Multidetector Computed Tomography Angiography (MD-CTA) of Coronary Artery Bypass Grafts – Update 2017

Multidetektor-Computertomografie-Angiografie (MD-CTA) aortokoronarer Bypässe – Update 2017

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ZUSAMMENFASSUNG

Hintergrund Die aortokoronare Bypassoperation stellt unverändert einen wichtigen Bestandteil in der Behandlung der koronaren Herzerkrankung insbesondere in fortgeschrittenen Krankheitsstadien dar. In der vorliegenden Arbeit soll der aktuelle Stellenwert der Multidetektor-CT-Angiografie (MD-CTA) bei Patienten nach stattgehabter aortokoronarer Bypassoperation (ACVB) dargelegt werden.

Methode Die vorliegende Übersichtsarbeit basiert auf Publikationen aus den Jahren 2007 – 2016 zur nicht-invasiven Bildgebung von Patienten nach ACVB-Operation, die an MD-CT-Geräten mit mindestens 64 Zeilen untersucht wurden. Voraussetzung für eine Berücksichtigung in der Analyse waren Angaben zu den absoluten Vorhersagewerten (richtig-positiv, richtig-negativ, falsch-positiv und falsch-negativ) bzw. ihre Berechnung musste möglich sein. Insgesamt konnten 13 Publikationen berücksichtigt werden, bei denen die EKG-getriggerte CT-Angiografie mit der konventionellen Koronarangiografie als Referenzstandard hinsichtlich Bypassoffenheit bzw. der Detektion von > 50 % Bypassstenosen verglichen wurde. Insgesamt wurden 1002 Patienten mit 2521 Bypässen in die Arbeit eingeschlossen.

Ergebnisse und Schlussfolgerung Die gepoolte Sensitivität und Spezifität in der Evaluation der Bypassoffenheit bzw. der Detektion von > 50 % Bypassstenosen betrugen 97,2 % und 97,5 %. Der gemittelte positiv prädiktive Wert und der gemittelte negativ prädiktive Wert erreichte 93,6 % bzw. 99 %. Durch prospektive EKG-Triggerung und einer Erhöhung des Pitch-Faktors konnte die Strahlenexposition in den neuesten Publikationen auf bis zu 2,4 mSv gesenkt werden. Die EKG-getriggerte MD-CTA ist eine schnelle und zuverlässige Methode zur Untersuchung von Patienten nach ACVB-Operation. Der größte Fortschritt der neueren CT-Scanner-Generationen ist eine signifikante Reduktion der Strahlenexposition bei einer unverändert hohen diagnostischen Genauigkeit in der Bypassbeurteilung in den vergangenen Jahren.

Kernaussagen

- Die MD-CTA ist eine zuverlässige, nicht-invasive Methode zur Beurteilung aortokoronarer Bypässe.
- Technische Weiterentwicklungen wie prospektive EKG-Triggerung, iterative Rekonstruktionsalgorithmen und high-pitch Technik führen zu einer deutlichen Reduktion der Strahlenexposition auf bis zu 2,4 mSv.
- In den vergangenen Jahren konnte die diagnostische Genauigkeit der MD-CTA auf konstant hohem Niveau gehalten werden, mit weiterhin ausgezeichneten Sensitivitäten und negativ prädiktiven Werten in Bezug auf Bypassoffenheit bzw. der Detektion relevanter Bypassstenosen.

ABSTRACT

Background Coronary artery bypass grafting (CABG) is still an important therapeutic approach in the treatment especially of advanced coronary artery disease. In this study, we elucidate the current role of multidetector computed tomography angiography (MD-CTA) in imaging patients after CABG surgery.

Method This study is based on recent reports in the literature (2007 – 2016) on imaging of CABG using 64-slice MD-CT scanners and beyond. We included 13 reports that compared ECG-gated MD-CTA with conventional invasive coronary angiography (ICA) as the reference standard for the assessment of graft patency and for the detection of > 50 % stenoses. These studies had to provide absolute values for true-positive, true-negative, false-positive and false-negative results or at least allow calculation of these numbers. In total, 1002 patients with 2521 bypass grafts were the basis for this review.

Results and Conclusion The sensitivity and specificity for the assessment of graft patency or the detection of > 50 % graft stenosis were 97.2 % and 97.5 %, respectively. The negative and positive predictive values were 93.6 % and 99 %, respectively. By using prospective ECG-gating and an increasing pitch factor, the radiation dose exposure declined to 2.4 mSv in the latest reports. ECG-gated MD-CTA provides a fast and reliable, noninvasive method for assessing patients after CABG. The most substantial benefit of the newest CT scanner generations is a remarkable reduction of radiation dose exposure while maintaining a still excellent diagnostic accuracy during recent years.

Key Points
- MD-CTA using 64-slice MDCT scanners and beyond is a reliable, noninvasive method for evaluating CABGs.
- Technical advances such as prospective ECG-gating, iterative reconstruction algorithms and high-pitch scanning lead to a remarkable drop-down in radiation dose exposures as low as 2.4 mSv.
- Despite significant dose reductions, MD-CTA could maintain a high diagnostic accuracy in evaluating CABGs in recent years.

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Introduction

Ischemic heart disease is still the most common cause of death in Europe [1]. Acute myocardial infarction, chronic ischemic heart disease and congestive heart failure caused about 19 % of all deaths in 2013 in Germany. In 2012, about 665 000 patients suffered from ischemic heart disease, 128 000 of whom died [2]. In the United States, coronary heart disease (CHD) caused approximately 788 000 deaths in 2009 [3]. Despite improving drug therapy, percutaneous coronary intervention (PCI) and coronary artery bypass grafting (CABG) are essential parts of therapy of coronary artery disease (CAD). In 2013, about 54 000 patients underwent CABG surgery, whereas 342 749 patients were treated with PCI in Germany [2]. Decreasing mortality rates of acute myocardial infarction (between 2000 and 2010: reduction of about 17 %) reveal the efficiency of the on-going medical progress.

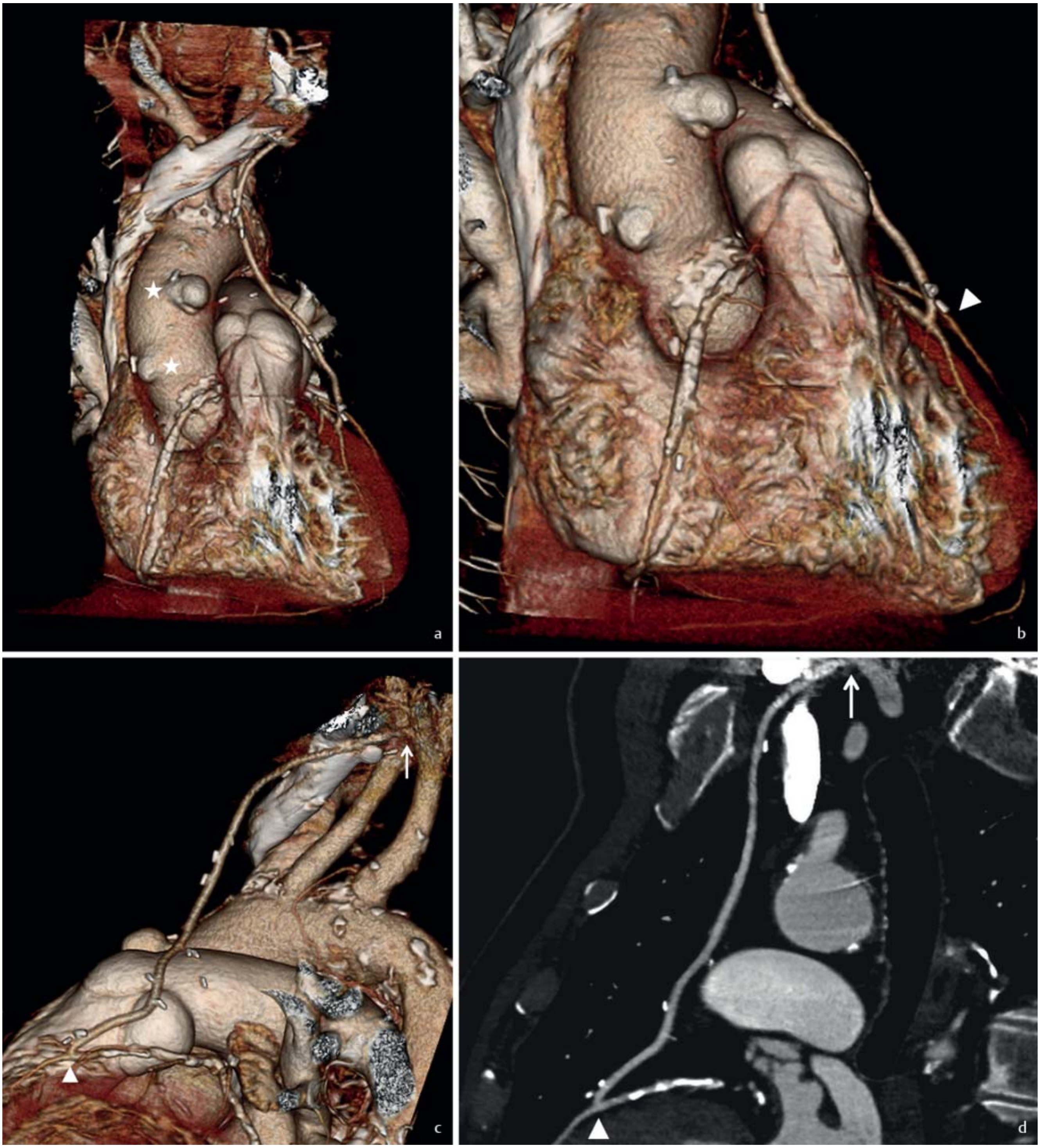
The main indications for bypass grafting are three-vessel disease (3VD) and left main disease (LM) [4]. The SYNTAX trial was a multicenter long-term randomized study that compared the outcomes of PCI with those of CABG in LM disease and 3VD [5]. After 5 years, there were significantly higher rates of MACCE (major adverse cardiac and cerebrovascular events) in the PCI-treated patients (37.3 % vs. 26.9 % in the CABG group) and significantly higher rates of estimated myocardial infarction (9.7 % vs. 3.8 % in the CABG group) than in the CABG group. These results indicate that patients with more complex lesions should undergo bypass grafting.

The need to image coronary artery bypass grafts postoperatively is due to their limited lifetime [6]. Several vessels have been used for coronary bypass grafting, whereas the internal mammary artery (IMA) is considered the vessel of choice [7]. As early as in 1972, George E. Green described the technique and the clinical course of internal mammary-to-coronary artery anastomosis in 165 patients and concluded that their graft patency rate is superior to that of saphenous vein grafts [6]. Tatoulis et al. revealed a ten-year graft patency rate for the right (RIMA) and left internal mammary artery (LIMA) to the left anterior descending artery (LAD) of about 95 % [8]. The ten-year RIMA and LIMA patency rate to the left circumflex artery (LCX) was around 90 % [8]. On the other hand, early graft occlusion within the first year after surgery in IMA grafts occurs in 3.4 % of women and 5.7 % of men [9].

Venous grafts in general show an inferior graft patency rate. Early disease of saphenous vein grafts (SVG) is caused by thrombosis. About 12 % of SVGs occlude early after grafting (up to 6 months after operation) [10]. Intimal hyperplasia results in delayed venous graft disease between 1 to 12 months, and atherosclerosis causes late graft disease starting as early as one year after CABG [11]. Ten years after CABG surgery, the patency rate of SVG drops down to 60 % [10] (▶ **Fig. 1, 2**).

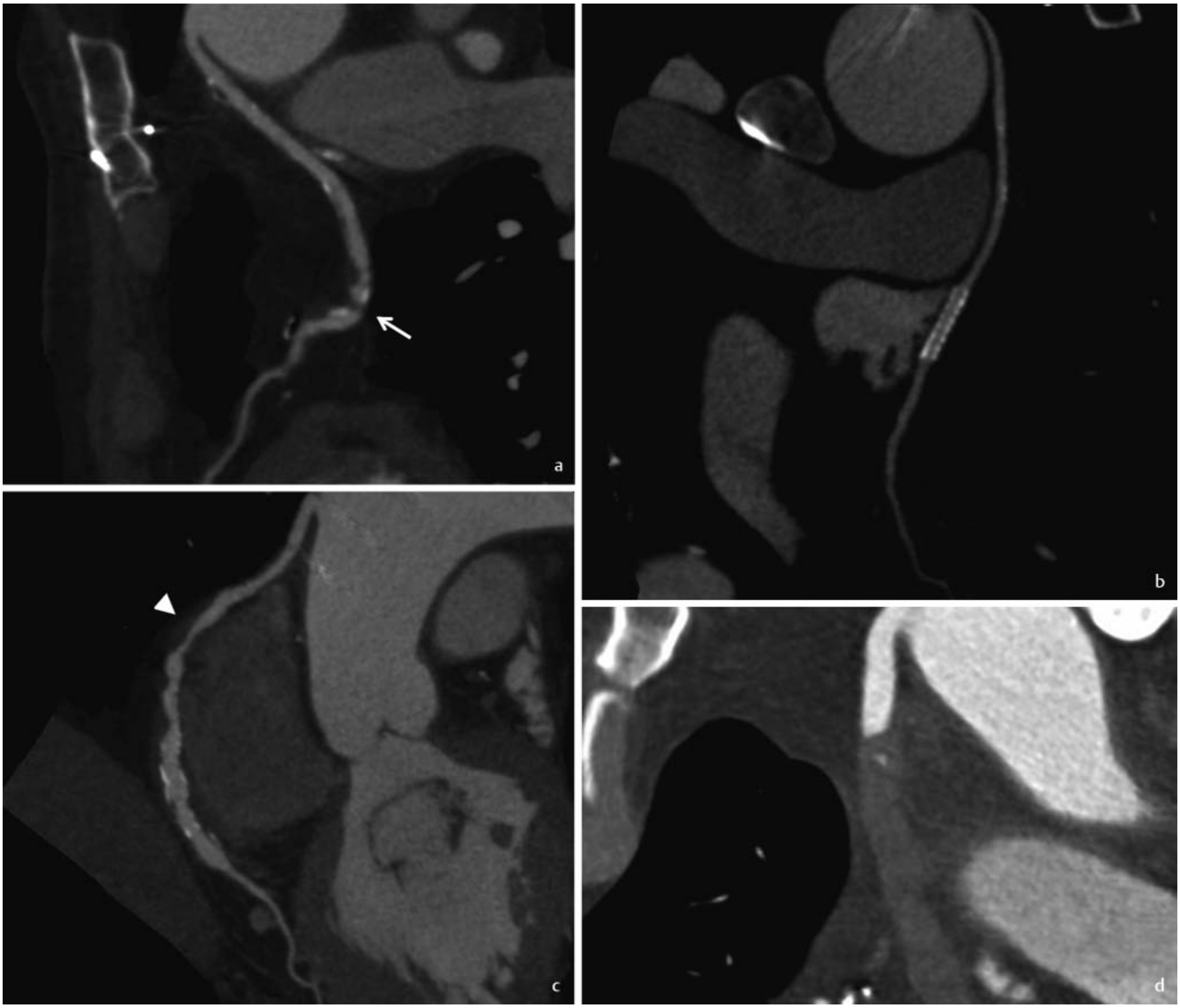
Nowadays, for complete arterial revascularization, radial artery and epigastric artery grafts can be used. A systematic review illustrates that radial artery grafts prepared as free grafts are superior to saphenous veins grafts at 1 – 5 years as well as > 5 years after operation concerning patency rates, but in comparison with IMA grafts, they show higher rates of acute occlusion [12]. In selected cases, epigastric artery grafts may be used for arterial revascularization of distal segments of the RCA (▶ **Fig. 3**).

MD-CTA of CABGs further helps in detecting patients with unprotected coronary territories, myocardial segments that are not adequately supplied due to stenosis or occlusion of coronary artery or bypass graft. In coronary artery bypass patients, MD-CTA appears to have a prognostic value by assessing unprotected coronary territories (UCTs) [13]. Patients without UCTs had the lowest rate for cardiac death and nonfatal myocardial infarction.



▶ **Fig. 1** Male patient 18 years after CABG surgery with suspected graft occlusion. Volume rendering **a–c** and curved planar reformation (CPR) **d** show a patent left internal mammary artery grafted to left anterior descending coronary artery with non-stenotic proximal origin (arrow) and distal anastomosis (arrowhead) as well as occluded vein grafts (asterisk).

▶ **Abb. 1** Männlicher Patient 18 Jahre nach ACVB-Operation mit Verdacht auf Bypass-Verschluss. Volume-Rendering **a–c** und die gekrümmte planare Rekonstruktion (CPR) **d** zeigen einen durchgängigen linken A. mammaria interna Bypass auf den Ramus interventricularis anterior mit nicht stenosiertem Ursprung (Pfeil) und distaler Anastomose (Pfeilspitze) sowie verschlossene Venenbypässe (Sternchen).



▶ **Fig. 2** Severe vessel degeneration in venous grafts more than 15 years old: graft sclerosis and severe stenosis (arrow) in LAD graft **a**, stent in LCX graft **b** and graft sclerosis, severe stenosis (arrowhead) and dilated segments in RCA graft **c**. CPR of an occluded vein graft **d**.

▶ **Abb. 2** Schwere Bypassdegeneration von mehr als 15 Jahre alten venösen Bypassgefäßen: Bypasssklerose und hochgradige Stenose (Pfeil) des Bypass auf die LAD **a**, Zustand nach Stent-PTCA des LCX-Bypass **b** und Bypasssklerose, hochgradige Stenose (Pfeilspitze) und segmentale Dilatationen des RCA-Bypass **c**. CPR eines verschlossenen venösen Bypass **d**.

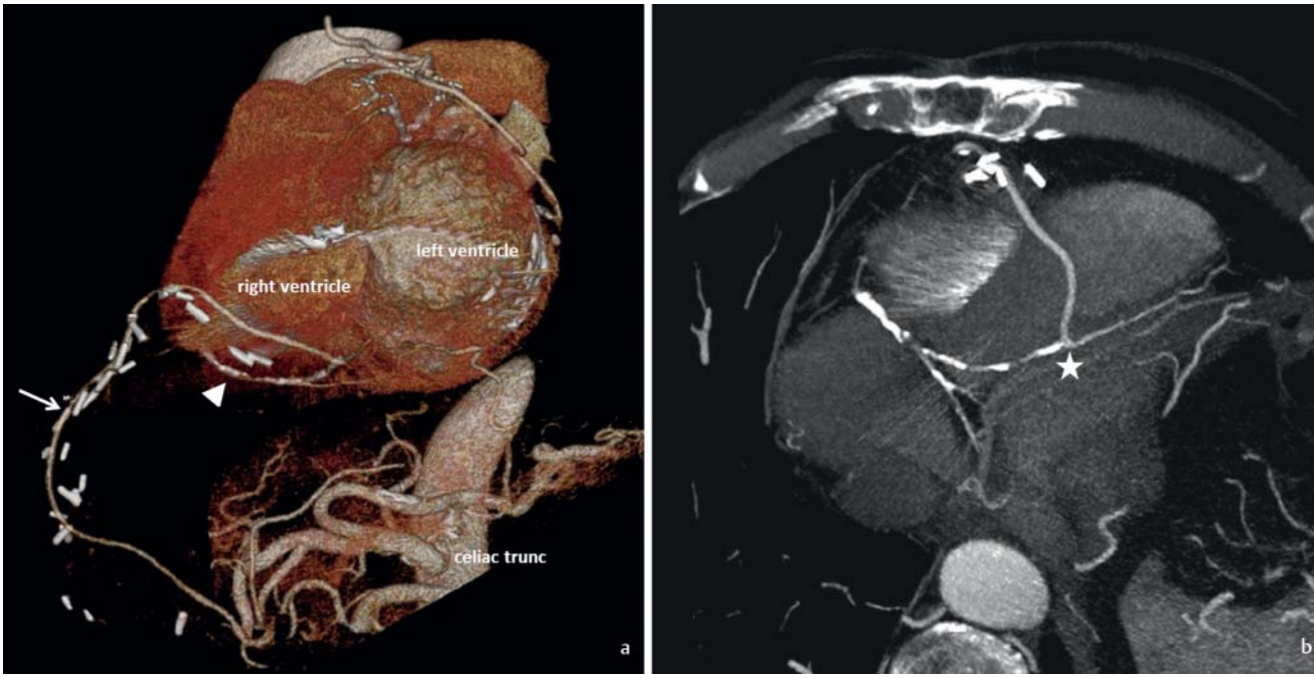
Search strategy and selection criteria

For the present review, we selected publications that compared the accuracy of MD-CTA in evaluating patients after CABG surgery performed on 64-slice and beyond scanners with ICA as the reference standard. Articles were searched in PubMed using combined terms "multidetector computed tomography" or "multidetector computed tomography angiography", "bypass graft" or "coronary artery bypass graft". These studies had to evaluate the accuracy of MD-CTA to detect graft occlusion or > 50 % graft stenosis as well as provide absolute numbers of true-positive, true-negative, false-positive and false-negative results or at least allow for calculation of these numbers. We found 13 references that met the inclusion criteria published between 2007 and 2016. Publications that were already evaluated in the review of Hamon et al. were excluded from this study [14]. Thus, a total of 1002 patients and 2521 bypass grafts from 13 publications could be included in the present study.

Diagnostic accuracy of MD-CTA

Assessment of CABG (▶ Table 1)

Many studies listed in ▶ **Table 1** achieved a negative predictive value and sensitivity of 100 % or nearly 100 % in 64-slice MDCT and beyond [15, 16]. The sensitivity and specificity ranged between 80 – 100 % and 93 – 100 % in the detection of graft stenosis



▶ **Fig. 3** Male patient with history of gastroepiploic bypass grafting in left anterior oblique caudal view. Conventional catheter angiography was not able to display the graft. MD-CTA shows a patent gastroepiploic bypass (arrow) to the right coronary artery (arrowhead) in volume rendering **a** and cardiac anastomosis (asterisk) in subvolume maximum intensity projection (MIP) **b**.

▶ **Abb. 3** Männlicher Patient mit Zustand nach Anlage eines Gastroepiploica-Bypass in LAO-Projektion (left anterior oblique) mit kaudaler Kippung. Die konventionelle Katheterangiografie konnte den Bypass nicht darstellen. In der CT-Angiografie findet sich ein durchgängiger Gastroepiploica-Bypass (Pfeil) zur rechten Koronararterie (Pfeilspitze) im Volume Rendering **a** und eine Maximum-Intensitäts-Projektion (MIP) der kardialen Anastomose (Sternchen) **b**.

> 50 % and graft occlusion. Sahiner et al. investigated 284 patients with a total of 684 bypass grafts, whereas Andreini et al. examined 119 patients with 277 bypass grafts [17, 18]. Both studies reported a sensitivity, specificity and negative predictive values of more than 97 %.

To our knowledge, only two studies have used 256-slice CT and 320-slice CT to assess bypass grafts compared with ICA [16, 19]. The diagnostic accuracy on 256- and 320-MDCT was similar to studies using 64-slice MDCT scanners.

Yuceler et al. described a trend towards lower image quality in patients with higher heart rates [16]. In the lower heart rate group, arterial grafts could be assessed more easily compared with arterial grafts in the higher heart rate group. Mean heart rates in most studies ranged between 58 – 70 beats/min. Only one study listed in ▶ **Table 1** investigated the accuracy of 64-slice CT in patients with a mean heart rate of 80 beats/min with a sensitivity and negative predictive value of 90 % and 98 %, respectively [20].

To calculate the sensitivity, specificity, positive as well as negative predictive value, we worked out exact values of true-positive, true-negative, false-positive and false-negative results in evaluating occlusion or substantial stenosis. After that, we calculated the pooled sensitivity, specificity, positive predictive value and negative predictive value (▶ **Table 2**). Compared with the reviews of Hamon et al. in 2008 (723 patients with 2023 bypass grafts) and Chan et al. in 2016 (1975 bypass grafts and 5364 patients), there were no significant differences with regard to sensitivity, specificity, positive predictive value and negative predictive value for detecting occlusion or substantial stenosis of bypass grafts [14, 21].

Assessment of native coronary arteries (▶ Table 3)

When imaging patients after coronary artery bypass grafting, one should try to assess the progress of CHD in the non-grafted vessels, too. ▶ **Table 3** lists all studies that additionally analyzed native coronary arteries. 7 out of 13 studies evaluated native coronary arteries, whereas 3 of these publications differentiate between distal runoffs (segment of the coronary artery at which the bypass graft was inserted and all segments distally to the inserted segment) and non-grafted coronary arteries [15].

The sensitivity and specificity in the detection of relevant stenosis in native coronary arteries ranged between 83 – 100 % and 77 – 100 %, respectively, whereas the negative predictive value ranged between 83 – 100 %. Most of the studies used a segment-based analysis and analyzed vessels with a diameter of more than 1.5 mm. Andreini et al. presented the largest number of patients (n = 119) with assessment of native coronary arteries after bypass grafting without distinguishing between distal runoffs and non-grafted coronary arteries. This publication achieved sensitivities and specificities ranging between 91 – 100 % and 98 – 99 %, respectively, with an excellent negative predictive value of 99 – 100 % [17].

Table 1 Diagnostic performance of 64-slice CT in the evaluation of CABG (occlusion and > 50 % stenosis).

Tab. 1 Diagnostische Genauigkeit der 64-Schicht CT in der Beurteilung von aortokoronaren Bypässen (Verschluss und > 50 % Stenose).

author [year]	CT scanner-sections	patients/bypasses	arterial/venous grafts	Se [%] total/arterial/venous	Sp [%] total/arterial/venous	PPV [%]	NPV [%]	radiation dose [mSv]
Andreini [2010] [17]	64-slice	119/277[1]						
		40/96[2]	44/52	100	100	100	100	3.5 ± 1.4[2]
		39/86[3]	43/43	100	100	100	100	7.4 ± 2.6[3]
		40/95[4]	45/50	100	98.4	96.7	100	27.8 ± 9.4[4]
Feuchtner [2007] [39]	64-slice	41/70	46/24	85	95	80	96	N/A[4]
Gorantla [2012] [40]	64-slice	36/89	34/55	95	98.5	75	99.4	14.7[4]
Lee [2011] [41]	64-slice	26/64						
		12/29[2]	13/16	92.3	93.7	92.3	93.7	6.5 ± 0.6[2]
		14/35[4]	18/17	93.3	90	87.5	94.7	21.2 ± 3[4]
Nazeri [2009] [42]	64-slice	98/287	89/198	98/100/98	97/99/95	96/67/97	99/100/97	N/A[4]
Onuma [2007] [43]	64-slice	53/146	65/73	–/100/100	–/91.4/98.1	–/73.7/95.5	–/100/98.1	N/A[4]
Romagnoli [2010] [44]	64-slice	77/210	115/97	–/100/94.4	–/97.7/98.4	N/A	N/A	N/A[4]
Sahiner [2012] [18]	64-slice	284/684	264/420	98.8/100/98.3	99.4/99.5/99.3	98.2/98/98.3	99.6/100/99.3	19.5 ± 7.2
Sahiner [2012] [20]	64-slice	71/173	71/102	80/100/60	98/97/99	73/71/75	98/100/98	17.2 ± 6.5[4]
Tochii [2010] [45]	64-slice	19/65[1]	30/35	100	93	16.7	100	N/A[4]
Weustink [2009] [15]	64-slice	52/152[1]	50/102	100	100	100	100	22.1 ± 2.8[4]
De Graaf [2011] [19]	320-slice	38/89	28/61	96/100/95	92/91/93	83/71/87	98/100/97	7.8 ± 3.3[4] 11.2 ± 4.1[4]
Yuceler [2014] [16]	256-slice	88/215	93/122	97.1	99.6	94.4	99.8	2.4 ± 0.9[2] 2.75 ± 0.5[2]

Se = sensitivity; Sp = specificity; PPV = positive predictive value; NPV = negative predictive value.
Se = Sensitivität; Sp = Spezifizität; PPV = positiver prädiktiver Wert; NPV = negativer prädiktiver Wert.

[1] segment-based analysis; non-evaluable bypass grafts were considered positive for occlusion and > 50 % stenosis.
Analyse auf Segmentebene; nicht evaluierbare Bypassgefäße wurden als positiv für Verschluss und > 50 % Stenose gewertet.

[2] prospective ECG-gated (BMI-adapted).
prospektive EKG-Triggerung (Dosis an BMI adaptiert).

[3] prospective ECG-gated (120 kV).
prospektive EKG-Triggerung (120 kV).

[4] retrospective ECG-gated; > 50 % diameter stenosis.
retrospektive EKG-Triggerung; > 50 % Stenose.

► **Table 2** Computed pooled sensitivity, specificity, positive predictive value and negative predictive value in studies listed in ► **Table 1** (occlusion and > 50 % stenosis of CABG).

► **Tab. 2** Berechnete gepoolte Sensitivität, Spezifität, positiv prädiktiver Wert und negativ prädiktiver Wert der Studien aus ► **Tab. 1** (Verschluss und > 50 % Stenose von aortokoronaren Bypässen).

author [year]	reports analyzed	patients/bypasses	Se [%]	Sp [%]	PPV [%]	NPV [%]
all studies listed in ► **Table 1**	13	1002/2521	97.2	97.5	93.6	99.0
64-slice CT listed in ► **Table 1**	11	876/2217	97.3	97.6	94.0	98.9
> 64-slice CT listed in ► **Table 1**	2	126/304	96.7	97.1	89.4	99.2
Hamon [2010] [14]	15	723/2023	97.6	96.7	92.7	98.9
Chan [2016] [21]	31	1975/5364	96.1	96.3	94.3	99.0

Se = sensitivity; Sp = specificity; PPV = positive predictive value; NPV = negative predictive value.
Se = Sensitivität; Sp = Spezifizität; PPV = positiver prädiktiver Wert; NPV = negativer prädiktiver Wert.

Current advances in examination technique

In recent years, there have been tremendous improvements regarding the technique of CT coronary angiography (CTCA), such as the introduction of prospective ECG triggering, the implementation of 64-slice and beyond CT scanners and – last but not least – the introduction of iterative reconstruction algorithms. These improvements have led to a significant drop in radiation dose exposure from about 15 mSv and more to less than 1 mSv going along with significant improvements in temporal resolution in CTCA [22, 23].

Imaging of coronary artery bypass grafts using MD-CTA results in higher radiation exposure basically due to the larger scan range. However, Yuceler et al. implemented a high-pitch spiral acquisition protocol with a second-generation 256-slice CT system for the evaluation of CABG, which resulted in a mean radiation dose of about 2.4 mSv [16]. The image quality of the graft segments was excellent in 92 % of the assessed segments [16]. Goetti et al. implemented a similar high-pitch CT protocol with diagnostic image quality in 99 % of cases [24]. However, in approximately 1 % of the evaluated grafts, the distal anastomosis could not be evaluated adequately due to insufficient diagnostic image quality.

Menke et al. compared prospectively triggered versus retrospectively gated MD-CTA of native coronary arteries by analyzing 20 studies with 3330 patients [25]. Diagnostic quality did not differ between prospective and retrospective gating techniques, whereas radiation dose was significantly lower in the prospectively gated patient group (factor 3.5) [25]. However, higher heart rates in the prospectively gated data sets caused a significant increase in step artifacts and lower image quality [24, 26]. The application of an iterative reconstruction technique in ECG-gated CTCA to rule out coronary artery disease enabled a radiation dose reduction of 63 % as shown by use of a 256-slice MD-CT scanner [23].

Although all studies listed in ► **Table 1** were performed on ≥ 64-row MDCT scanners, we could reveal relevant differences concerning radiation dose. Based on different acquisition techniques (retrospective vs. prospective ECG-gating, different tube voltages, iterative reconstruction algorithm vs. filtered back projection and pitch factor), the radiation dose ranged between 2.4 (256-slice high-pitch MD-CTA) and 27.8 mSv (retrospectively gated MD-CTA). Although conventional catheter angiography is still regarded as the reference standard in evaluating coronary artery bypass grafts, it is an invasive procedure that is associated with complications ranging between 1 % and 5 % [27, 28]. Compared with ICA, MD-CTA offers additional information such as delineation of the anatomical course of bypass grafts and their topographic relationship to the sternum and the right ventricle, the assessment of the remodeling of bypass grafts, aortic diseases, pathologies of heart valves and extracardiac findings such as pulmonary emphysema or suspicious lung nodules (► **Fig. 4**). These findings help in the preoperative planning of redo cardiac surgery, and preoperative CT imaging thus reduces the incidence for bypass graft injury [29].

Pesenti-Rossi et al. investigated the potential benefit of prior CTCA before ICA in patients after coronary artery bypass grafting [30]. In a prospective non-randomized trial, 147 patients with a history of CABG surgery were divided into two groups. Group 1 underwent first-line MD-CTA of CABG while group 2 underwent first-line ICA. 33 of 75 patients (44 %) in group 1 needed further investigation with ICA. Compared with group 2, second-line ICA in group 1 was associated with a significantly lower radiation dose and a significantly lower amount of applied iodinated contrast volume. As most patients in group 1 did not need ICA, there were no differences in cumulative effective dose between the two groups (5.0 vs. 5.1 mSv). MD-CTA of CABG without ICA resulted in an average effective dose of 3.9 mSv. The authors concluded that MD-CTA could serve as a kind of a roadmap for ICA.

▶ **Table 3** Diagnostic performance of 64-slice CT in the evaluation of native coronary arteries (occlusion and > 50 % stenosis).

▶ **Tab. 3** Diagnostische Genauigkeit der 64-Schicht CT in der Beurteilung der nativen Koronararterien (Verschluss und > 50 % Stenose).

author [year]	CT scanner sections	patients/native coronary arteries	Se [%] distal runoffs/ non-grafted	Sp [%] distal runoffs/ non-grafted	PPV [%] distal runoffs/ non-grafted	NPV [%] distal runoffs/ non-grafted
Andreini [2010] [17]	64-slice	119/277[1]				
		40/194[2]	91	99	91	99
		39/232[3]	100	99	96	100
		40/202[4]	100	98	94	100
Nazeri [2009] [42]	64-slice	98/356	97	90	96	93
Onuma [2007] [43]	64-slice	53/144	83.3/100	80.2/87.5	37.5/96.8	97.1/100
Romagnoli [2010] [44]	64-slice	77/226[1]	95/NA	97/NA	N/A	N/A
Sahiner [2012] [18]	64-slice	284/1020[1]	NA/97.8	NA/99	NA/96	NA/99.5
Weustink [2009] [15]	64-slice	52/208[1]	95/97	100/92	100/83	99/99
De Graaf [2011] [19]	320-slice	38/152	88/83	89/77	67/77	97/83

Se = sensitivity; Sp = specificity; PPV = positive predictive value; NPV = negative predictive value; Non-evaluable native coronary arteries were considered positive for occlusion and > 50 % stenosis.
Se = Sensitivität; Sp = Spezifizität; PPV = positiver prädiktiver Wert; NPV = negativer prädiktiver Wert; nicht evaluierbare native Koronararterien wurden als positiv für Verschluss und > 50 % Stenose gewertet.
[1] segment-based analysis.
Analyse auf Segmentebene.
[2] prospective ECG-gated (BMI-adapted).
prospektive EKG-Triggerung (Dosis an BMI adaptiert).
[3] prospective ECG-gated (120 kV).
prospektive EKG-Triggerung (120kV).
[4] retrospective ECG-gated; > 50 % diameter stenosis.
retrospektive EKG-Triggerung; > 50 % Stenose.

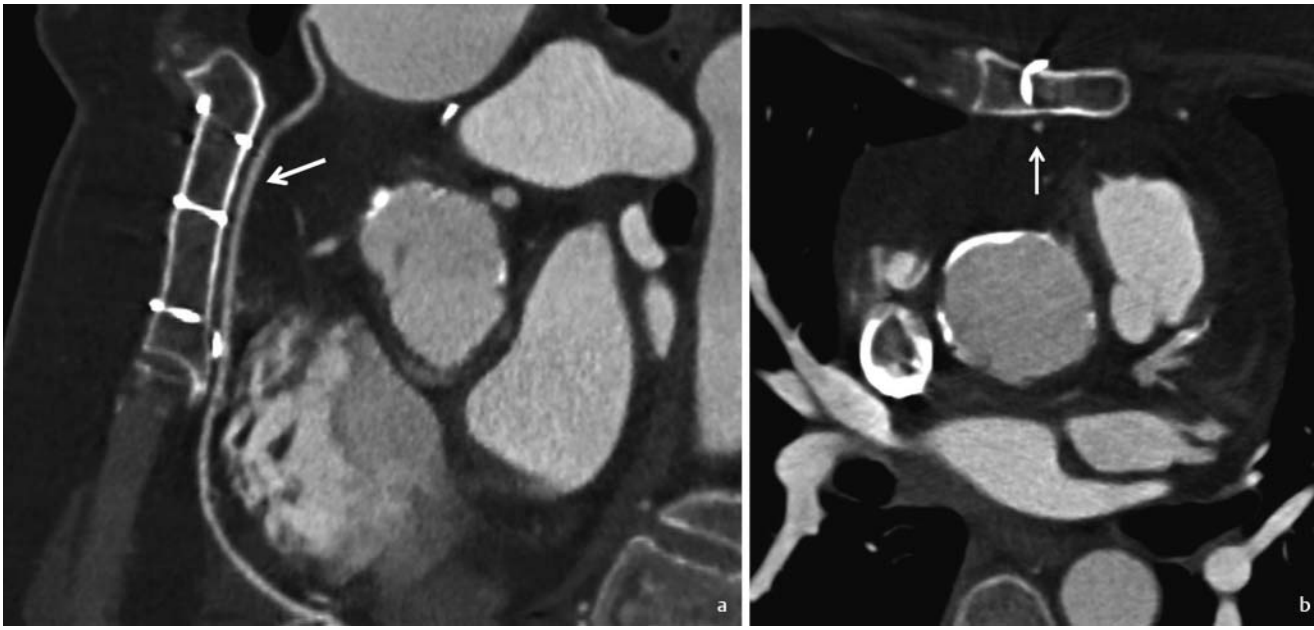
Furthermore, MD-CTA plays a crucial role in investigating complications of cardiothoracic surgery (CABG surgery, valve surgery), e. g. mediastinitis, pericardial and pleural effusions, hematoma, acute graft thrombosis or aortic dissection (▶ **Fig. 5**).

Recommendations

Current Appropriate Use Criteria for Cardiac Computed Tomography comprise symptomatic patients after CABG, localization of CABG and assessment of retrosternal anatomy prior to repeat chest or cardiac surgery [31]. For asymptomatic patients more than five years after CABG, the use of MD-CTA is considered to be uncertain and thus needs further investigation. In asymptomatic patients less than five years after bypass grafting, MD-CTA is regarded as inappropriate.

In the consensus recommendations of the German Radiology Society (DRG), the German Cardiac Society (DGK) and the German Society for Pediatric Cardiology (DGPK), computed tomography should only be performed if graft patency has to be assessed in symptomatic patients and in cases in which conventional catheter angiography is not able to display all CABGs [32].

In our clinical routine, MD-CTA of CABGs is also applied in asymptomatic patients with a positive stress test as well as in patients with atypical chest pain and ambiguous stress tests. Furthermore, MD-CTA plays an important role in preoperative planning for redo cardiac surgery or in the documentation of the postoperative outcome, especially after off-pump CABG surgery. Before redo cardiac surgery, the anatomical course of bypass grafts, especially of LIMA-to-LAD grafts in relation to the sternum, as well as anatomical information of the right ventricle in relation to the sternum are very helpful in order to avoid intraoperative complications (▶ **Fig. 6**).



▶ **Fig. 4** CPR **a** and axial image **b** of a patent venous graft to the right coronary artery located directly retrosternal (arrow).

▶ **Abb. 4** CPR **a** und axiales Bild **b** eines offenen, nicht stenosierten venösen Bypasses zur rechten Koronararterie mit Verlauf unmittelbar retrosternal (Pfeil).

Future perspectives

Morphologic assessment of native coronary arteries by MD-CTA in patients with CABG surgery did not show relevant improvements in evaluating substantial stenosis over the past decade. Thus, it can be anticipated that future research should focus on the assessment of myocardial perfusion in CABG patients to detect stenosis-related myocardial ischemia.

In recent years, there have been an increasing number of studies concentrating on the assessment of myocardial perfusion with cardiac computed tomography, which allows detection of myocardial perfusion defects under rest and/or stress. In 2010, Bamberg et al. published first experiences with dynamic myocardial stress perfusion imaging in a 69-year-old study participant using a quantitative 3 D imaging technique to calculate regional MBF [33]. Radiation dose exposure for CTA and CT perfusion imaging (CTP) as "one-stop-shop" cardiac procedure was about 12 mSv.

Okada et al. compared rest and stress (with use of a pharmacological vasodilator such as dipyridamole or adenosine) myocardial CT perfusion with rest and stress single photon emission CT (SPECT) perfusion [34]. In their study, they reported a good correlation between CT and SPECT in the detection of myocardial perfusion defects. Even under resting conditions they revealed most of the reversible SPECT defects by CT perfusion imaging. Tashakkor et al. analyzed CT perfusion studies and achieved a sensitivity, specificity, PPV and NPV of 81 %, 93 %, 87 % and 88 %, respectively, for the combination of CTCA and CTP versus ICA and fraction flow reserve (FFR) [35].

The CORE320 study is a prospective, multicenter, multinational study which deals with the diagnostic performance of 320-MDCT for detecting CHD including the accuracy of a combined CTCA and CTP protocol compared to ICA and SPECT as the reference for the detection of flow-limiting coronary artery disease [36]. CTCA and CTP versus CTCA alone lead to an increase in specificity (54 % to 73 %) and accuracy (69 % to 75 %) in patients with known and unknown CHD.

The median radiation dose exposure of CCTA combined with CTP was 8.47 mSv (CTA: 3.16 mSv, CTP: 5.31 mSv), whereas the radiation exposure of the reference standard SPECT was 9.75 mSv [37].

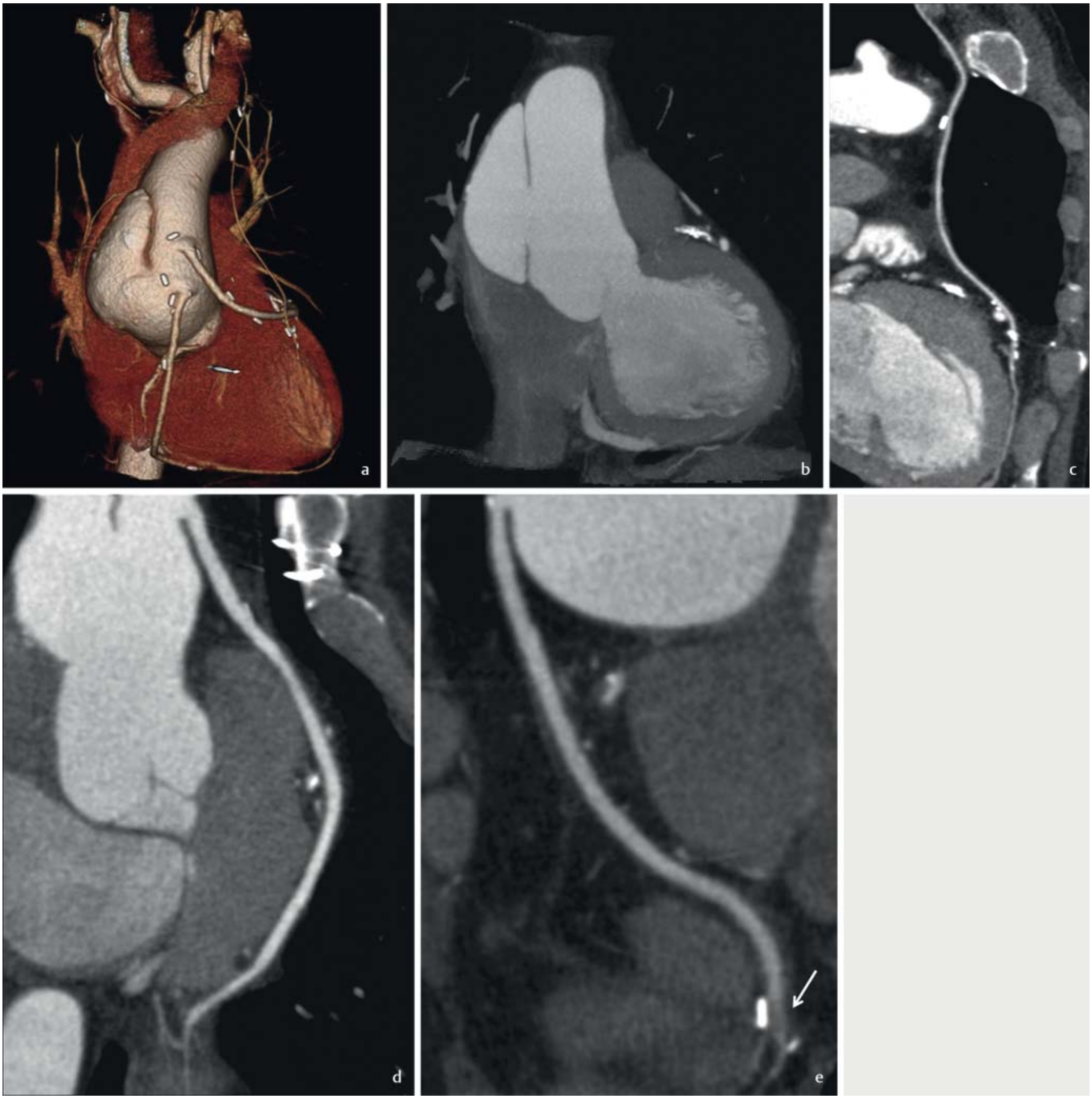
Kawai et al. analyzed CTCA and stress-rest myocardial perfusion (SPECT) in 204 patients after CABG surgery to calculate UCTs and the summed rest score (calculated out of segmental perfusion scores during stress and rest) [38]. UCTs and the summed rest score in combination are very helpful for risk stratification in patients after CABG surgery.

To our knowledge, there are no published studies concerning CTP of patients after CABG. The fact that further improvements in CT technology have the potential to reduce radiation dose exposure will hopefully help to bring CT perfusion measurements into the clinical routine, especially in cardiac imaging to detect myocardial ischemia but as well in oncologic imaging to assess tumor vascularization before and after chemotherapy.

Limitations

The present study has some limitations. We have to exclude some studies because these studies did not publish absolute numbers of true-positive, true-negative, false-positive and false-negative results or did not allow calculation of these values.

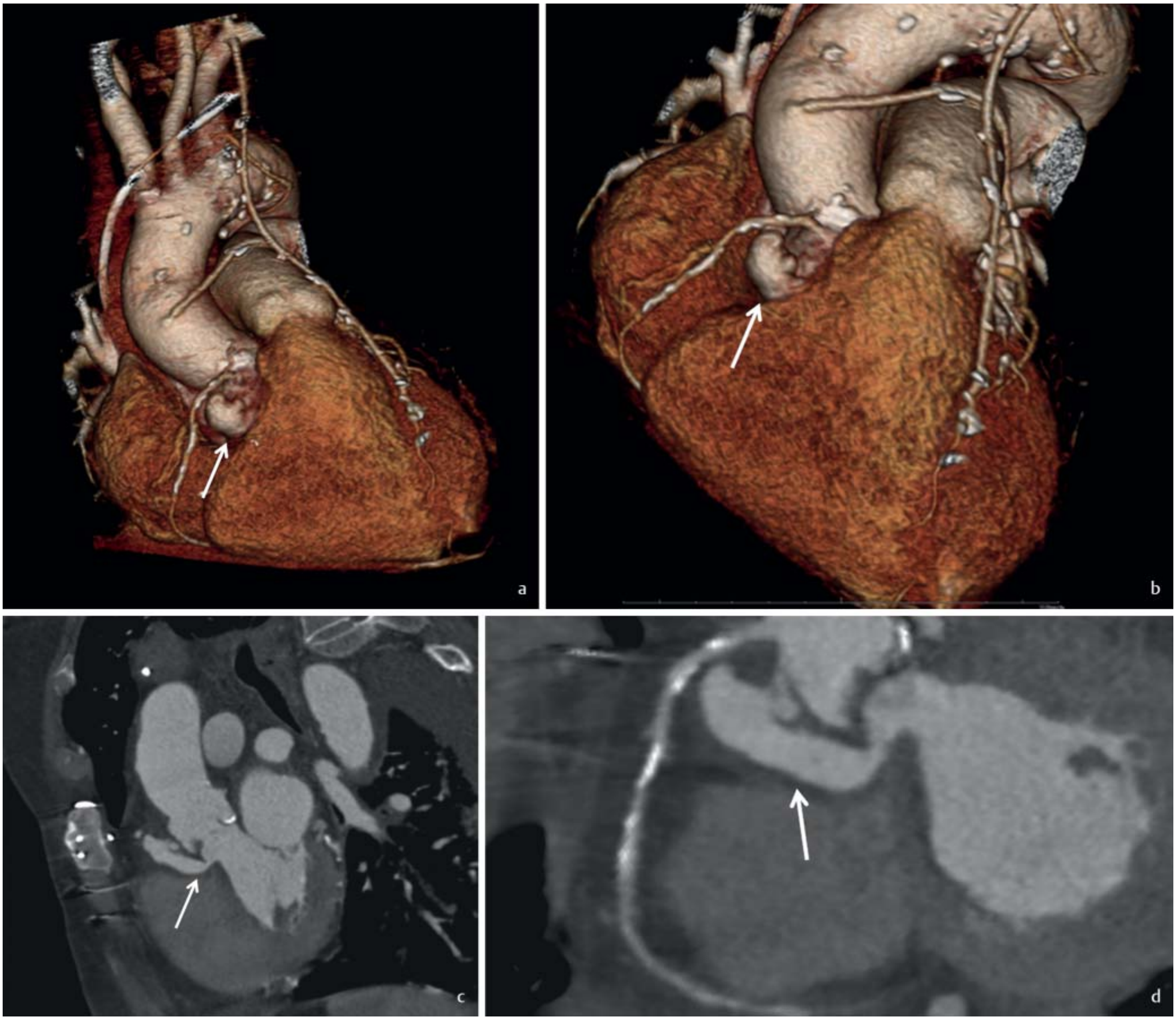
Only 7 out of 13 studies evaluated native coronary arteries. Two studies did not differentiate between distal runoffs and non-



▶ **Fig. 5** Subacute aortic dissection Type A in a patient three years after CABG surgery. Note intimal flap and aneurysm of the ascending aorta in volume rendering **a** and subvolume maximum-intensity projection **b**. IMA graft **c**, vein grafts to posterolateral artery **d** and RCA **e** are patent. Note beam hardening artifact in distal RCA graft with darker lumen near the clip.

▶ **Abb. 5** Subakute, auf die ascendierende Aorta beschränkte Dissektion bei einem Patienten drei Jahre nach ACVB-Operation. Intima Flap und Aneurysma der Aorta ascendens im Volume Rendering **a** und in der Subvolumen-Maximum-Intensitäts-Projektion **b**. IMA-Graft **c**, venöse Bypässe zum Posterolateralast **d** und zur rechten Koronararterie **e** sind durchgängig. Nachweis eines Aufhärtungsartefaktes im distalen RCA-Bypass mit dunklerem Lumen angrenzend an den Clip.

grafted coronary arteries, two publications either report distal runoffs or non-grafted coronary arteries and three publications distinguish between distal runoffs and non-grafted arteries. Furthermore, more than half of the studies used segment-based analysis compared to artery-based analysis so that diagnostic performance is hard to compare in this heterogeneous group of studies.



▶ **Fig. 6** Male patient seven years after CABG surgery. Echocardiography revealed endocarditis of the aortic valve. MD-CTA was performed preoperatively in order to evaluate topography and demonstrates open LIMA graft to LAD and open venous graft to posterolateral artery. Volume rendering **a, b** and multiplanar reformation **c, d** show subvalvular pseudoaneurysm (arrow) caused by infection caudal to the stenosed right coronary artery.

▶ **Abb. 6** Männlicher Patient mit Zustand nach ACVB-Operation vor 7 Jahren. In der Echokardiografie wurde eine Aortenklappenendokarditis diagnostiziert. Die CT-Untersuchung wurde zur Operationsplanung durchgeführt und dokumentiert einen offenen LIMA Bypass zur LAD sowie einen durchgängigen venösen Bypass auf einen Posterolateralast. Im Volume Rendering **a, b** und in der multiplanaren Reformation **c, d** findet sich ein subvalvuläres Pseudoaneurysma (Pfeil) bedingt durch die Infektion unmittelbar unterhalb der stenosierten rechten Koronararterie.

Summary

MD-CTA still offers high diagnostic accuracy in the evaluation of coronary artery bypass grafts, which has been unchanged despite the implementation of newer scanner generations. The most substantial benefit of the newest CT scanner (64 slices and beyond) is a remarkable reduction of radiation dose exposure. Pooled diagnostic quality of the evaluated studies did not change compared with previous studies performed on 64-MDCT. One of the two studies using 256-slice and 320-slice CT reached excellent values for sensitivity and NPV (97 % and 99.8 %, respectively) as well as the lowest radiation dose exposure (2.4 mSv) [16].

The challenge of assessing CABG in the coming years will be a further reduction of radiation dose while maintaining excellent diagnostic accuracy as well as an improvement in diagnostic accuracy in the assessment of native coronary arteries, possibly by combining MD-CTA with myocardial perfusion measurements.

Conflict of Interest

The authors declare that they have no conflict of interest.

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