrasound</td>
</tr>
<tr>
<td>Dynamic 2-D ultrasound vs traditional palpation</td>
<td>1.71; 1.25-2.32</td>
<td>1.84; 1.47-2.32</td>
<td>1.51; 1.07-2.14</td>
<td>1.31; 1.08-1.58</td>
</tr>
<tr>
<td>First-attempt success, RR; 95% CI</td>
<td>Not reported</td>
<td>SMD, −0.97; 95% CI, −1.38 to −0.55</td>
<td>MD, −1.13; 95% CI, −1.58 to −0.69</td>
<td>MD, −1.26; 95% CI, −1.58 to −0.94</td>
</tr>
<tr>
<td>Mean attempts to success</td>
<td>Not reported</td>
<td>SMD, −0.79; 95% CI, −1.03 to −0.54</td>
<td>MD, −74.77; 95% CI, −137.89 to −11.64</td>
<td>MD, −43.18; 95% CI, −80.22 to −6.13</td>
</tr>
<tr>
<td>Mean time to success, s</td>
<td>Not reported</td>
<td>SMD, 0.17; 0.07-0.41</td>
<td>0.17; 0.07-0.41</td>
<td>0.39; 0.16-0.95</td>
</tr>
<tr>
<td>Hematoma complications, RR; 95% CI</td>
<td>Not reported</td>
<td>Insufficient and potentially spurious</td>
<td>Insufficient and potentially spurious</td>
<td>Sufficient and conclusive</td>
</tr>
<tr>
<td>Trial sequential analysis</td>
<td>Not applied</td>
<td>Not applied</td>
<td>Not applied</td>
<td>Applied</td>
</tr>
<tr>
<td>Evidence of effect</td>
<td>Not applied</td>
<td>Not applied</td>
<td>Not applied</td>
<td>Moderate for first-attempt failure, low for mean attempts to success and hematoma complications, and very low for mean time to success</td>
</tr>
<tr>
<td>GRADE</td>
<td>Not applied</td>
<td>Not applied</td>
<td>Not applied</td>
<td>Low</td>
</tr>
<tr>
<td>Doppler ultrasound vs traditional palpation</td>
<td>RR, 1.01; 95% CI, 0.90-1.14</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>First-attempt success</td>
<td>Not reported</td>
<td>Not reported</td>
<td>Not reported</td>
<td>Applied</td>
</tr>
<tr>
<td>Trial sequential analysis</td>
<td>Not applied</td>
<td>Not applied</td>
<td>Not applied</td>
<td>Sufficient and conclusive</td>
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<tr>
<td>Evidence of effect</td>
<td>Not reported</td>
<td>Not reported</td>
<td>Not reported</td>
<td></td>
</tr>
<tr>
<td>GRADE</td>
<td>Not applied</td>
<td>Not applied</td>
<td>Not applied</td>
<td></td>
</tr>
</tbody>
</table>

GRADE = Grading of Recommendations Assessment, Development, and Evaluation; MD = mean difference; RCT = randomized controlled trial; RR = relative risk; SMD = standardized mean difference. See Table 1 legend for expansion of other abbreviation.

*Derived from first-attempt failure rate.
Conclusions

Our meta-analysis suggested that dynamic 2-D ultrasound guidance but not Doppler ultrasound guidance significantly reduced first-attempt failure for radial artery catheterization compared with traditional palpation. The use of dynamic 2-D ultrasound guidance for radial artery catheterization decreases first-attempt failure, mean attempts to success, mean time to success, and the occurrence of hematoma complications. Dynamic 2-D ultrasound guidance is recommended as an adjunct to aid radial arterial catheterization.

Acknowledgments

Author contributions: W.-J. G. contributed to the conception and design of the study, acquisition of data, analysis and interpretation of data, drafting and revising of the article, and final approval of the version to be published; X.-D. W. and F. W. contributed to acquisition of data, analysis and interpretation of data, drafting the article, and final approval of the version to be published; Z.-L. M. and X.-F. G. contributed to the conception and design of the study, analysis and interpretation of data, revising the article, and final approval of the version to be published.

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Additional information: The e-Appendix, e-Tables and e-Figures can be found in the Supplemental Materials section online.

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