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Radiological diagnosis of acute mesenteric ischemia in adult patients: a systematic review and meta-analysis

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Computed tomography (CT) is widely used in diagnosing acute mesenteric ischemia (AMI), but robust identification of distinctive subtypes and stages of progression is lacking. Systematic literature search in PubMed, Cochrane Library, Web of Science and Scopus was conducted in May 2024. Studies including at least 10 adult patients and reporting radiological diagnosis of AMI *versus* no AMI or transmural ischemia *versus* no transmural ischemia were included. Meta-analyses on sensitivity and specificity of different radiological features in diagnosing AMI were conducted. From 2628 titles, 490 studies underwent full text review, and 81 were included in 14 meta-analyses. Diagnostic accuracy of CT angiography (CTA) was high - sensitivity of 92.0% and specificity of 98.8% (I^2 45% and 79%, respectively), but lower for other CT protocols (sensitivity 75.8 and specificity 90.5; I^2 83%). In most included studies, distinction of subtypes and severity of AMI (non-transmural or transmural) was not possible. Amongst the non-vascular features, absent/reduced bowel wall enhancement provided the best prognostic value (sensitivity 57.9 and specificity 90.1). CTA is the method of choice for diagnosing AMI with high diagnostic accuracy. None of the non-vascular features alone is sufficiently reliable to diagnose AMI or its progression to transmural necrosis, whereas a combination of different radiological features conveys a potential.

Keywords Acute mesenteric ischemia, Computed tomography, Diagnostic accuracy, Adult, Radiology

Acute mesenteric ischemia (AMI) may develop through distinct etiopathogenetic mechanisms and results in high mortality[1,2]. Computed tomography (CT), the diagnostic method of choice for diagnosing or excluding AMI, has been increasingly used and developed during the past few decades; however, no major improvement in AMI survival has been achieved[1,2].

CT angiography (CTA) can reveal vascular stenosis or occlusion and non-vascular signs that suggest intestinal injury. There is consensus on biphasic CTA - with arterial and portal venous phases – being the gold standard in diagnosing AMI, but some uncertainty regarding the usefulness of unenhanced images remains[3–9]. Unenhanced images allow assessment of bowel wall attenuation and its comparison with the enhanced phase, and visualization of intramural/submucosal hemorrhage[8,9].

The definitions of the subtypes of AMI and conditions considered under the AMI umbrella (e.g., strangulating bowel obstruction) are not unified, complicating direct comparison of studies on AMI. While the diagnosis of transmural AMI will usually be confirmed during surgery, the diagnosis of non-transmural AMI is mainly confirmed by survival without bowel resection after restored perfusion through revascularization in the case of occlusive AMI, or through optimization of vascular filling and vascular tone in the case of non-occlusive AMI

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(NOMI). The same non-vascular signs may reflect ischemic and reperfusion injury, depending on the subtype of AMI[9], complicating the diagnosis and influencing all the related meta-analyses.

Evidence regarding the accuracy of CT in diagnosing AMI is largely based on small retrospective studies, and different subtypes of AMI pooled in meta-analyses[10,11]. The accuracy of CT in diagnosing AMI and related specific non-vascular features is expected to depend on the CT protocol and to differ between the subtypes of AMI[12], but so far these differences have been insufficiently assessed. Previous systematic reviews originate from more than a decade ago[11,13], and more recent ones have only looked at radiological predictors of transmural AMI[10,14]. A systematic review on multi-slice computed tomography (MSCT), published in 2019, included eight cohort/case control studies and demonstrated very high sensitivity and specificity of MSCT in diagnosis of AMI, however, without distinguishing between the different subtypes of AMI[15].

Meta-analyses assessing the value of specific radiological signs characterizing bowel wall pathology in different subtypes of AMI in comparison to no AMI are not available.

We aimed to assess the accuracy of CT in the diagnosis of AMI and its different subtypes in adult patients.

Methods

Study population and research questions

After assessing available studies, it occurred that studies did not uniformly use contrast-enhanced CT, but in many cases reported different phases, including non-enhanced CT, pooled into one group. For this reason, we modified our research questions of the original study protocol, omitting "contrast-enhanced," as we were not able to separate results based on contrast enhancement.

We defined our study population as adult patients (aged ≥ 18 years) with any subtype of AMI (arterial occlusive, venous, non-occlusive) and formulated the following research questions:

1. What is the accuracy of computed tomography in diagnosing AMI?
2. What is the accuracy of computed tomography in diagnosing transmural intestinal ischemia?

Inclusion criteria

- Clinical studies of any type including at least 10 patients in whom acute mesenteric ischemia was considered in their diagnostic workup;
- Studies reporting confirmation of the final diagnosis of AMI at surgery, contrast-enhanced computed tomography, invasive mesenteric angiography, endoscopy and/or histopathological examination;
- Studies reporting radiological diagnosis or specific radiological features of AMI *versus* no AMI or transmural AMI vs. no transmural AMI reported with measures of effect obtainable in a form of sensitivity, specificity or odds/risk ratio.

Exclusion criteria

- Experimental studies;
- Studies of pediatric patients;
- Studies with fewer than 10 adult patients;
- Papers not reporting original patient data (e.g., reviews, editorials);
- Studies where AMI was not the studied condition or was not confirmed as defined above;
- Studies recruiting patients before the year 2000;
- Studies where data were not extractable in a way necessary for the analysis.

Evidence searches

A systematic literature search was performed in PubMed, The Cochrane Library, Web of Science and Scopus. The search was not restricted by language. Search strategies are presented in Supplement 1. According to the study protocol (PROSPERO CRD42024543387), common searching for studies assessing the risk factors, and clinical and radiological predictors of AMI was performed. After retrieving eligible studies and data extraction, the findings/studies were split into two parts; the current review summarizes the "radiological" part, whereas the "clinical" part is published in a separate paper.

The search was limited to studies published after 01.01.2001, aiming to identify all studies commencing patient recruitment in the current millennium. This time limit was set, based on the availability of and advances in CT-scan diagnostics[11], and is in line with our previous systematic review on AMI incidence and outcomes, defining earlier and later studies with the cut-off at year 2000[1]. The final search was performed in June 2024. Additional searching was performed, reviewing the reference lists of systematic reviews and the individual studies, included in the review.

Study selection and data extraction

Titles and abstracts of studies identified, following the predefined search strategy, and after removal of duplicates, were screened independently by two reviewers to identify eligible studies for full text review. Full texts of the selected studies were independently assessed by two reviewers. For any disagreements during title/abstract and full text review consensus was reached involving a third reviewer as needed. Google translate was used in the full text review phase to translate non-English full texts in languages other than the Finnish, French, German, Italian, and Russian that were known to the co-authors.

The following information was extracted from studies, included in the systematic review: study setting, patient selection, age, gender, diagnostic modality, number of patients with and without AMI (or transmural

ischemia vs. no transmural ischemia), number of patients with outcome (radiological feature) in all groups, sensitivity and specificity and/or odds ratio of the diagnostic modality for diagnosis of AMI, progression, subtype and localization of AMI (if available).

Assessment of studies and data extraction was performed by clinicians of different specialties (surgery, critical care, gastroenterology, radiology) with at least 5 years of clinical experience and previous experience in the process of performing a systematic review.

Study quality assessment

The QUADAS-2 tool to assess risk of bias and applicability of studies included in the review was used in parallel by two research team members[16]. Decisions were made after reaching consensus, with involvement of a third reviewer as needed. Overviews of QUADAS-2 assessment results for all the included studies and per each meta-analysis were made. When a study was judged as "low" on all the four key domains assessed, it was judged as having "low risk of bias" / "low concern regarding applicability"; when a study was judged "high" or "unclear" on at least one of the domains, it was judged as being "at risk of bias" / having "concerns regarding applicability". A summary of the number of studies that found low, high or unclear risk of bias and applicability concerns for each of the domains assessed, for all the included studies and per each meta-analysis was compiled.

Data synthesis and analysis

Two-by-two contingency tables were constructed and sensitivity and specificity calculated where possible for each variable studied as a predictor of AMI and these calculated values were used in analyses. If sensitivity and specificity reported in the original paper and values calculated based on provided numbers of patients in the same paper were different, the recalculated values based on reported numbers of patients were used.

Adjusted odds ratios for each variable studied as a predictor of AMI were extracted as reported in the original papers.

We performed meta-analysis, when at least two studies had reported adjusted odds ratios or data in an extractable format.

A random-effects model was used to calculate pooled sensitivity and specificity. We assessed study heterogeneity by I squared measures. Studies with an I-squared value below 25% were considered homogeneous, those of 26–50% were considered to show low, 51–75% moderate and over 75% high heterogeneity, respectively.

Subgroup analyses for definition of study population, imaging modalities, different subtypes of AMI and severity/stage of AMI were performed when possible.

The following subpopulations were assessed separately:

- AMI, excluding strangulating bowel obstruction (SBO).
- AMI, including SBO.

The following subtypes of AMI are presented separately:

- Venous occlusive (mesenteric venous thrombosis).
- Non-occlusive.

Subtypes of AMI could not be distinguished in most of the studies, therefore the largest subtype – arterial occlusive AMI – is presented separately only for vascular signs and otherwise reported within the large group of any subtype.

The following comparisons, based on severity/stage of AMI, are presented:

- AMI (any stage of severity) vs. no AMI.
- Transmural intestinal ischemia vs. no transmural ischemia (may include both no ischemia and non-transmural ischemia).

Studies based solely on SBO, reporting transmural ischemia vs. no transmural ischemia, were also included in the analysis with the rationale that such patients were included in the AMI group in many studies.

For specific radiological features, we also included studies assessing only patients with AMI (no control group) and accordingly report only sensitivity, but no specificity.

If a subtype of venous AMI or NOMI was reported separately as a part of a larger mixed cohort of all subtypes of AMI, we presented this subgroup separately on respective Forest plot, whereas the overall analysis included only the large group. If a study assessed only one subtype of AMI, it was included in the meta-analysis for overall total.

For vascular signs, we performed two meta-analyses: (1) diagnostic accuracy of arterial or venous occlusion identifying AMI in a mixed cohort patients with any subtype of AMI; (2) diagnostic accuracy of arterial or venous occlusion in patients with arterial or venous occlusive AMI.

Sensitivity analysis, excluding all the studies with high risk of bias from the analysis was also considered.

Results

The searches identified 2607 titles, and 21 additional studies were identified from systematic reviews and individual study reference lists. In total, 490 studies were selected for full text review (Fig. 1).

We were unable to retrieve 6 papers; 387 papers were excluded after full text review (Fig. 1); data extraction was performed for 95 studies. A full list of radiological variables reported in identified studies is presented in Supplement 2 Table S1. Fourteen meta-analyses – including 81 studies – were performed on sensitivity and

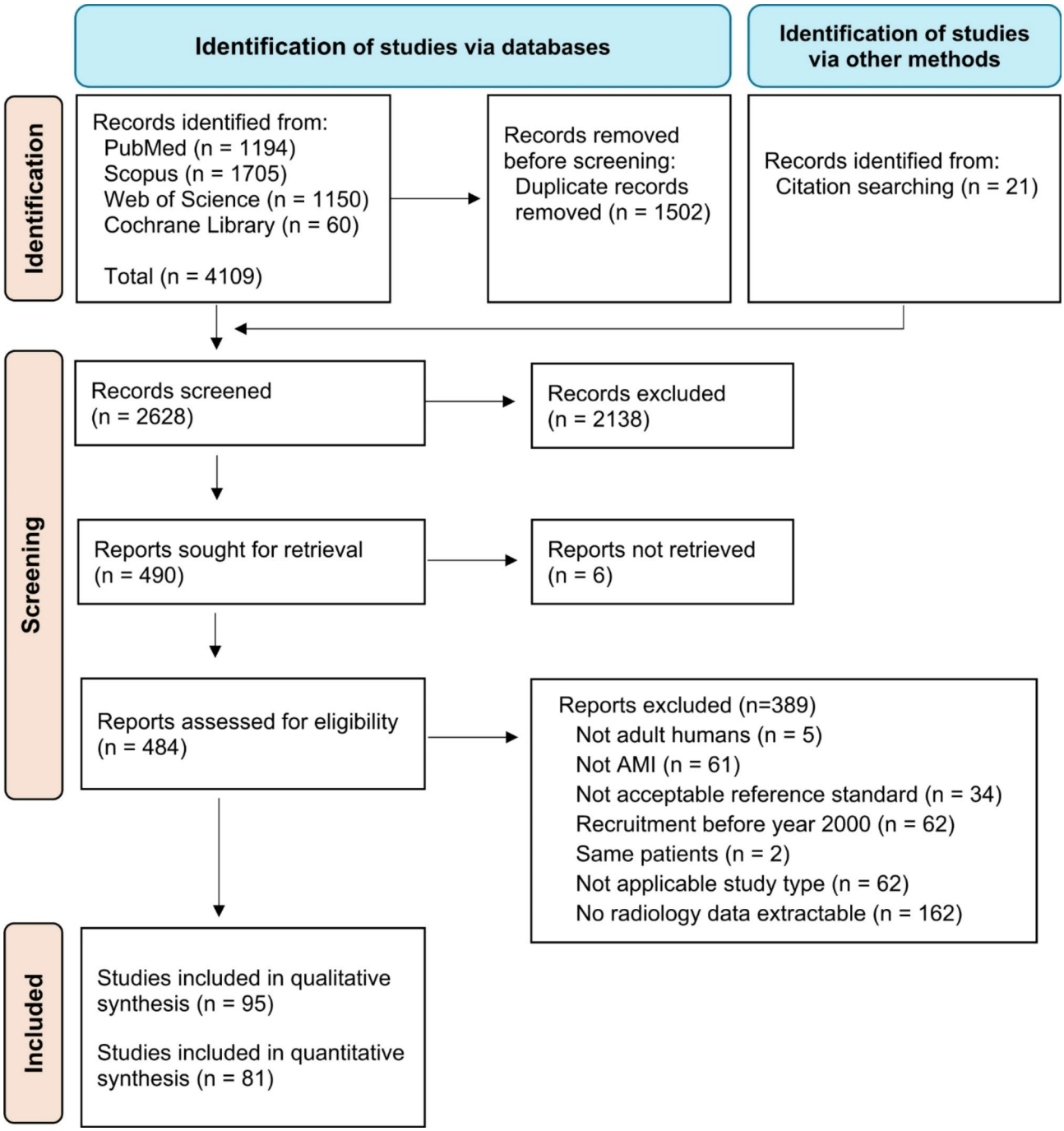

Fig. 1. Flow diagram.

specificity (Table 1; Figs. 2, 3, 4, 5 and 6 and Supplement 3 Figures S1–S9)[8,17–96], . One study reported odds ratios, but sensitivity and specificity could not be calculated[55]. Three non-English papers were finally included in the study, two in Russian and one in Chinese[43,51,70].

The accuracy of the diagnosis of AMI with CT considering any applicable features (hereafter referred as "composite diagnosis") is presented in Fig. 2.

In diagnosing AMI, the highest sensitivity (92.5, 95% CI 85.6–96.2) and specificity (98.5, 95% CI 90.8–99.8) were observed in studies looking at CT angiography (CTA) in patients with AMI, excluding patients with SBO. Sensitivity was lower for studies using also other CT enhancement phases (CTA not performed for all patients), with variable signals in studies including vs. excluding patients with SBO (Table 1; Fig. 2). Diagnostic accuracy was worse among patients with NOMI, but this finding is based on only 2 studies (Fig. 2).

For all non-vascular signs, sensitivity was insufficient to allow appropriate identification of AMI (Table 1; Figs. 2, 3, 4, 5 and 6 and Supplement 3 Figures S1–S7). Sensitivity was highest for mesenteric signs (stranding,

Variable	Number of studies (patients)	Sensitivity (95% confidence interval)	I^2	Specificity (95% confidence interval)	I^2	Adjusted odds ratio (95% confidence interval) [*N* of studies][5]
Composite diagnosis of AMI[1]	24[2] (3391)	85.5 (78.1–90.6)	78%	96.1 (91.0–98.3)	88%	
AMI any stage with CTA	12 (2028)	92.0 (86.3–95.5)	45%	98.8 (95.1–99.8)	79%	NA
Excluding SBO	10 (1107)	**92.5 (85.6–96.2)**	49%	**98.5 (90.8–99.79)**	72%	NA
Including SBO	2 (921)	89.8 (84.8–93.4)	0%	**99.5 (98.7–99.8)**	0%	NA
AMI any stage with any CT modality (including CTA)	8 (1363)	75.8 (63.3–85.1)	83%	90.5 (78.8–96.1)	88%	7.4 (2.3–24.0) [1]
Excluding SBO	6 (352)	74.9 (51.0–89.5)	83%	69.3 (48.4–84.5)	79%	7.4 (2.3–24.0) [1]
Including SBO	2 (429)	65.9 (44.5–82.3)	75%	**97.2 (81.7–99.6)**	90%	NA
Transmural ischaemia in SBO	5 (582)	80.4 (63.6–90.6)	88%	**95.2 (92.3–97.1)**	0%	NA
Bowel wall characteristics						
Reduced/absent enhancement of the bowel wall	37 (3840)	57.9 (50.4–65.1)	85%	90.8 (85.5–94.4)	83%	14.3 (6.4–31.2) [3]
AMI vs. no AMI	14 (1484)	46.1 (34.3–58.3)	83%	**95.9 (90.1–98.4)**	71%	22.9 (7.9–66.2) [1]
Transmural vs. no transmural	23 (2402)	**64.7 (56.7–72.4)**	83%	86.9 (79.0–92.1)	85%	8.1 (2.5–26.1) [2]
Thickening of the bowel wall	47 (5238)	56.4 (50.4–62.2)	79%	63.4 (53.7–71.8)	90%	3.1 (1.1–8.5) [1]
AMI vs. no AMI	18 (1855)	**61.0 (50.4–72.0)**	84%	67.0 (46.9–82.4)	73%	NA
Transmural vs. no transmural	29 (3393)	53.3 (46.4–60.1)	70%	61.8 (50.6–71.8)	93%	3.1 (1.1–8.5) [1]
Pneumatosis intestinalis[4]	41 (4103)	32.9 (22.2–45.7)	77%	95.2 (82.4–98.8)	62%	2.36 (1.1–5.1) [2]
AMI vs. no AMI	20 (2043)	27.0 (20.3–35.0)	75%	**98.2 (93.3–99.5)**	68%	NA
Transmural vs. no transmural	21 (2070)	44.8 (20.7–71.6)	79%	84.1 (37.6–97.9)	57%	2.36 (1.1–5.1) [2]
Bowel wall thinning[3]	8 (617)	30.5 (21.4–41.5)	74%	97.9 (88.6–99.7)	48%	NA
AMI vs. no AMI	2 (193)	22.0 (7.6–49.1)	93%	**97.5 (62.4–99.9)**	0%	NA
Transmural vs. no transmural	6 (434)	33.6 (25.4–42.9)	43%	**98.0 (85.3–99.8)**	65%	NA
Unenhanced hyperattenuation	7 (571)	22.8 (12.7–37.4)	86%	99.8 (53.8–100.0)	0%	NA
AMI vs. no AMI	3 (178)	18.2 (6.1–43.3)	89%	**100.0 (0.0–100.0)**	0%	NA
Transmural vs. no transmural	4 (393)	26.2 (13.7–44.3)	84%	**99.1 (56.1–100.0)**	0%	NA
Hyperenhancement	12 (1163)	18.8 (10.6–31.1)	86%	82.3 (65.2–92.0)	93%	NA
AMI vs. no AMI	7 (620)	26.4 (12.7–47.0)	89%	89.0 (60.4–97.7)	95%	NA
Transmural vs. no transmural	5 (553)	12.8 (7.8–20.2)	27%	75.4 (60.4–86.0)	80%	NA
Other non-vascular features						
Mesenteric stranding/ edema	31 (3487)	77.4 (66.0–85.8)	87%	47.5 (36.4–58.9)	93%	3.7 (1.2–10.3) [2]
AMI vs. no AMI	14 (1562)	**63.5 (45.0–78.7)**	90%	59.3 (46.7–70.7)	82%	NA
Transmural vs. no transmural	17 (1971)	**85.9 (74.2–92.8)**	82%	39.4 (25.3–55.4)	95%	3.7 (1.2–10.3) [2]
Ascites	46 (4888)	66.5 (57.1–74.8)	86%	62.0 (50.8–71.9)	67%	5.3 (2.6–10.4) [2]
AMI vs. no AMI	18 (1715)	53.7 (42.0–64.9)	85%	60.3 (33.2–82.3)	92%	NA
Transmural vs. no transmural	28 (3183)	**74.6 (62.6–83.8)**	87%	63.2 (51.9–73.2)	89%	5.3 (2.6–10.4) [2]
Bowel dilatation[3]	31 (3062)	59.6 (54.3–64.7)	71%	69.0 (60.9–76.1)	84%	4.8 (2.1–10.7) [1]
AMI vs. no AMI	18 (1743)	56.4 (50.4–62.2)	65%	68.8 (57.9–77.9)	84%	4.8 (2.1–10.7) [1]
Transmural vs. no transmural	13 (1319)	**63.4 (54.4–71.6)**	73%	69.4 (56.8–79.7)	85%	NA
Portomesenteric venous gas[4]	29 (3000)	18.9 (13.7–25.6)	82%	99.0 (95.6–99.8)	49%	NA
AMI vs. no AMI	18 (1937)	16.9 (10.8–25.5)	87%	**99.6 (99.6–99.6)**	61%	NA
Transmural vs. no transmural	11 (1063)	22.6 (14.9–32.8)	65%	**96.3 (89.0–98.8)**	24%	NA
Solid organ infarction [2]	9 (742)	21.2 (11.3–36.4)	82%	88.7 (48.3–98.5)	93%	NA
AMI vs. no AMI	9 (742)	21.2 (11.3–36.4)	82%	88.7 (48.3–98.5)	93%	NA

Table 1. Summary of findings on accuracy of radiological diagnosis (Forest plots available in Figs. 2, 3, 4, 5 and 6 and supplemental figures S1-S9). Not all results were available in all studies (e.g. Only sensitivity for some, Only odds ratio for some). Legend: AMI- acute mesenteric ischemia; CT – computed tomography; CTA – computed tomography angiography; SBO – strangulating bowel obstruction. Transmural vs. no transmural – transmural bowel ischemia vs. no transmural ischemia (may include no ischemia). Highlighted in bold for subgroup analyses: sensitivity > 90% and specificity > 95% for the composite diagnosis and sensitivity > 60% and specificity > 90% for specific features. [1] in studies on SBO only transmural ischemia was considered as AMI. [2] one study reported results for CTA and CT separately. [3] studies assessing only patients with SBO were not included, as bowel dilatation (potentially leading to bowel wall thinning) is a sign of SBO. Studies including patients with SBO among AMI were included, results are presented separately in Supplemental Figures S1 and S2. [4] some studies included only patients with pneumatosis intestinalis (PI) and distinguished between patients with and without AMI, therefore specificity in these studies is always 0. [5] adjusted odds ratios as reported in individual studies. Number of studies is reported in square brackets. Result of a meta-analysis is presented if several studies reported adjusted OR.

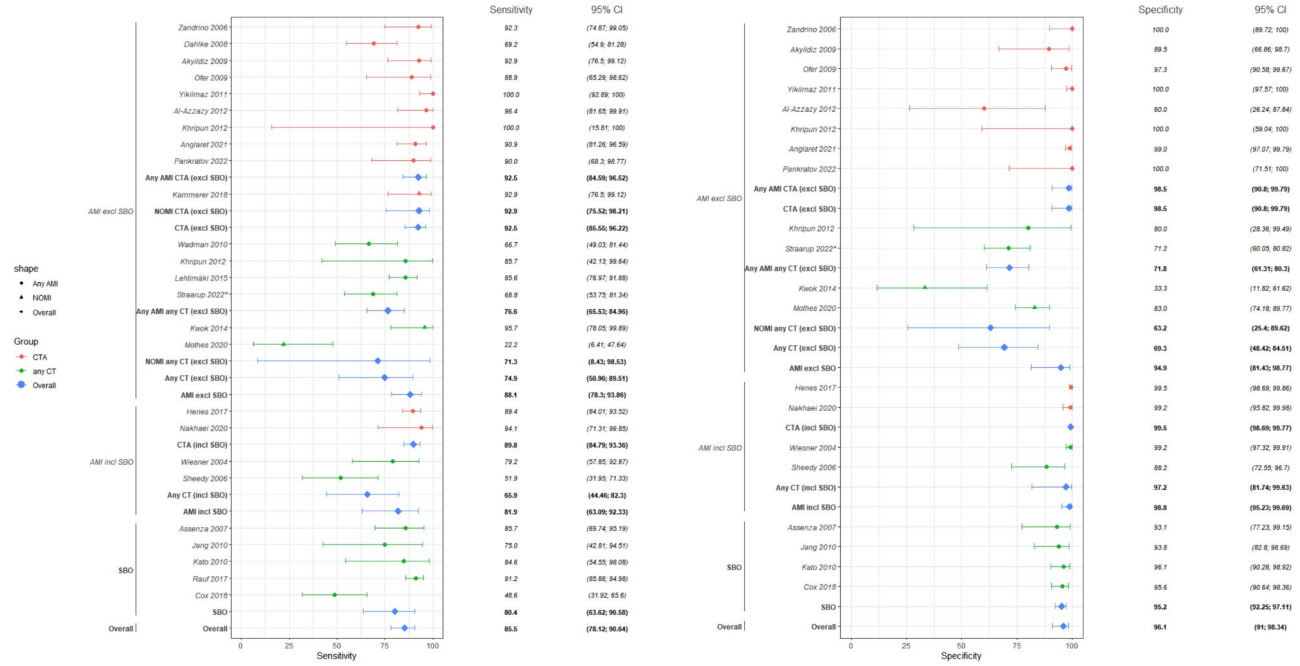

Fig. 2. Accuracy of diagnosis of AMI with composite radiological assessment.

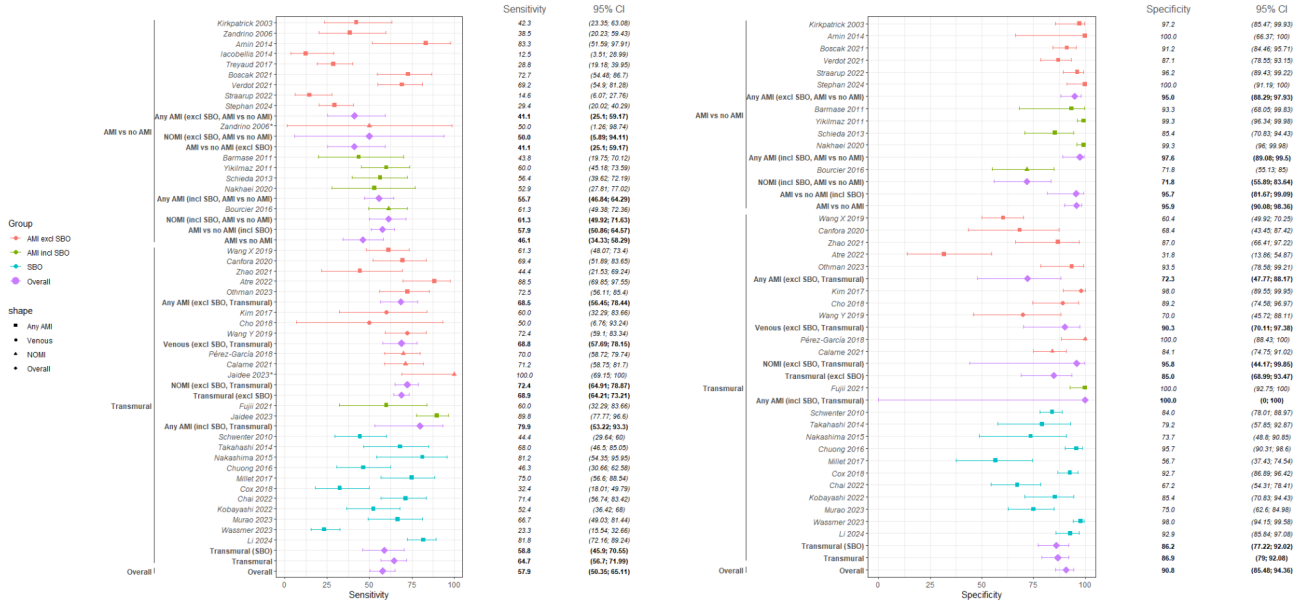

Fig. 3. Diagnostic accuracy of absent or reduced bowel wall enhancement.

edema, effusion), being 77.4% overall and 85.9% for transmural intestinal ischemia. However, specificity for this feature was low, with 47.5% (36.4–58.9) for overall and 39.4% (25.3–55.4) for transmural ischemia.

Specificity of 90% or higher was reached for bowel wall thinning, portomesenteric venous gas and unenhanced hyperattenuation for both comparisons (AMI vs. no AMI and transmural ischemia vs. no transmural ischemia), and for reduced/absent bowel wall enhancement and pneumatosis intestinalis for comparison of AMI vs. no AMI.

For non-vascular features, we did not identify any clear differences between subtypes of AMI except that bowel wall thickening showed higher sensitivity for venous AMI. Subtypes of AMI were often not presented separately, leaving data for subgroup analyses scarce and precluding separation of arterial occlusive AMI as a subgroup in our analyses.

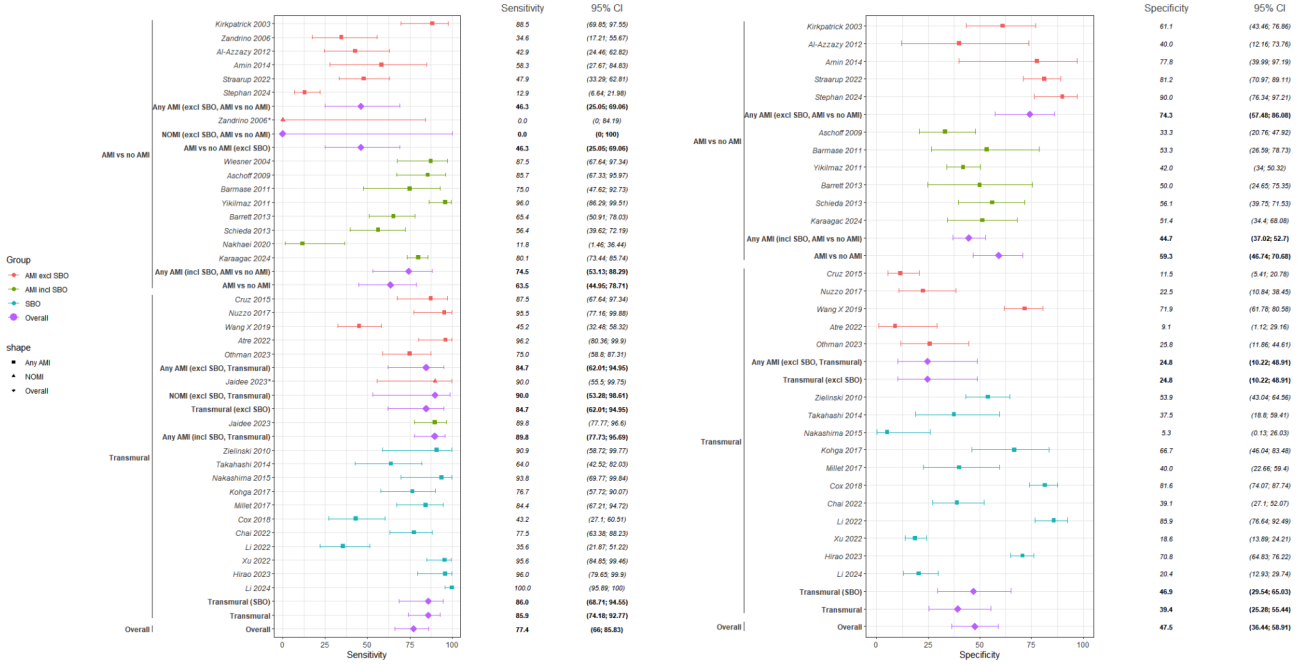

Fig. 4. Diagnostic accuracy of mesenteric signs (stranding, edema, effusion).

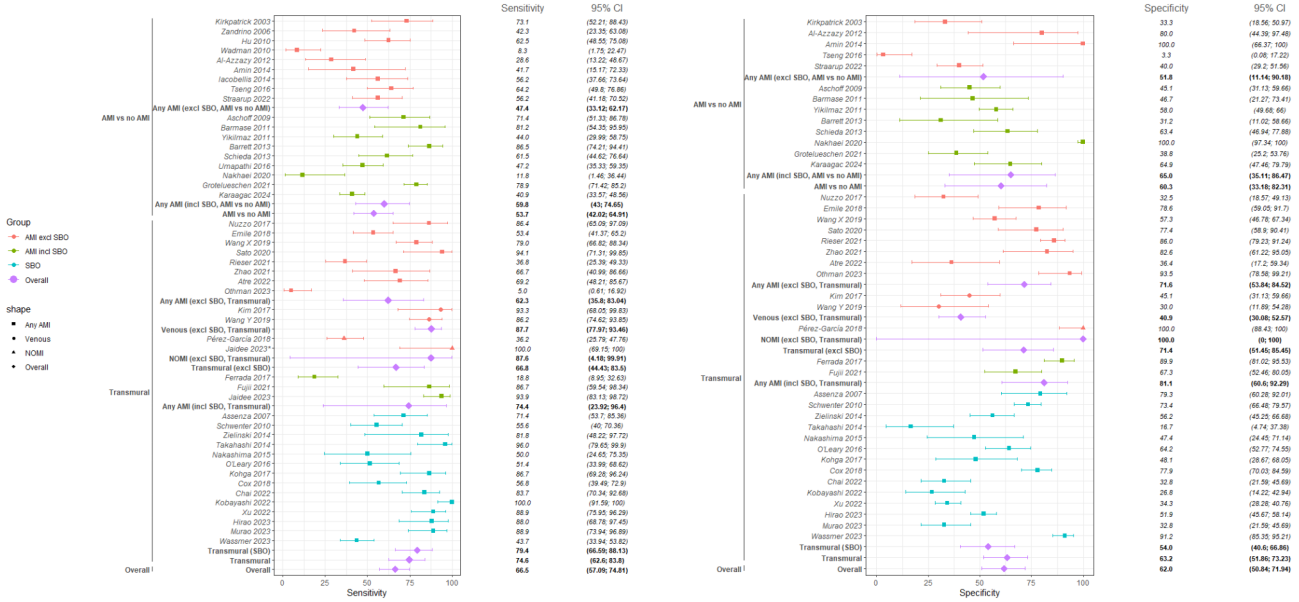

Fig. 5. Diagnostic accuracy of ascites.

Although several non-vascular signs demonstrated high specificity, none of them achieved sufficient accuracy for a standalone diagnosis of AMI. Overall diagnostic performance was the best for reduced/absent bowel wall enhancement in the comparison to transmural vs. no transmural ischemia.

Analysis of vascular signs in an unselected population including all patients with different subtypes of AMI (Figure S8) demonstrated low sensitivity (46.2, 95% CI 22.1–72.3) and high specificity (98.7, 95% CI 94.6–99.7) for arterial occlusion. For venous occlusion, both sensitivity (93.6, 95%CI 17.7–99.9) and specificity were high (94.3, 95% CI 12.9–100.0), but with very wide confidence intervals. These results should be interpreted with caution and considered mainly for description of the prevalence of different subtypes rather than for diagnostic accuracy for arterial or venous occlusive AMI. A specific analysis of arterial and venous AMI (Figure S9) was inconclusive due to the limited number of available studies.

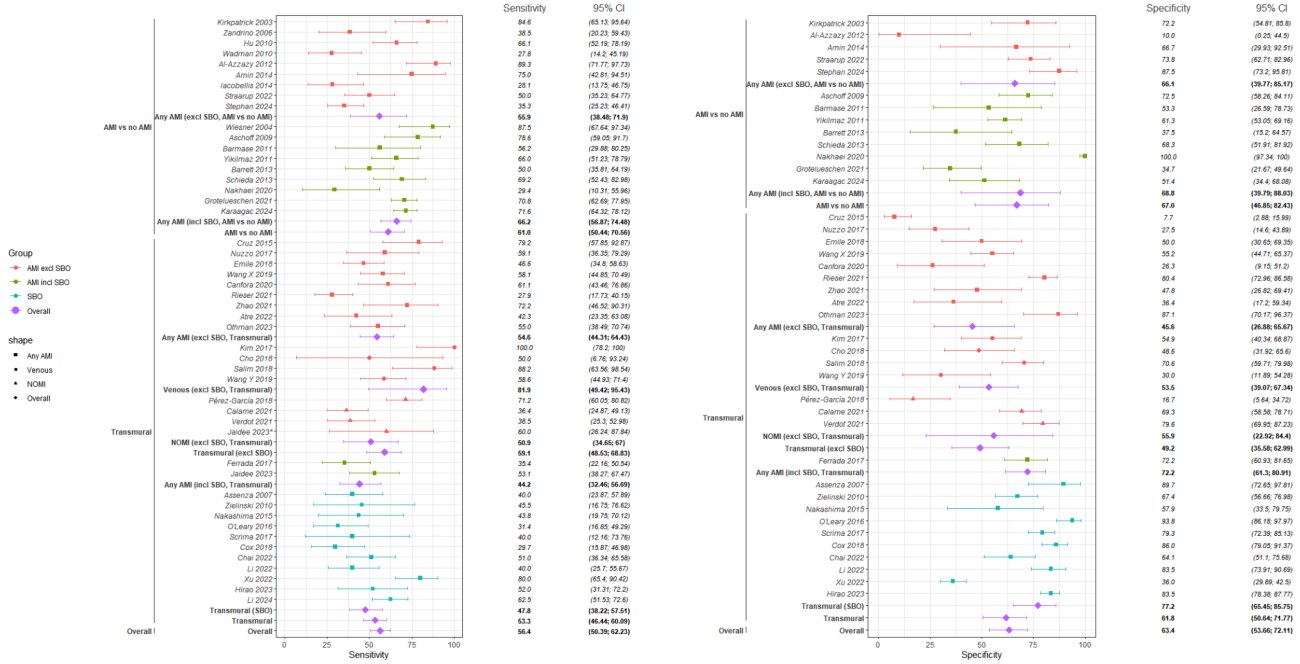

Fig. 6. Diagnostic accuracy of bowel wall thickening.

Study quality assessment

The QUADAS-2 assessments of risk of bias and applicability concerns are provided for all the studies included in the systematic review, in Supplement 4. Assessment results, considering the 4 key domains in the QUADAS-2 tool (patient selection, index test, reference standard, and flow of patients through the study and timing of the index test(s) and reference standard, i.e. "flow and timing"), are provided in Supplement 4 Figure S10.

Of the 81 studies, altogether only 16 studies had both "low risk of bias" and "low concern regarding applicability" across all the assessed domains, and provided high quality information for the systematic review[20,31,34,35,45,52,53,57,66,69,71,78–80,86,91].

Overview of risk of bias and applicability concerns in the included studies by the 4 key domains, assessed with the QUADAS-2 tool, is provided in Supplement 4 Figure S11. Study quality by domain was also separately assessed in the 14 meta-analyses, but due to quality concern(s) in most of the studies, the quality "picture" in different meta-analyses did not differ remarkably from the general quality "picture" of the 81 studies included in the systematic review.

Although several studies at low risk of bias/concerns were identified, sensitivity analyses were not performed due to an insufficient number of studies remaining in each subgroup.

Discussion

This systematic review confirms that CTA offers high sensitivity and specificity for a composite diagnosis (considering all radiological features) of AMI, However, none of the specific non-vascular radiological features alone is accurate to diagnose AMI or determine its stage. This study also highlights issues in reporting the results in available studies, particularly the limited granularity in defining AMI subtypes, the CT modalities used, and the severity or stage of AMI.

Study population

There is no consensus on whether patients with SBO developing bowel ischemia should be included under the nomenclature of AMI. Many studies included in the current systematic review, considered SBO together with AMI, without reporting the subtypes of AMI. As radiological signs reflecting transmural intestinal ischemia in SBO can resemble those in vascular AMI, we included studies reporting transmural ischemia in patients with SBO (studies assessing only SBO).

Our results did not show a consistent pattern when comparing subgroups that included or excluded SBO. However, when all subgroups were combined, the overall findings, were similar to previous meta-analyses. Yang et al. reported sensitivity of 94% and specificity of 97% for diagnosing AMI using MSCT with different enhancement protocols[15]. In this meta-analysis, two of the seven studies conducted after 2000 included SBO patients. Two studies included by Yang *el al.*were excluded from our overall analysis because they focused only on specific radiological features and estimated the overall diagnostic accuracy just retrospectively[21,53].

Our analysis demonstrated slightly higher sensitivity in composite diagnosis of AMI in studies using CTA not considering SBO within AMI. However, for other CT protocols not limited to CTA (only two studies), the signal was in the opposite direction, showing better prediction in studies including SBO. This confirms that inclusion/exclusion of SBO is a factor causing confusion in comparisons of studies[97]. Bowel dilatation and bowel

thinning, considered in radiological diagnosis of AMI, can also be directly caused by SBO. Diagnosis of non-transmural intestinal ischemia in patients with SBO is subjective and ischemia may be only very local. These issues serve to emphasize the need for detailed reporting in future studies, instead of pooling SBO and different subtypes of AMI together.

Many studies lacked control group. Among those that had it, the controls ranged from individuals undergoing abdominal or cardiac surgery without AMI to those with benign pneumatosis intestinalis.

Subtypes of AMI

Different subtypes of AMI have different characteristics on CT scanning but may share similar clinical features[2]. Accordingly, patients with different etiologies of AMI are referred to CT when AMI is suspected, and then CT often helps to identify the etiology. Therefore, our description of vascular occlusion together in all subtypes of AMI (Figure S8) could be seen as just an epidemiological description, whereas the results of this approach are similar to earlier findings with low overall sensitivity[8]. Although these results may seem confusing, it highlights that in many cases of intestinal ischemia the vascular occlusion is not detected or present. This underlines the variety of AMI and indicates the need for clearer unified definitions and nomenclature[98]. The results of individual studies included in our broad analysis of vascular signs are fully dependent on the particular study population (subtypes of AMI) and it is known that different hospitals detect different proportions of subtypes of AMI[2,98]. Analysis focusing specifically on the accuracy of CT diagnosis of arterial and venous AMI yielded surprisingly few eligible studies (Supplement 3 Figure S9), and is of limited value.

NOMI and venous AMI are presented separately wherever possible, as they may be most prone to diagnostic bias. This potential bias in classification of patients in studies, included in our systematic review, also needs to be considered when interpreting the results. Thrombosis of mesenteric veins does not always lead to intestinal ischemia, making clinical symptoms crucial for diagnosing venous AMI. In contrast, clinical symptoms and signs of NOMI are often unreliable due to prior sedation and vasopressor use in intensive care patients. Accordingly, CT can confirm venous occlusion, but not venous AMI, whereas the absence of clear vascular findings does not rule out NOMI. NOMI is the most dynamic form of AMI that may switch from ischemia to reperfusion and back several times. It would be most warranted to distinguish ischemia from reperfusion (that both potentially lead to a sustained clinical picture of shock). A small retrospective study including 20 patients with NOMI) showed that mesenteric fat stranding, bowel wall thickening and unenhanced hyperattenuation may indicate reperfusion[9]. This deserves attention and provides a platform for future investigations in this area.

Imaging modality and specific features

In included studies, the CT modality was often reported only as overall numbers, preventing separate analyses of each enhancement phase. This hindered our ability to determine the optimal modality for assessing bowel wall features, and to evaluate the significance of non-enhanced CT in diagnosing AMI[8,9]. However, unenhanced hyperattenuation of the bowel wall showed high specificity. Additionally, a few studies reported a difference in bowel wall attenuation between unenhanced and enhanced imaging, as a potential feature, helping to identify bowel ischemia[99,100]. Recent advances in dual-energy CT may allow visualization of all potential features, including the option of virtual non-contrast images and visualization of subtle changes in bowel wall enhancement[101,102], but this method requires further investigation .

To achieve accurate diagnosis and treatment of AMI, a diagnostic method should distinguish between three conditions: no AMI, non-transmural AMI, and transmural AMI. In addition to missing necessary detailsin available studies, there is no gold standard for immediate detection of non-transmural AMI. If vascular occlusion with acute symptoms is early revascularized without later development of bowel necrosis, then non-transmural AMI was likely present, allowing retrospective diagnosis. However, there are no specific clinical features confirming bowel ischemia, and distinguishing between the chronic and acute mesenteric ischemia is not always straight-forward[103–105]. Moreover, evaluation of the severity of intestinal damage (from the serosal side) during surgery may well include some extent of subjectivity. For example, a patient with NOMI but allocated to surgery could receive a diagnosis of no AMI or non-transmural AMI, depending on the surgeon's decision. Further research should focus on finding an optimal combination of different radiological features best distinguishing between non-transmural and transmural intestinal ischemia to assist in management decisions.

Studies included in the analysis of composite diagnosis indicating high diagnostic accuracy, often did not report individual specific features (only 8/24 reported any specific signs), and majority of studies reporting specific signs did not report overall assessment (58/82). However, our findings suggest that simultaneous assessment of all radiological aspects together with clinical assessment may result in appropriate diagnosis. Some scores combining clinical, laboratory and radiological assessment have been proposed, but none of them are yet validated[14,66].

Previous meta-analyses looking at odds ratios of radiological features predicting transmural necrosis, identified ascites[10,14], pneumatosis intestinalis[10,14], portomesenteric venous gas[10], decreased or absent bowel wall enhancement[10], bowel wall thinning[10], bowel dilatation[10]and portomesenteric venous thrombosis[14]as potentially relevant. In general, our results are in line with these findings. Portomesenteric venous thrombosis as a factor indicative of transmural necrosis[36], is interesting, as it may be related to secondary thrombosis in different subtypes of AMI and to mechanical occlusion in SBO. Our analysis of vascular signs (Supplement 3 Figure S8), demonstrating relatively high sensitivity and specificity (although with very wide confidence intervals) for venous occlusion may support the hypothesis that in the late phase (often associated with transmural AMI) venous thrombosis occurs in several different subtypes of AMI. Relatively large number of potentially useful features, while insufficient for standalone diagnosis, suggests that future studies should assess their different combinations. Importantly, the best combinations of features distinguishing non-transmural from transmural ischemia may differ between subtypes of AMI.

Limitations and strengths

This systematic review and meta-analysis has several limitations originating from the included studies. Most of the included studies are retrospective single-center studies with variable or absent control groups. Definitions of AMI vary between the studies, with some studies excluding SBO and some including it under AMI. Reporting of diagnostic modality and different radiological features is highly variable and sometimes unclear. Different subtypes of AMI and severity/progression of AMI are not reported in many studies. Unclear reporting in studies in several cases necessitated interpretation and recalculation of the outcomes that may not have yielded correct results in all cases. Even though in all the included studies radiological assessments were performed by radiologists, data collection was often done by non-radiologists and retrospectively. Reporting the presence or absence of the potential signs of AMI by radiologists is shown to depend on whether or not suspicion of AMI has been raised prior to the radiological diagnostics[2,57]. Accordingly, retrospective re-evaluation of the findings may differ from the contemporary clinical diagnosis. Additionally, it may be relevant that included studies commonly originate from hospitals with special interests in AMI, and even there the proportions of different subtypes of AMI are expected to be highly variable[2,98]. Our approach in constructing the groups for comparisons, mainly with the group of "no transmural AMI" including also patients with no AMI, and inclusion of SBO with transmural ischemia in the analysis, may be criticized. Our method for forming comparison groups may be questioned, especially since the "no transmural AMI" group includes patients without AMI, and because we included SBO with transmural ischemia in the analysis. However, we combined all studies in the meta-analyses to provide a broad overview and highlight key issues for future research. By this, we continue using the approach similar to our research on AMI incidence and biomarkers.

The strengths of our study are the rigorous methodology and the attempt to create subgroups which probably need different approaches. At the same time, we provide a broad overview allowing identification of issues that need to be considered in planning and reporting future studies.

Conclusions

CTA is the preferred method for diagnosing AMI, offering high diagnostic accuracy. However, no single non-vascular feature is sufficient to reliably diagnose AMI or its progression to transmural necrosis. A combination of various radiological features potentially including those from unenhanced imaging, may provide a promising diagnostic approach and should be assessed in future studies. While identification of vascular occlusion on CTA helps to determine the etiology of AMI, it is not sufficient on its own to diagnose or rule out AMI due to the heterogenous pathophysiologic mechanisms involved. Future studies should provide detailed reporting of subtypes of AMI as well as location and progression of AMI.

Data availability

Evidence tables will be made available at reasonable request sent to the corresponding author.

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Author contributions
ARB drafted and all authors developed and confirmed the study protocol. EK performed literature searches, KTL developed data extraction tables, ARB, KTL, AF, KK, MM, MR, JS and KT performed data assessment. MK performed analyses, ARB drafted the manuscript, all authors reviewed and approved the final version of the manuscript.

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Declarations

Competing interests
The authors declare no competing interests.

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