

# Radiological Fusion Criteria of Postoperative Anterior Cervical Discectomy and Fusion: A Systematic Review

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## Abstract

**Study Design:** Systematic review.

**Objectives:** Diagnosis of pseudarthrosis after anterior cervical fusion is difficult, and often depends on the surgeon's subjective assessment because recommended radiographic criteria are lacking. This review evaluated the available evidence for confirming fusion after anterior cervical surgery.

**Methods:** Articles describing assessment of anterior cervical fusion were retrieved from MEDLINE and SCOPUS. The assessment methods and fusion rates at 1 and 2 years were evaluated to identify reliable radiographical criteria.

**Results:** Ten fusion criteria were described. The 4 most common were presence of bridging trabecular bone between the endplates, absence of a radiolucent gap between the graft and endplate, absence of or minimal motion between adjacent vertebral bodies on flexion-extension radiographs, and absence of or minimal motion between the spinous processes on flexion-extension radiographs. The mean fusion rates were 90.2% at 1 year and 94.7% at 2 years. The fusion rate at 2 years had significant independence ( $P = .048$ ).

**Conclusions:** The most common fusion criteria, bridging trabecular bone between the endplates and absence of a radiolucent gap between the graft and endplate, are subjective. We recommend using  $<1$  mm of motion between spinous processes on extension and flexion to confirm fusion.

## Keywords

anterior cervical discectomy and fusion, ACDF, anterior cervical fusion, arthrodesis, cervical fusion, cervical spine, dynamic radiography, fusion criteria, pseudarthrosis, spinous process

## Introduction

Numerous methods are available to diagnose pseudarthrosis after anterior cervical fusion, but diagnosis can be challenging, and the surgeon and independent reviewers may disagree.<sup>1</sup> The diagnosis often depends on the surgeon's subjective assessment because universally accepted radiographic criteria are not available. Surgical reexploration may be the most reliable method,<sup>2</sup> but it is impractical, and it is best to make a diagnosis prior to reoperation even in symptomatic patients. Reliable diagnostic criteria for radiographic evaluation are clinically important. Previous studies have compared criteria for assessing fusion,<sup>3-5</sup> but information on which methods of evaluating of cervical fusion are the most commonly used, or which criteria are the most reliable is lacking. This systematic review analyzed recently published studies of criteria for assessing fusion after anterior cervical spine surgery.

## Methods

### Search Strategy

We searched MEDLINE and SCOPUS using the keywords "anterior cervical discectomy and fusion ACDF and fusion rate," "ACDF and complication," "ACDF and outcome," "ACDF and arthrodesis," and "ACDF and pseudarthrosis" for articles published between January 1, 2011 and June 30, 2016.

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The search was limited to English-language articles describing studies in human subjects published in 7 journals (*Spine*, *The Spine Journal*, *European Spine Journal*, *Journal of Neurosurgery*, *Neurosurgery*, *Journal of Bone and Joint Surgery*, and *Global Spine Journal*). The search returned 160 citations in MEDLINE and 207 in SCOPUS. After deleting 144 duplications, we reviewed the remaining 226 articles for studies of the diagnostic performance of imaging to assess cervical fusion or diagnose pseudarthrosis. Two reviews were excluded, and three articles not found in the original search were retrieved from their reference lists. The 59 articles included in this review are listed in Table 1.<sup>6-65</sup> Data collection, analysis, and manuscript preparation followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Figure 1).<sup>66</sup>

### Inclusion and Exclusion Criteria

As our aim was to assess the clinical value of the radiologic determination of postoperative anterior cervical fusion. The inclusion and exclusion criteria shown in Table 2 included publication year, journal, study subjects, surgical level, surgical procedure, and study design. To evaluate current trends, we excluded articles published before 2010. We tried to maintain accuracy and reliability by narrowing the range of journals, excluding articles not in English language, review articles, or case studies. We also excluded animal, in vitro, or biomechanical research, and reports of thoracic or lumbar surgery. Only studies of anterior or anterior–posterior cervical fusion procedures were included.

### Data Extraction

The extracted data included the timing of follow-up, graft construction, radiographic modality, fusion rate, patient number, study design, and the radiographic criteria used to assess fusion (see Table 1). A cross-sectional listing of the radiographic criteria used to assess anterior cervical fusion is shown in Table 3. The 1-year fusion rate was reported in 8 articles, and the 2-year fusion rate was reported in 23. Two investigators independently extracted the data.

### Statistical Analysis

We calculated the mean 1- and 2-year fusion rates, and the significance of differences of the reported 1- and 2-year fusion rates using the chi-square test. Differences in the 2-year fusion rates determined by the criteria shown in Table 3 and reported in 19 articles were analyzed by single-factor analysis of variance (Table 4). Differences were considered statistically significant if  $P$  was  $<.05$ . Statistical software R, version 2.8.1 (The R Foundation for Statistical Computing, Vienna, Austria) was used for the statistical analysis.

## Results

The mean postoperative follow-up ranged from 1 month to more than 7 years. Some studies reported only follow-up evaluation; others reported multiple postoperative assessments. A variety of interbody graft materials was used, including titanium cage, mesh cage, carbon-fiber reinforced polymer (CFRP) cage, polyetheretherketone (PEEK) cage allografts, autograft of iliac crest or fibula; and hydroxyapatite (HA) block, zero-profile cage, carbon-fiber cage, or expandable cage grafts, all with or without contents. The plate systems used included resorbable metal or titanium plates; standalone interbody grafts without plates were also used. The imaging modalities included radiographs and computed tomography (CT). Magnetic resonance imaging was not used. The radiographic criteria are shown in Table 1. A few articles did not report their criteria in detail. We counted 120 mentions of radiographic criteria for assessing fusion (Table 2). Table 3 shows 10 types of fusion criteria organized as 4 major (I-IV) and 6 minor groups (V-X).

- I. The presence of bridging trabecular bone between the endplates was used in 44 studies and was the most common criterion. Two articles specified more than 50% trabecular bone bridging as the criterion.
- II. The absence of a radiolucent gap between the graft and the endplate was the criterion in 31 articles and was often mentioned along with bridging trabecular bone. Four articles defined this criterion as radiolucency occupying less than 50% of the graft vertebral interface.
- III. Motion between vertebral bodies on flexion-extension radiographs was used in 24 articles. In 8 articles, no measurement of the extent of motion was reported. In the remaining articles, the upper limit of the accepted degree of angulation ranged from  $1^\circ$  to  $4^\circ$ ; several included a requirement of  $<3$  mm of translation. One article simply required absence of angulation or translation.
- IV. Motion between the spinous processes seen on flexion-extension radiographs indicated pseudarthrosis and was used for assessment in 11 articles. Of these, 6 articles defined fusion as the absence of motion. In 3, fusion was defined as the absence of a maximum of  $>2$  mm of motion between the spinous processes, 1 set the upper limit at 3 mm, and 1 defined pseudarthrosis as  $\geq 1$  mm movement between the spinous processes.
- V. Four articles required absence of signs of implant failure.
- VI. Two articles assessed magnified images of dynamic radiographs.
- VII. One article required  $\leq 3$  mm loss of disc height.
- VIII. One article defined endplate sclerosis as indicating pseudarthrosis.

**Table 1.** Criteria for Assessing Fusion After Cervical Fusion Surgery.

Study	Follow-up	Graft	Imaging	Fusion Criteria	Fusion Rate/Evaluation Time	Patients (N)	Study Design
Hermansen et al <sup>6</sup> Stachniak et al <sup>7</sup>	Follow-up for 2 years Evaluation at 6 and 9 months	Bicortical iliac autograft or carbon fiber cage PEEK spacers filled with rhBMP-2 impregnated type I collagen sponge and titanium plates	X-ray CT	Bridging bone anteriorly or through the disk space Not defined	72.6% / 2 years 100% / 9 months	73 30	RCT Cohort
Lebl et al <sup>8</sup>	Mean follow-up at 11.4 and 16.0 months	Titanium cage with allograft + titan plate structural allograft + bioabsorbable plate	X-ray (flexion-extension views)	Bony bridging across the interbody space	86.2% / recent follow-up	29	Cohort
Cardoso et al <sup>9</sup>	Mean follow-up at 18 months	PEEK prevail plate, PEEK cages with rhBMP-2 + resorbable plate	X-ray (flexion-extension views) and CT	Absence of motion on flexion-extension X-ray and the presence of trabeculae bone on CT	100% / last follow-up	31	Cohort
Lee et al <sup>10</sup>	Mean follow-up at 21.4 and 22.3 months	PEEK with the iliac cancellous bone	X-ray (flexion-extension views) and CT	Fusion: presence of bony extension into the space between the graft and absence of segmental motion. Pseudarthrosis: disconnection of the bony trabeculae with a radiolucent line around the instrument or segmental motion of 3° or more	98% / last follow up	50	RCT
Marotta et al <sup>11</sup>	Mean evaluation at 77 months	Carbon fiber cage containing HA without plate	X-ray and CT	Not defined (osteointegration of the cage)	87% / between 54 and 90 months	132	Cohort
Yao et al <sup>12</sup>	Evaluation at 6 and 12 months	CFRP cage with autogenous iliac crest bone	X-ray (flexion-extension views)	Fusion: no radiolucent gap or evident motion between 2 adjacent vertebral bodies on flexion-extension images or the endplates had disappeared in both adjacent vertebral bodies and the 2 vertebral bodies formed a block	91.1% / 6 months 100% / 12 months	67	Prospective cohort
Guo et al <sup>13</sup>	Mean follow-up at 37.7, 37.3, and 37.3 months	Titanium mesh with local autograft bone + plate PEEK cage + plate	X-ray (flexion-extension views)	Absence of motion of more than 2 mm between spinous processes on flexion-extension views, absence of radiolucent gap between graft and endplate, and continuous bridging trabeculae at graft and endplate junction	99% / last follow up	120	Cohort
Conic et al <sup>14</sup>	Evaluation at 1.5, 3, 6, 12, and 24 months	Allograft + plate	X-ray (flexion-extension views) and CT	(1) Bridging trabecular bone, (2) angular motion <5°, (3) translational motion <3 mm, and (4) <50% radiolucency along bone-implant interface	82% / 24 months	133	RCT
Sugawara et al <sup>15</sup>	Evaluation at 6 months and 1 and 2 years	Titanium cage with β-TCP or HA	X-ray (flexion-extension views) and CT	Dynamic motion of the spinous process of <3 mm, bony bridging between vertebrae, and absence of halo around cages	60% / 1 year 92% / 2 years	105 people 165 segment	Cohort
Ghiselli et al <sup>16</sup>	Evaluation at least 1 year	Osseous interbody grafts	X-ray (flexion-extension views) and CT	Fusion on CT: bony trabeculation across fusion level and lack of lucency at graft/vertebral body junction; bridging bone seen on CT, and 1° to 4° of motion or less on flexion-extension	Not mentioned	22	Prospective cohort
Lin et al <sup>17</sup>	Evaluation at 24 months	ACDF: cage + plate or ACCF: titanium mesh cage + plate	X-ray (flexion-extension views) and CT	(1) No motion across the fusion site on flexion-extension, (2) trabeculae across fusion site, or (3) no lucency across fusion site or around any screw sites	100% / 24 months	120	Cohort
Liu et al <sup>18</sup>	Evaluation at 3, 12, and 24 months	Titanium mesh or cage with autograft bone + plate	X-ray (flexion-extension views) and CT	No motion across the fusion site on the flexion-extension X-rays or CT and bridging bony trabeculae between endplate and graft	95.4% / 24 months	286	Cohort
Ba et al <sup>19</sup>	Evaluation at 5-10 years	CFRP cage with local decompression bone + plate	X-ray (flexion-extension views) and CT	Solid bridging bone on lateral X-ray and CT	100% / final follow-up	207	Cohort
Wu et al <sup>20</sup>	Evaluation at 3 months; mean follow-up at 6.58 years	Titanium box cage with autologous anterior iliac crest cancellous bone	X-ray (flexion-extension views)	Lack of motion between vertebral bodies and cages on flexion-extension views and absence of any dark halo around the cage on AP and lateral views or bone bridging intervertebral space through or around the cage	95.6% / 3 months 100% / final follow-up (at least 5 years)	57	Cohort
Liu et al <sup>21</sup>	Mean follow-up at 26.1 months	ACDF: cages + plate or ACCF: titanium mesh cage + plate	X-ray (flexion-extension views)	(1) Absence of motion between spinous processes, (2) absence of radiolucent gap between graft and endplate, (3) continuous bridging bony trabeculae at graft-endplate interface	94.4% / last follow up	180	Cohort

(continued)

Table 1. (continued)

Study	Follow-up	Graft	Imaging	Fusion Criteria	Fusion Rate/Evaluation Time	Patients (N)	Study Design
Song et al <sup>22</sup>	Evaluation at 6 weeks; 3, 6, 9, 12, 18, and 24 months; and annually thereafter; follow-up at least 5 years	Autogenous iliac bone graft + plate, cage with autogenous iliac bone chips + plate, autogenous iliac or fibular bone grafts + Halo-vest	X-ray (flexion-extension views)	Absence of motion between spinous processes on flexion-extension views and absence of radiolucent defect or halo around iliac bone graft or cages or a bridging bone anterior or posterior to cage or iliac bone graft at graft-plate junction	90% / 24 months	40	Cohort
Heilbusch et al <sup>23</sup>	Not defined	PEEK cage filled with small bone pieces from excised bone spurs	X-ray	Double lucency around the titanium of the PEEK cage	32.3/35.6 levels / not mentioned	148	Cohort
Song et al <sup>24</sup>	Evaluation at 6 weeks; 3, 6, and 12 months; and 2 years	iliac bone or PEEK cage with cancellous bone + plate	X-ray	New bone formation on the exterior of the cage and partial or complete loss of radiopaque line at endplates with sclerotic changes of bony bridges between vertebral endplate and grafted bone in the interior of the cage	90.2% / 2 years	78	Cohort
Song et al <sup>25</sup>	Evaluation at 6 weeks and 3, 6, 9, 12, 18, and 24 months	PEEK cage with cancellous iliac crest + plate	X-ray (flexion-extension views) and CT	(1) <2° movement on lateral flexion-extension views, (2) bridging trabecular bone between endplates on AP-lateral views, (3) no signs of implant failure of anterior plate system, (4) <50% radiolucency in perimeter surrounding cage. CT used as a secondary measure when bridging trabecular bone not observed or ambiguous on X-ray	100% / 24 months	43	Cohort
Phillips et al <sup>26</sup>	Evaluation at 24 months	Tricortical allograft + plate	X-ray (flexion-extension views)	Continuous bridging bone between adjacent endplates of involved motion segment, radiolucent lines at ≤50% of graft-vertebra interface, and ≤ 2° segmental rotation on lateral flexion-extension X-ray	92.1% / 24 months	151	RCT
Vaccaro et al <sup>27</sup>	Evaluation at 24 months	Structural allograft + plate	X-ray (flexion-extension views)	Bridging trabecular bone without evidence of pseudarthrosis (no apparent bridging trabecular bone and range of motion >3 mm in translation and >2° in rotation)	89.1% / 24 months	140	RCT
Chen et al <sup>28</sup>	Mean follow-up at 97.2 and 102.1 months	Stand-alone titanium box cage or PEEK box cage with local decompression bone from anterior hypertrophic osteophyte	X-ray (flexion-extension views)	(1) Absence of motion between spinous processes on dynamic lateral X-ray, (2) absence of radiolucent gap between graft and endplates, (3) continuous bridging bony trabeculae at graft-endplate interface	100% / final follow up	80	RCT
Delamarter et al <sup>29</sup>	Evaluation at 6 weeks; 3, 6, and 12 months; and annually thereafter for a minimum of 5 years	Allograft bone spacers and local bone packed around or within the allograft + plate	X-ray and CT	Not defined	Not mentioned	106	RCT
Hey et al <sup>30</sup>	Evaluation at 2 years	Cage packed with bone autograft mixed with demineralized bone matrix	X-ray	Bridwell classification <sup>65</sup>	100% / 2 years	7	Cohort
Lu et al <sup>31</sup>	Evaluation at 1 year	PEEK cage with rhBMP-2-soaked collagen sponge + plate	X-ray (flexion-extension views) and CT	Fusion; spinous distance on flexion-extension lateral dynamic X-ray < 2 mm, absence of lucency within interface of bone graft-vertebral body interface. CT performed if X-ray findings equivocal (no abnormal motion, but persistent lucency at bone-graft interface, or difficult to assess)	94.7% / 1 year	150	Cohort
Maroon et al <sup>32</sup>	Not defined	Not defined	X-ray (flexion-extension views)	Not defined	Not mentioned	15	Cohort
Yoshii et al <sup>33</sup>	Evaluation at 2 years	HA blocks with iliac crest cancellous bone + plate, autologous tricortical strut of iliac crest + plate	X-ray (flexion-extension views) and CT	(1) Absence of radiolucent zone between HA and endplates on reconstructed CT, (2) continuous bone bridging across intervertebral space on lateral sides of HA block on reconstructed CT, and (3) lack of translation or angulation on lateral flexion-extension X-ray	92% / 2 years	51	Prospective cohort
Zigler et al <sup>34</sup>	Evaluation at 6 weeks; 3, 6, 12, 18 months; and annually thereafter for a minimum of 5 years	Allograft bone spacers and, when available, local bone + plate	X-ray (flexion-extension views)	More than 50% trabecular-bridging or bone mass maturation with increased or maintained bone density at site, <2° motion, no visible gaps in fusion mass, <3 mm loss of disc height, no implant loosening, that is, no halos or radiolucencies around implant	88.9% / 2 years 92.5% / 5 years	106	RCT
Coric et al <sup>35</sup>	Evaluation at 6 weeks; 3, 6, and 12 months; and annually thereafter for a minimum of 48 months	Structural corticocancellous allograft + plate	X-ray (flexion-extension views)	Composite of >50% trabecular-bridging bone, ≤2° of motion, and no implant loosening	97% / 6 years	33	RCT
Park et al <sup>36</sup>	Mean follow-up at 64.2 months	PEEK cage with iliac crest autograft bone	CT	Bridwell grading system on final CT, only grade I defined as fusion (fused with remodeling and trabeculae)	95.2% / 5 years	21	Cohort

(continued)

**Table 1.** (continued)

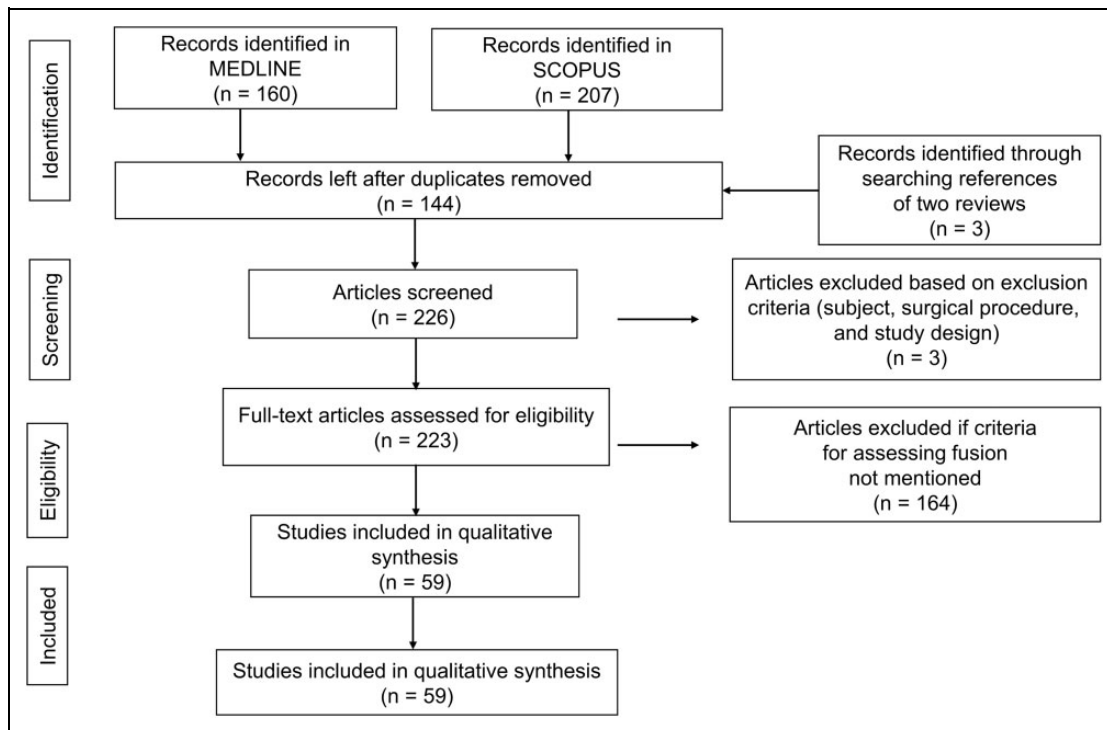
Study	Follow-up	Graft	Imaging	Fusion Criteria	Fusion Rate/Evaluation Time	Patients (N)	Study Design
Barbagallo et al <sup>37</sup>	Evaluation at 6 weeks; 3, 6, and 12 months; and annually thereafter; Mean follow-up at 27.3 months	Zero-profile cage or standalone CFRP cage with bone substitute	X-ray	No radiolucencies detected in graft-endplate area, bridging trabeculation	94.5% / last follow up	32	Prospective cohort
Song et al <sup>38</sup>	Evaluation at least 1 year	Autocortical graft, allograft, and synthetic cage + plate	CT	Extragraft bone bridging, was more reliable and accurate to determine anterior cervical fusion than intragraft bone bridging	Not mentioned	101	Cohort
Njoku et al <sup>39</sup>	Mean follow-up at 9.76 months; fusion was assessed at a minimum of 7-month follow-up	Zero-profile cage with silicon-substituted calcium HA	X-ray (flexion-extension views) and CT	Bony bridging across intervertebral space on CT or <4° of dynamic flexion-extension X-ray	50/54 levels / latest follow up	41	Cohort
Iwasaki et al <sup>40</sup>	Evaluation at 1, 2, 3, and 6 months	Box-type titanium cage with harvested cancellous bone alone or + plate	X-ray (flexion-extension views) and CT	Dynamic X-ray to identify segment stability of 2 vertebrae, thin-section CT to identify bridging bone formation between endplates of fused vertebral bodies outside cage, and no visible radiolucency around cage	100% / 6 months	16	Cohort
Fay et al <sup>41</sup>	Evaluation at 24 months	ACDF + plate and ACCF + plate	X-ray and CT	Not defined	100% / 24 months	40	Cohort
Eastlack et al <sup>42</sup>	Evaluation at 6, 12, and 24 months	PEEK cage with allograft cellular bone matrix + plate	X-ray and CT	Continuous bridging bone, that is, trabecular continuity across involved motion segment from endplate to endplate	87% cases have bridging bone / 24 months (Not mentioned about fusion)	182	Prospective cohort
Lee et al <sup>43</sup>	Mean follow-up at 21.3 months	PEEK cage with demineralized bone matrix + plate	X-ray (flexion-extension views)	Bridwell fusion grading system <sup>65</sup> and flexion-extension X-ray (magnified 200%), fusion defined as grade 1–2 and absence of motion on flexion-extension X-ray	89.5% / last follow up	95	Cohort
van Eck et al <sup>44</sup>	Mean follow-up at 31 months	Tricortical autograft or corticocancellous allograft + plate	X-ray (flexion-extension views) and CT	Pseudarthrosis defined as >2 mm of motion between fused spinous processes on flexion-extension X-ray, hardware loosening, or CT evidence of absence bridging trabeculae	92% / last follow up	672	Cohort
Song et al <sup>45</sup>	Evaluation at least 1 year	Graft + plate	X-ray (flexion-extension views) and CT	Nonunion defined as no bridging bone and/or radiolucency at graft-vertebral junction; interspinous motion <1 mm cutoff for detection of anterior cervical pseudarthrosis on X-ray magnified 150%	Not mentioned	125	Cohort
Chen et al <sup>46</sup>	Evaluation at 2 and 6 months and annually thereafter; mean follow-up at 41.9 months	Zero-profile spacer, cage with demineralized bone matrix + plate	X-ray and CT	Not defined	92.8% / 6 months 100% / final follow-up	69	Prospective cohort
Shi et al <sup>47</sup>	Mean follow-up and evaluation at 30.1 and 30.5 months	PEEK cage with excised osteophytes and β-TCP, zero-profile spacer with excised osteophytes and β-TCP	X-ray (flexion-extension views)	Less than 2° motion on flexion-extension X-ray and absence of radiolucency gap between graft and endplate	86.8% / 3 months 100% / final follow-up	38	Cohort
Lee et al <sup>48</sup>	Mean follow-up at 44.6 months; minimum follow-up more than 2 years	Stand-alone cage with allograft	X-ray	Bony bridge on a lateral X-ray	82.2% / last follow-up	28	Cohort
Jeyamohan et al <sup>49</sup>	Evaluation at 6, 12, and 24 months	Carbon-fiber cage with HA, type I collagen, and autologous iliac crest bone marrow aspirate + plate	CT	Bridging osseous trabeculae spanning each operative level without any intervening X-ray lucencies	93.8% / 2 years	112	RCT
Engquist et al <sup>50</sup>	Minimum follow-up at 12 months	Cylindrical titanium implant with autologous bone or trabecular metal cage + plate	X-ray (flexion-extension views)	Absence of movement between fused segments on flexion-extension X-ray	100% / 3 months	30	RCT
Phillips et al <sup>51</sup>	Follow-up at 1.5, 3, 6, and 12 months and thereafter annually for 7 years	Allograft and plate	X-ray (flexion-extension views)	Continuous bridging bone between adjacent endplates of involved motion segment, radiolucency lines at ≤50% of the graft-vertebra interfaces, and ≤2° segmental rotation on lateral flexion-extension X-ray	94.4% / 5 years	126	RCT
Skeppholm et al <sup>52</sup>	Evaluation at 1 and 2 years	Tricortical iliac crest bone graft + plate	X-ray (flexion-extension views) and CT	Not defined	Not mentioned	153	RCT
Li et al <sup>53</sup>	Evaluation at 3, 6, 12, and 60 months	Tricortical iliac crest graft or PEEK cage with bone	X-ray (flexion-extension views)	Not defined	Not mentioned	35	Cohort

(continued)

Table 1. (continued)

Study	Follow-up	Graft	Imaging	Fusion Criteria	Fusion Rate/Evaluation Time	Patients (N)	Study Design
Lau et al <sup>54</sup>	Mean follow-up for ACCF is 32.1 months and for ACDF is 22.1 months	ACCF: PEEK cage or expandable cages with allograft or autograft + plate ± PSF ACDF: allograft or PEEK cage with allograft or autograft + plate ± PSF	X-ray (flexion-extension views)	Pseudarthrosis defined as (1) radiolucent lines or absence of bridging trabecular bone across fusion site, (2) motion between spinous processes on flexion-extension X-ray, or (3) motion between vertebral bodies on flexion-extension X-ray	93.2% / minimum follow-up 1 year	44	Cohort
Davis et al <sup>55</sup>	Evaluation at 48 months	Corticocancellous allograft + plate	X-ray (flexion-extension views)	Fusion of both treated levels: <2° angular motion on flexion-extension X-ray and evidence of bridging bone across disc space and radiolucent lines at ≤50% of graft vertebral interfaces	85.2% / 4 years	81	RCT
Wang et al <sup>56</sup>	At least 12 months, mean follow-up at 24 months	Zero-profile anchored spacer with excised local osteophytes to contain rhBMP-2, stand-alone cages + plate	X-ray (flexion-extension views), CT	(1) Absence of motion between spinous processes on dynamic lateral X-ray, (2) absence of radiolucent gap between graft and endplates, (3) continuous bridging bony trabeculae at graft-endplate interface. Two-dimensional CT reconstruction if X-ray is unclear	100% / 3 and 6 months	63	Cohort
Chen et al <sup>57</sup>	Mean follow-up at 28.8 and 29.6 months	Self-locking stand-alone PEEK cage with porous bioceramic artificial bone, PEEK cage with porous bioceramic artificial bone + plate	X-ray (flexion-extension views) and CT	Nonunion defined as >2° range of motion on flexion-extension lateral X-ray or a radiolucent gap between graft and endplate on X-ray or CT scans in at least one operative level at the last follow-up	88.9% / last follow-up	54	Cohort
Vanichkachorn et al <sup>58</sup>	Evaluation at 6 and 12 months	PEEK cage with viable cellular cancellous bone matrix and demineralized cortical bone + supplemental anterior fixation	X-ray (flexion-extension views) and CT	Bridging bone across adjacent endplates on thin cut CT with angular motion on flexion-extension X-ray	93.5% / 1 year	31	Prospective cohort
Mayo et al <sup>59</sup>	Evaluation at 6 months and 1 year	Cage with local autograft, allograft, or bone graft substitute + plate	CT	Bony bridging on 3 sequential cuts in sagittal and coronal planes on CT. Pseudarthrosis defined as endplate sclerosis, subchondral cysts, or haloing around cages or pedicle screws	100% / 1 year	124	Case series
Liu et al <sup>60</sup>	Evaluation at 1, 3, and 6 months and annually thereafter Mean follow-up at 23.8 months	PEEK cage with rhBMP-2 + plate	X-ray (flexion-extension views) and CT	(1) Absence of motion between spinous processes, (2) absence of radiolucent gap between graft and endplate, and (3) continuous bridging bony trabeculae at the graft-endplate interface	100% / 3-6 months 100% / final follow-up	60	Cohort
Arnold et al <sup>61</sup>	Evaluation at 12 months	Cortical allograft ring filled with autograft bone + plate or cortical allograft ring with i-Factor + plate	X-ray (AP, lateral, flexion, extension views), CT	Bridging trabecular bone between involved motion segments, translational motion <3 mm and angular motion <5°. If lack of evidence of bridging bone on 12-month plain X-ray, then CT used to make final determination of fusion, defined as trabecular bone formation patterns within intervertebral disc space or bridging bone formation that crossed interspace	90.7% / 12 months	313	RCT
McAnany et al <sup>62</sup>	Evaluation at 6 or 12 months	Interbody allograft with combination of demineralized bone matrix, cancellous cadaveric bone, and live mesenchymal stem cells + plate	X-ray (flexion-extension views), CT	Bridging bone inside and outside the graft. Absence of lucent lines at the graft-host bone interface	91.2% / 1 year	114	Cohort
Liu et al <sup>63</sup>	Minimum follow-up for 2 years; mean follow-up for 45.7 months	Autologous bone with or without titanium mesh cage + plate	CT	Fusion defined as bridging trabeculae on CT; lack of fusion when no bridging trabeculae seen and/or bony gap seen at graft-vertebral body junction	46.2% / final follow-up	26	Cohort
De la Garza-Ramos et al <sup>64</sup>	Evaluation at 3, 6, and 12 months	Iliac autograft or allograft	X-ray and CT	Not defined	91.8% / 12 months	26	Cohort

Abbreviations: ACCF, anterior cervical corpectomy and fusion; ACDF, anterior cervical discectomy and fusion; AP, anteroposterior;  $\beta$ -TCP,  $\beta$ -tricalcium phosphate; CFRP, carbon fiber reinforced polymer; CT, computed tomography; HA, hydroxyapatite; PEEK, polyetheretherketone; PSF, posterior spinal fusion; rhBMP-2, recombinant human bone morphogenetic protein-2; Cohort, retrospective cohort study or not mentioned whether retrospective or prospective; RCT, randomized control study.



**Figure 1.** Study selection flowchart for search of articles pertaining to radiological fusion criteria.

**Table 2.** Inclusion and Exclusion Criteria for Selection of Articles.

	Inclusion Criteria	Exclusion Criteria
Period	Published between January 1, 2011 and June 30, 2016	Published before 2010
Journals	<i>European Spine Journal</i> <i>Global Spine Journal</i> <i>Journal of Bone and Joint Surgery</i> <i>Journal of Neurosurgery: Spine</i> <i>Neurosurgery</i> <i>Spine</i> <i>The Spine Journal</i>	
Subjects	Human study	Animal, in vitro, biomechanical study, review, letter
Surgical level	Cervical spine	Thoracic or lumbar spine
Surgical procedure	Anterior fusion or anterior-posterior fusion	Posterior fusion, facet fusion
Study design	Randomized controlled studies Cohort studies Case-control studies Cross-sectional studies Case series	Review article Case study

- IX. One article defined subchondral cysts as indicating pseudarthrosis.
- X. One article defined fusion by double-lucency around the titanium marker of PEEK cages on radiographs.

various combinations of criteria reported by 19 articles were not significantly different ( $P = .60$ ).

### Discussion

In 8 articles, the mean 1-year fusion rate was 90.2%. In 23 articles, the mean 2-year fusion rate was 94.7%. The 1-year fusion rates were not significantly different,  $\chi^2(0.95) = 21.0$ , degrees of freedom ( $df$ ) = 12,  $P = .30$ , but the 2-year fusion rates were significantly different,  $\chi^2(0.95) = 43.8$ ,  $df = 30$ ,  $P = .048$ . The differences in 2-year fusion rates observed with

We found 4 major criteria (I-IV) that were used to assess fusion, and except for those that did not specify fusion criteria, all articles used least 1 of the 4 or combinations of the 4. All but 2 articles that reported fusion 1- or 2-year fusion rates used the bridging trabecular bone criterion (I). The 2-year fusion rates determined using combinations including criterion I were not

**Table 3.** Criteria for Assessing Fusion or Pseudarthrosis After Cervical Fusion Surgery.

Fusion or Pseudarthrosis Criteria	Cumulative No. of Cases
I. Presence of bridging trabecular bone between the endplates	Total 44
Bridging degree not stated	42
More than 50% trabecular bridging	2
II. Absence of a radiolucent gap between the graft and the endplate	Total 31
Radiolucent rate not stated	27
Less than 50% of graft vertebral interfaces	4
III. Cutoff angulation or translation between vertebral bodies on flexion-extension X-rays	Total 24
Angulation or translation not reported	8
0° and 0 mm	1
2° and 3 mm	1
5° and 3 mm	2
2°	8
3°	1
4°	2
1°-4°	1
IV. Cutoff of motion between spinous processes on flexion-extension X-ray	Total 11
0 mm	6
2 mm	3
1 mm	1
3 mm	1
Implant failure	Total 4
Magnified images	Total 2
Loss of disk height (pseudarthrosis criteria)	Total 1
Endplate sclerosis (pseudarthrosis criteria)	Total 1
Subchondral cysts (pseudarthrosis criteria)	Total 1
Double-lucency around titanium marker of PEEK cage on X-ray	Total 1

**Table 4.** Combination of Fusion Criteria and Fusion Rate at 2 Years.<sup>a</sup>

Combination of Fusion Criteria	Fusion Rate at 2 Years
Bridging trabecular bone (I)	72.6%, 90.2%, 100%
Bridging trabecular bone (I) + radiolucent gap (II)	93.8%, 100%
Bridging trabecular bone (I) + radiolucent gap (II) + angulation or translation between vertebrae (III)	82%, 88.9%, 92%, 100%, 100%
bridging trabecular (I) + radiolucent gap (II) + motion between spinous process (IV)	90%, 92%, 100%, 100%
bridging trabecular (I) + angulation or translation between vertebrae (III)	89.1%, 92.1%, 95.4%, 100%, 100%

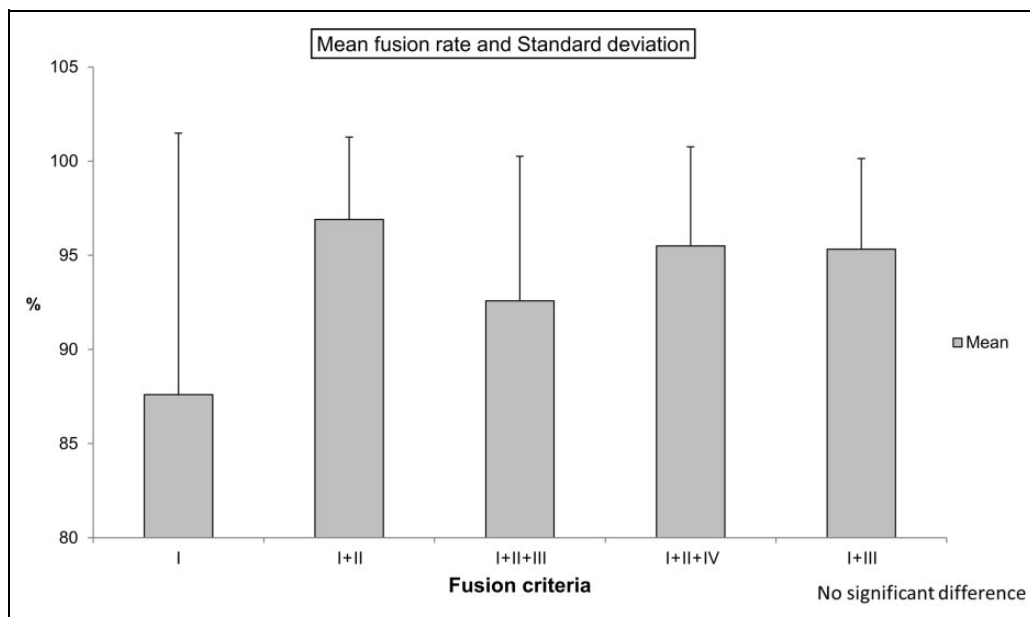
<sup>a</sup>Combinations that were reported in 2 or more articles were analyzed.

significantly different, but the mean fusion rate of only criterion I was the lowest in those combinations, regardless of using the minimum number of criteria (Figure 2). The 1-year fusion rates reported in the reviewed articles were not significantly different, but the 2-year fusion rates were ( $P = .048$ ). The 1- and 2-year fusion rates reported in 29 articles had a large range from 60% to 100%. Some articles reported solid fusion rates of 100% at 3 months and others reported rates of 42% at 4 years. As expected, the fusion rates fluctuated widely. We considered that the range in reported fusion rates resulted from differences in radiographic interpretation as well as fusion level, type of implant, patient history, and surgical technique.

It was difficult to decide which criteria were the most reliable, but the most highly documented criteria and the most objective radiographic assessments had the strongest support. Criterion I, visualization of bridging trabecular bone between the endplates, was the most commonly used criterion, followed

by the absence of radiolucency between graft and endplate (criterion II). Both criteria are subjectively determined because there is no objective scale to measure the findings, at least on plain radiographs. It is therefore not unusual for clinicians to add CT imaging to overcome this drawback. It has been reported that pseudarthrosis can be accurately identified on both plain X-ray films and CT images.<sup>2,67</sup> However, even the evaluation of CT images is somewhat subjective. Several articles used a cutoff value of 50% of the space between graft and endpoint to satisfy these criteria, that is, trabecular bone bridging at least 50% of the gap or radiolucency involving less than 50%. Disappearance of the endplates of the 2 adjacent vertebral bodies might also be helpful in deciding whether fusion had been accomplished. Motion of vertebral bodies on flexion-extension radiographs (criterion III) involves an upper limit of Cobb angles ranging from 0° to 5° and an upper limit for translation ranging from 0 to 3 mm. When Cobb angles were





**Figure 2.** Mean fusion rate with combined fusion criteria.

calculated, the endplates could be rotated with an apparent angle mismatch in the extension and flexion views. Kaiser et al<sup>3</sup> reported that an interspinous distance of  $\geq 2$  mm on dynamic radiographs was a more reliable indicator of pseudarthrosis than an angular motion of  $2^\circ$  using Cobb angle measurements. They recommended the use of interspinous distance rather than Cobb angles (quality of evidence class II and strength recommendation B).<sup>3</sup> By itself, instability of the anterior-posterior diameter is generally considered to indicate nonfusion; accepting any motion between vertebral bodies is not recommended.

Eleven articles reported cutoff values for motion between spinous processes on flexion-extension radiographs (criterion IV) ranging from 0 to 3 mm. A value of 0 mm was used in 6 studies. A gap of 0.1 mm would indicate failure of fusion by this criterion, calculating the distance between spinous processes in flexion-extension views is difficult to do without error. Consistent measurement to that degree of precision is extremely difficult to attain without using a standardized coordinate system for radiographic measurements.<sup>68,69</sup> Two studies overcame this difficulty using magnified images.<sup>43,45</sup> If the vertebral bodies are completely solid, fused masses anteriorly and posteriorly in the facets without any defect, then interspinous motion on flexion-extension views will be 0 mm. Until the facets fuse posteriorly, interspinous process motion of  $<1$  mm can be observed even with confirmed anterior fusion. A 2-mm cutoff value was reported in 3 articles. Studies published before those reviewed here included several radiographic criteria for pseudarthrosis, including a gap  $>2$  mm between the spinous processes on lateral flexion-extension radiographs,<sup>70</sup> and a gap  $>2$  mm between the tips.<sup>71</sup> A study by Song et al<sup>45</sup> that was reviewed here reported that a difference of  $<1$  mm in interspinous motion was an accurate criterion with good specificity and positive predictive value. That finding was based on

images magnified by 150% and superjacent interspinous motion  $\geq 4$  mm to ensure adequate flexion and extension. The evidence was rated as level II.<sup>45</sup>

Some of the minor criteria (V-XI) might be useful as an adjunct to the diagnosis of cervical fusion, but we believe that they are not acceptable on their own as criteria for assessing fusion. Adopting level II or higher evidence, we recommend a difference of  $<1$  mm of motion between the spinous processes on lateral flexion-extension radiographs as the fusion criterion. When we evaluated the reported recurrence of symptoms or neck pain after surgery, images that appeared at first glance to show fusion and bridging the trabecular bone were occasionally correctly diagnosed as pseudarthrosis using our recommended fusion criterion. The relative motion of spinous processes allows for objective evaluation, is easy to use, and is clear to every evaluator.

There are some study limitations. First, if the fusion level, type of implant, patient history, and surgical technique were all included in the analysis, the fusion rates would be different. However, the small size of the subgroups would be too small to evaluate accurately. Second, the review included articles with low evidence levels and whose primary clinical endpoint was not fusion rate. By including them in the analysis along with studies using the 4 major criteria, the fusion rates would be different.

## Conclusion

The presence of bridging trabecular bone between the endplates was the most commonly used definition of fusion. The use of both CT images and plain radiographs might be needed for this assessment, and even the evaluation of CT is somewhat subjective. A criterion of no motion at all between spinous processes on flexion-extension radiographs may be too strict.

The published evidence supports a cutoff value of <1 mm of movement is recommended when confirming fusion.

### Declaration of Conflicting Interests

The author(s) declared the following potential conflicts of interest with respect to the research, authorship, and/or publication of this article: Dr Riew owns stock in Osprey, Expanding Orthopedics, Spineology, Spinal Kinetics, and Nexgen Spine and receives honorarium from Advanced Medical, Grand Rounds, Medtronic, Zeiss, and Zimmer Biomet. Dr Tanaka has received honoraria from Amgen Inc, Asahi Kasei Pharma Corporation, Amgen Astellas BioPharma K.K., Kyocera Medical Corporation, Daiichi Sankyo Company, Limited, Teijin Pharma Limited., Eli Lilly Japan K.K., Pfizer Japan Inc, endowments from Astellas Pharma Inc, Ayumi Pharmaceutical Corporation, Bristol-Myers Squibb, Pfizer Japan Inc, Daiichi Sankyo Company Limited, Chugai Pharmaceutical Co, Ltd, and grants from The Japan Agency for Medical Research and Development (AMED), Japan Society for the Promotion of Science (JSPS)/Grant-in-Aid for Scientific Research (A), and the Japan Society for the Promotion of Science (JSPS)/Grant-in-Aid for Exploratory Research.

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