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High-Pitch Carbon Dioxide Contrasted CT Angiography: Pilot Study

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Abstract

Purpose This study was designed to evaluate CO_2 computed tomography angiography (CO_2-CTA) of the iliac and lower limb arteries in patients with contraindications for iodinated contrast agent (ICA).

Methods Five patients with contraindications for ICA were examined using CO_2-fluoroscopic enhanced angiography (CO_2-FLA) and CO_2-CTA using a high-pitch examination protocol. Objective (vessel diameter) and subjective (visual score) image quality parameters were evaluated. Pathological findings in both modalities were compared.

Results CO_2-CTA was feasible in all patients without adverse side effects, except for CO_2 injection-associated pain. Objective vessel analysis revealed no significant difference in diameters as determined by CO_2-CTA and CO_2-FLA (0.44 ± 0.4 and 0.46 ± 0.41 mm, $p = 0.93$). CO_2-CTA had on average a higher image-quality score (2.6 ± 1.0 vs. 2.3 ± 1.0, $p = 0.009$). While for pelvic and upper leg CO_2-CTA advantageous (3.1 ± 0.74 vs. 2.7 ± 0.9, $p = 0.0014$) at good quality scores, for calf vessels no significant improvement was visible (1.9 ± 1.0 vs. 1.7 ± 0.9, $p = 0.49$) and scores were poorer.

Conclusions CO_2-CTA with high-pitch CT was feasible in a limited number of patients. Image-quality scores were on average higher for CO_2-CTA than for CO_2-FLA, while limited imaging quality in the vessels below the knee needs further work on the CT protocol. An added value of cross-sectional imaging was apparent but needs further quantification.

Keywords Carbon dioxide angiography · Computed tomography angiography · Peripheral vascular disease · Alternative contrast agents · Contrast agent contraindications

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Introduction

Standard modalities for noninvasive imaging of the iliac and lower limb arteries are computed tomography angiography (CTA) using iodinated contrast agent (ICA) and magnetic resonance angiography (MRA) with Gadolinium (Gd)-based contrast imaging [6]. With recent developments of these techniques, catheter-based diagnostic angiographic procedures are no more recommended for the standard workup in patients suffering from peripheral artery occlusive disease, PAOD [7, 18, 27]. Additional advantage of these techniques lies in the possibility for secondary post-processing, facilitating morphologic analyses, e.g., in the case of eccentric stenoses [23, 24].

All aforementioned methods have inherent limitations, mostly due to the used contrast agents, which can cause allergies, contrast-induced nephropathy, thyrotoxicity, or nephrogenic systemic fibrosis [3, 10, 22, 25]. MR imaging, which would provide contrast-free imaging, such as TOF-angiography, is prohibited or limited in patients with pacemakers, prosthetic heart valves, or other metallic foreign bodies. Metal-bearing stents are another limitation for MR-based techniques, because they usually produce strong artifacts [15, 26]. These limitations prevail, especially in elderly, diabetic patients—the predominant patient group in need of vascular imaging underlining the need for replacement techniques [8]. For some contraindications for MRA, technological developments, such as MRI-compatible pacemakers and implants, could provide a solution. For the problems associated with ICAs, such as contrast-induced nephropathy, which presents with incidence rates of 1.6–2.3 % in the general population undergoing CTA [19], and almost a fourfold increase in patients attributed to risk groups [28], concerns remain high, especially given the clinical consequences in affected patients. Alternatively ultrasound imaging can provide valuable information about the vascular tree with good sensitivity; however, it is operator-dependent and can be time-consuming, does not depict the vasculature in its entirety, and can have limitations in severely calcified vessels [6].

The search for alternatives to Gd- or iodine-based contrast agents for vascular imaging lead to the intravascular application of carbon dioxide (CO_2)—a negative contrast agent—that has been used successfully in fluoroscopic angiography (FLA) for many years [9, 11]. CO_2 is an odorless gas, which is eliminated in a single pass through the lungs [9]. With the caveat of neurotoxicity and gas-trapping, it can be used for any subdiaphragmal arterial angiographic examination and intervention. Therefore, applying CO_2 to cross-sectional vascular imaging, such as CT, seemed to be a next logical step. Besides its application in digital subtraction angiography (DSA), it has to date not been used for vascular CT applications in human subjects while nonvascular applications, such as virtual colonoscopy [4] or virtual hysteroscopy [1], are performed. Several preclinical tests were performed using CO_2 as a vascular contrast agent in the CT environment, one study showed the feasibility of pulmonary artery CO_2-CTA [2], although some animals suffered from severe complications, questioning the safety of CO_2 for pulmonary applications. In another animal study, the endovascular placement of aortic stent grafts was shown [16]. Earlier experiments [14] showed that prolonged bolus injections lead to improved image quality in a pig model. All of these results, however, were not achieved in a clinically approved setting. Because no clinically approved system allows for prolonged CO_2 injection, we drew the conclusion that increasing CT speed to follow a shorter CO_2 bolus using high-pitch protocols would be a viable option. Indeed, further experiments with high-pitch CT using only clinically approved materials [20] yielded superior results over the standard-pitch approach in a pig model. After these promising results, this work reports the results of a subsequent prospective patient study on CO_2-CTA employing high-pitch CT examination protocols.

Methods

Five patients (65–81 years, three men, two women, recruited consecutively from October 2010 to August 2011) were examined using standard CO_2-based FLA (CO_2-A) and CT-based CO_2 angiography (CO_2-CTA) in a same day, same catheter setting. All patients gave written, informed consent to this Institutional Review Board (IRB) and Radiation Protection Agency-approved study at least 24 h before the examination (protocol number EK141/07 from 24 August 2009). Inclusion criteria were requested pelvic and lower limb imaging with contraindication to ICA (serum creatinine $\geq$1.5 mg/dl, eGFR <45 ml/min) and a clinical need for a radiologic diagnostic workup, as well as informed, written consent to both examinations and the IRB-approved study protocol. Exclusion criteria were contraindications to CO_2 administration, such as AV-fistula, pulmonary insufficiency, or pulmonary hypertension, and failure to give written, informed consent to the examinations or the study protocol. A list of indications and patient characteristics can be found in Table 1.

Study Protocol

The left brachial artery was punctured with a 22G needle under local anesthesia and a 4F micropuncture sheath (Terumo, Tokyo, Japan) was introduced in Seldinger's technique. A brachial approach was chosen to avoid any sheath-related obstructions of the CO_2 flow into the iliac arteries. A 4F pigtail catheter with a radiopaque tip (Cook Medical, Bloomington, IN) was advanced into the infrarenal aorta, without the use of contrast agent. Projectional angiography of the infrarenal aorta, pelvis, femoral, and crural arteries using 40–100 ml CO_2 injection volume per run via a syringe-based CO_2 injection device (Optimed, Ettlingen, Germany) was performed. Angiography was performed with the patients' legs in a slightly elevated

Table 1 Patient characteristics

Numbers	Age (years)	Reason for CO_2	Cr. pre/post (eGFR pre/post) [mg/dl]	History	Clinical question	Therapy
1	75	RF III°	1.8/1.5 (37/46)	PAOD, Fontaine stage IIb	Evaluation pelvic and lower limb arteries	Conservative
2	78	RF III°	1.5/1.8 (34/27)	Patient with suspicion of inguinal pseudoaneurysm after Y-stent graft	Depiction of pseudoaneurysm, perioperative pelvic and lower limb CT-angiography	Operative repair of lymphocele (not aneurysm)
3	81	RF III°	3.1/3.4 (14/13)	PAOD, Fontaine stage IV left, renal insufficiency	Evaluation pelvic and lower limb arteries	PTA left calf
4	65	Postoperative RF	2.6/2.4 (25/27)	Patient with suspicion of a AAA and PAOD, Fontaine stage IV	Evaluation pelvic and lower limb arteries	Y-prothesis
5	74	RF IV°	4.5/4.2 (13/14)	Patient w/PAOD, Fontaine stage IV	Evaluation pelvic and lower limb arteries	Iliaco-iliacal bypass

Only minor changes to the creatinine/eGFR levels occurred, most probably due to physiological fluctuation. All patients were deemed unfit for iodinated, contrast-enhanced angiography by the referring vascular surgeon

RF renal failure, *PAOD* peripheral arterial disease, *AAA* aortic abdominal aneurysm, *PTA* percutaneous transluminal angioplasty

position, as recommended for CO_2-contrasted angiograms to compensate for the known buoyancy effect during CO_2 angiography [9]. Routinely, no analgesia was used, although in two patients the administration of 3.75 mg of piritramide was necessary to cope with CO_2 injection-related pain. Although in one of the patients, piritramide fully resolved the CO_2 injection-associated pain, the other patient still reported painful injections, resulting in some motion artifacts. After completion of conventional CO_2 angiography, patients were relocated to the CT room and transferred to the CT table in supine position, also with slightly elevated legs [9]. A dislocation of the pigtail catheter was ruled out using the scout view, confirming a deep infrarenal position of the catheter's radiopaque tip. Dual-source, high-pitch CT angiography (Siemens Somatom Definition, Siemens Healthcare, Forchheim, Germany) was performed after a single injection of 100 ml of CO_2. Parameters of the used CT protocol were: 110 mAs_{eff}, 120 kV, collimation 2 × 64 × 0.6 mm, pitch 3.0, and 2-s start delay, acquisition direction: superior–inferior. After imaging, the catheter was removed and the brachial puncture site was manually compressed for at least 10 min and full hemostasis was confirmed. A sterile compression bandage was applied, and the patients were monitored for another 24 h.

Measurements

The imaging studies were evaluated using objective and subjective criteria. For objective analysis vessel diameters of corresponding anatomical positions were measured and compared between CO_2-A and CO_2-CTA. These vessel diameters were measured at four distinct positions for all vessel territories [aorta, common iliac artery (CIA), internal iliac artery (IIA), external iliac artery (EIA), common femoral artery (CFA), superficial femoral artery (SFA), profound femoral artery (PFA), popliteal artery (PA), anterior tibial artery (ATA), tractus tibiofibularis (TF), posterior tibial artery (PTA), and fibular artery (FA)] using a multiplanar reformation (MPR) tool, equidistantly dividing each vessel in three parts by two readers in consensus. The three measured values were averaged for each vessel territory. Furthermore, the applied dose was recorded for every examination and compared among the groups.

The subjective analysis was carried out using VRT (Virtual Rendering Technique, Lung preset, Siemens Leonardo, Siemens Healthcare, Forchheim, Germany) images. A four-point scale was used (1—nondiagnostic: vessel anatomy was not depicted, 2—diagnostic: vessels were sufficiently depicted with minor restrictions, 3—good: vessels and collaterals were well depicted, 4—excellent: main and up to second order collaterals were depicted surpassing the necessary diagnostic quality). Statistical analysis was performed using SPSS 19 (SPSS. Inc., Chicago, IL) and MedCalc (MedCalc Software, Mariakerke, Belgium). Tests performed were Student's *t* test, analysis of variances, and Bland–Altman plots.

Pathological Findings

Fluoroscopic and CT imaging of all five patients were reviewed by two experienced radiologists, and pathological findings in both modalities were recorded in consensus. Each pathological finding was classified into vascular (hemodynamics-related, vessel anatomy change-related), and nonvascular. The list was consolidated from both modalities and for each finding was determined if it is visible in DSA, CTA, or both modalities.

Postprocessing

Other techniques for postprocessing were tested and evaluated. Minimal intensity projections (mIPs) provided by the PACS system proved to be useful (10-mm thickness, rotating mIP, iSite, Philips, Best, The Netherlands). Because many other vascular postprocessing tools are designed with a positive contrast agent in mind, a dedicated MeVisLab (Version 2.1, MeVis, Bremen, Germany) also was used to postprocess the imaging data. A postprocessing network was created, where two threshold-based nodes selected calcifications and bone structure (300–3,072 HU), another selected CO_2 and air (−1,024 to −300 HU). By manual selection of seeding points, the air in the patient volume and larger air collections in the bowels were removed using region growing. The resulting images were added pixel wise and calcifications and CO_2 were colored differently in a volume rendering view. Furthermore, curved MPRs were performed along the vasculature using MeVisLab. These postprocessing steps took typically less than 15 min to perform per patient.

Results

In all examinations, no adverse side effects were observed, although in all cases the typical discomfort related to CO_2 injections was reported by the patients in the angiographic as well as the computed tomographic examinations. In two instances, pain medication was necessary and administered. No complications due to the angiographic approach (left brachial) occurred, in all cases, the patients were inpatients discharged to their respective wards after the procedures. The applied radiation dose for the CO_2-CTA was 529 ± 215 mGy cm (DLP) and 5.25 ± 1.88 mGy ($CTDI_{vol}$), respectively. The corresponding dose for the CO_2-DSA was 21,398 ± 8,442 cGy cm^2, with on average 9.2 ± 3.1 series.

Objective Analysis

Bland–Altman method comparison plotting revealed no systematic difference in vessel diameters between angiography and CO_2-CTA (average diameter CT: 0.44 ± 0.4 mm, DSA: 0.46 ± 0.41 mm, $p = 0.93$; Fig. 1). Whereas the pelvic diameters were slightly larger in CT compared with DSA (0.73 ± 0.49 vs. 0.67 ± 0.58 mm, $p = 0.46$), upper leg diameters were almost identical (0.54 ± 0.22 vs. 0.54 ± 0.19 mm, $p = 0.99$) and lower leg diameters were smaller in CT (0.19 ± 0.21 vs. 0.23 ± 0.21 mm, $p = 0.13$).

Subjective Analysis

CO_2-CTA had on average a higher image quality score than conventional angiography (2.6 ± 1.0 vs. 2.33 ± 1.0, $p = 0.009$). Further divided by vessel territory, the average image-quality scores for aorta, CIA and EIAs, and the CFA and SFA were diagnostic (score ≥2.0; Table 2). On a broad scale, pelvic and upper leg CO_2-CTA was rated advantageous (3.1 ± 0.74 vs. 2.7 ± 0.9, $p = 0.0014$) at good

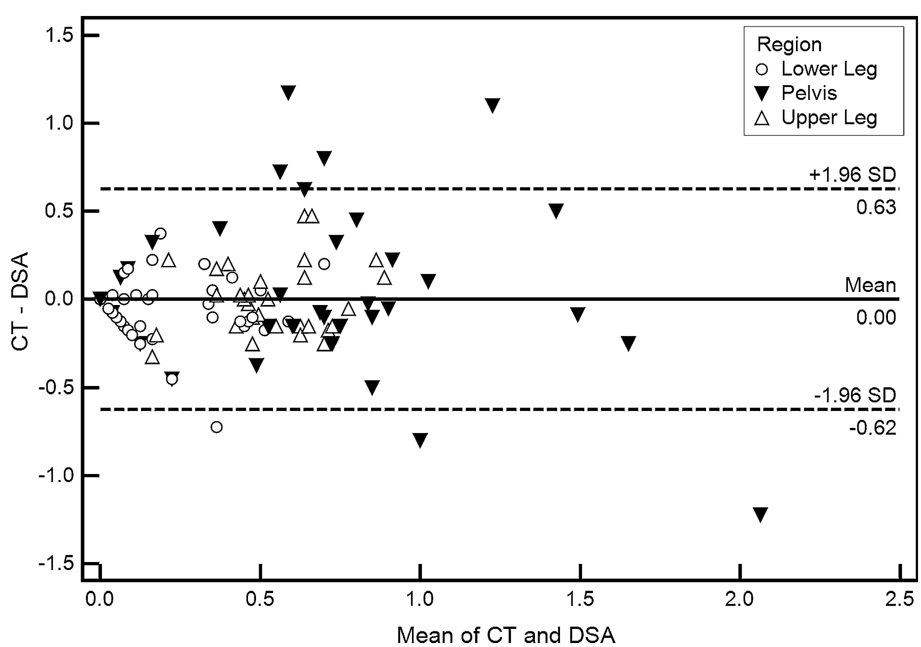

Fig. 1 Bland–Altman plot of angiographic and computed tomography vessel diameters. Whereas most values remain between the ±1.96 standard deviations, some outliers are visible for pelvic vessels, probably due to projection artifacts. *CFA* common femoral artery, *CIA* common iliac artery, *EIA* external iliac artery, *IIA* internal iliac artery, *PA* popliteal artery, *PFA* profound (deep) femoral artery, *SFA* superficial femoral artery

Table 2 Quality scores for different vessel regions for digital subtraction angiography and CO_2 CT angiography

	CO_2 CT		DSA	
	Average ± SD	Median (Min–Max)	Average ± SD	Median (Min–Max)
Aorta	3.5 ± 0.6[a]	3.5 (3–4)	3.4 ± 0.5	3 (3–4)
CIA	3 ± 0.7	3 (2–4)	3.1 ± 0.8[a]	3 (1–4)
IIA	2.6 ± 1.2[a]	3 (1–4)	1.5 ± 0.7	1 (1–3)
EIA	3.2 ± 0.4[a]	3 (2–4)	2.4 ± 0.7	3 (1–3)
CFA	3.4 ± 0.3[a]	3 (3–4)	3 ± 0	3 (3–3)
PFA	3.1 ± 0.3[a]	3 (2–4)	3 ± 0.9	3 (1–4)
SFA	3 ± 0.2	3 (2–4)	3 ± 0	3 (3–3)
PA	2.9 ± 0.8[a]	3 (1–4)	2.6 ± 0.5	3 (1–3)
ATA	2 ± 0.9[a]	2 (1–3)	1.3 ± 0.2	1 (1–2)
TF	2.2 ± 1.3[a]	2.5 (1–4)	2.1 ± 1.7	1.5 (1–4)
PTA	1.8 ± 1.3[a]	1 (1–4)	1.5 ± 0.5	1 (1–3)
FA	1.4 ± 0.5	1 (1–3)	1.8 ± 0.8[a]	1.5 (1–3)

CT computed tomography, *DSA* digital subtraction angiography, *SD* standard deviation, *CIA* common iliac artery, *IIA* internal iliac artery, *EIA* external iliac artery, *CFA* common femoral artery, *SFA* superficial femoral artery, *PFA* profound femoral artery, *PA* popliteal artery, *ATA* anterior tibial artery, *TF* tractus tibiofibularis, *PTA* posterior tibial artery, *FA* fibular artery

[a] Superior scores

quality scores; for calf vessels, no significant improvement was visible (1.9 ± 1.0 vs. 1.7 ± 0.9, $p = 0.49$) and scores were poorer. The dependent IIA and PFAs were rated worse, resulting in a score of 1.1 ± 0.3 (CO_2-CTA) and 1.2 ± 0.4 (DSA), respectively. The further distally located superficial femoral and PAs had mixed results (1.7 ± 0.9 [CO_2-CTA] and 1.5 ± 0.8 [CO_2-DSA], respectively).

Pathological Findings

The respective vascular territories were assessed comparatively in CO_2-CTA and CO_2-angiography: 41 pathological findings were recorded, 36 (88 %) related to the vascular system, 5 (12 %) in other organ systems, such as bony structures or bowel (Figs. 2, 3). Categorized into changes in vasculature (calcifications, aneurysms), hemodynamic changes (filling defects, collateralizations), and other (healed fractures, sigmoid diverticulosis, intervertebral disc herniations), 12 (29 %), 20 (49 %), and 9 (22 %) were found, respectively. Regarding only outcome-relevant findings, 79.4 % of the findings were present in both modalities, 2.9 % in DSA only (due to lacking contrast in the CT examination), and 17.6 % in CT only (either due to information provided by the cross-sectional imaging or poor diagnostic quality of the DSA).

Discussion

Noninvasive, cross-sectional imaging of the arterial pelvic and lower limb vasculature using MRA and CTA is an established part of the clinical workup of patients [7, 18, 27]. Compared with solely diagnostic catheter-based angiography, CTA offers the opportunity to image all arteries from the abdominal aorta to the lower legs within one examination with only a single injection of contrast agent. Furthermore, due to its cross-sectional nature, CTA features the inherent advantage to depict entire vascular pathologies, e.g., complete dimensions of aneurysms, including non-perfused parts or plaque morphology. In addition, pre-procedural CTA is routinely used for sizing of aortic aneurysms and sizing of prosthesis before stent-graft implantation [13, 21]. Due to the high incidence of renal failure in patients with PAD, there is a population of patients with contraindication for ICAs but have the need for vascular imaging. Although MRI-based, contrast-free techniques can be used, many of these elderly patients are likely to as well present with contraindications for this modality [8]. For these patients CO_2-CTA may be a viable option. So far, there is only experimental data on CO_2-CTA showing the technical feasibility in large animal models [14, 16, 20]. Our goal was to transfer this approach into a first-in-men study.

The results show a good agreement between catheter-based CO_2 angiography and CO_2-CTA regarding vessel diameters in different vascular territories (Fig. 1). Especially for smaller vessels of the lower leg, there were no relevant differences. However, rated image quality of the calf vessels was nondiagnostic, and depiction was insufficient in multiple cases. This might be attributable to mistiming of the CO_2 bolus or due to vascular filling defects, as in CO_2-DSA depiction quality was limited, too. In CO_2-DSA, some authors propose selective and super-selective catheterization of the vessels under investigation [11]. This approach could be potentially translated to CT-CO_2 as well, although it was not within the scope of this study and would change the protocol considerably. The selective and superselective approaches also could improve the diagnostic value of the proposed method in the more distal vessels. However, because this was no viable option in the described setting image quality in both DSA and CO_2-CTA have room for improvement.

The pathologies found in the comparatively performed FLA were concordant with the findings in CO_2-CTA. High-pitch CO_2-CTA seemed to be able to follow the CO_2 bolus during run-off, although no standard pitch control (e.g., pitch 1.0) imaging was performed. The cross-sectional imaging information of CO_2-CTA added further diagnostic value to the examination both for primary diagnostic targets, and, not surprisingly to a great extent for secondary diagnoses and incidental findings.

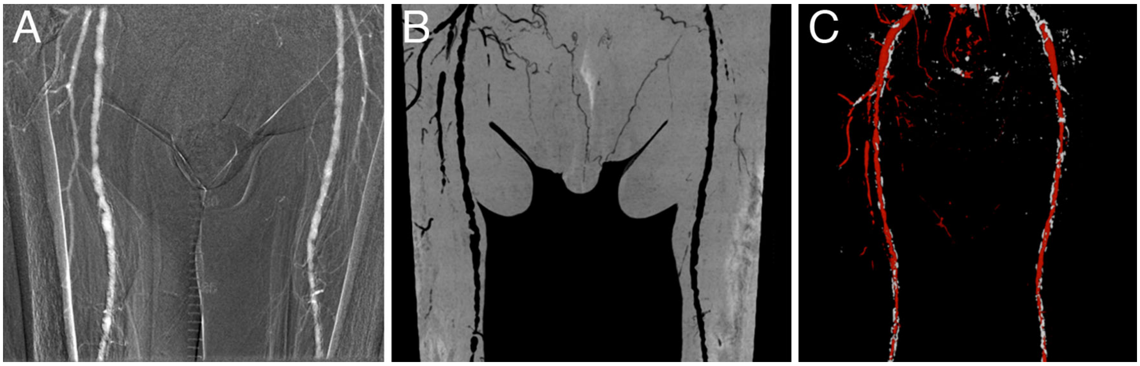

Fig. 2 Calcifications as apparent in DSA (**A**) and VRT (**C**) postprocessing (*left–right*) in a patient with PAD. Whereas minimum intensity projections (**B**) discard information about the calcifications, information about the extent of arteriosclerosis can be assessed in the postprocessed image

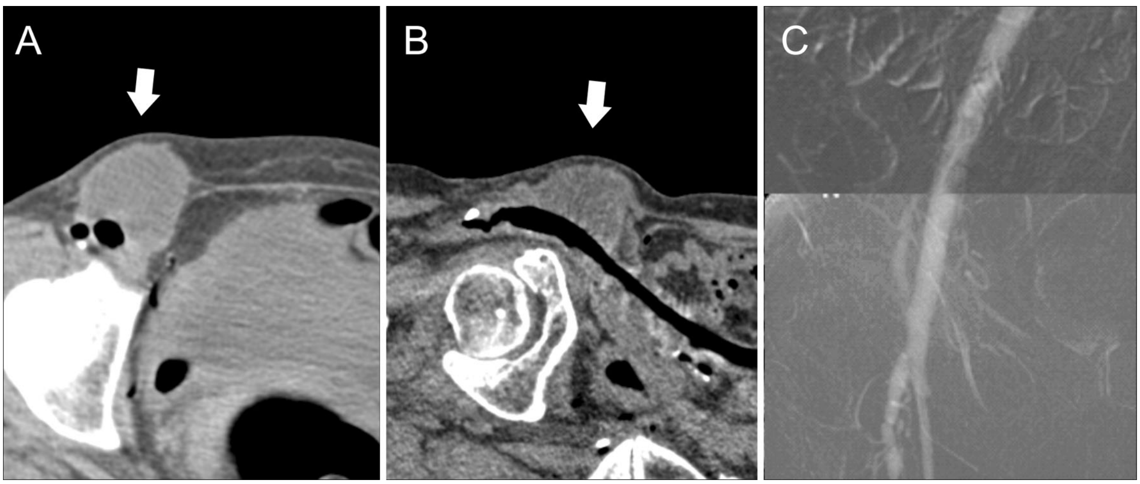

Fig. 3 Lymphocele in CO_2-CTA (**A** axial, **B** sagittal) and DSA (**C**) of the femoral artery in a patient with a bifemoral aortic stent graft. Whereas the finding is clearly visible in CO_2-CTA, DSA does not permit the assessment of the pathology

CT-CO_2 readily produced images with diagnostic value without the risk of contrast-related renal complications. The procedure is more complex than standard CT angiography, as a preparation step in an angiographic suite needs to be performed. Other logistical issues, such as planning two rooms at a time, need to be considered, because they add further complexity to the examination, although a catheterization on the CT table is conceivable.

Because CO_2-enhanced CT angiography is an entirely new examination method, it is difficult to value the findings definitely. Especially the problem of bolus fragmentation (discontinuity of the CO_2 bolus as it progresses through the vascular system) and the differentiation of bolus fragmentation from stenosis are hindering definite diagnoses as the technique is carried out in this study. This problem has to be resolved before a widespread application of the technique can be recommended. One possible solution could be the application of shuttle-mode scanning, where the area of interest is imaged multiple times. The increased dose applied through multiple imaging passes can be potentially reduced through applying low dose protocols made feasible through the high contrast between CO_2 and tissue (ΔHU > 1,000 HU) compared with contrast agent-based scanning (ΔHU ca. 300 HU).

Although the availability of high-pitch CT protocols is currently limited to dual-source CT scanners, single-source CT scanners with wide detectors will soon be capable of similarly rapid data acquisition.

Another issue with this new method is the fact that no standardized postprocessing methods are readily available and/or evaluated. One relatively simple and practical approach is to employ mIPs to the datasets, although the information on calcifications is being discarded by the transfer function of the visualization technique. Another option is to use 3D curved MPR (Fig. 4), with the advantage of having the full range of density information at hand. For 3D surface renderings, most common software packages do not provide options for visualizing negatively

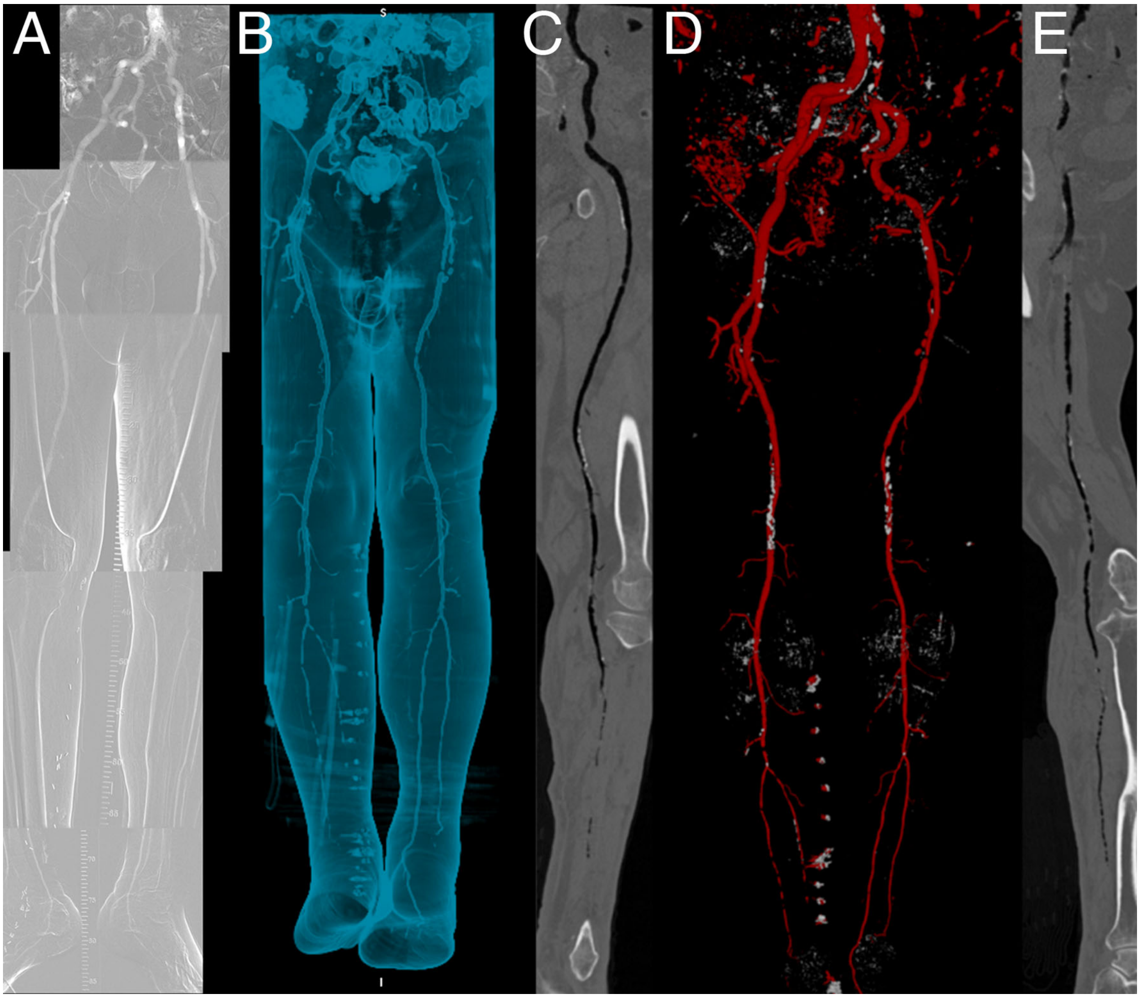

Fig. 4 Patient with PAD in **A** CO_2-DSA, **B** CO_2-CTA in volume rendering technique (lung window setting), **C** left leg multiplanar reformation (MPR), **D** threshold postprocessing, and **E** MPR right leg. A tortuous anatomy of the pelvic arteries with a filling defect in both DSA and CT are visible on the *left* common iliac artery (*grey arrows*), probably due to buoyancy effects. Calcifications are prominently visible in the popliteal artery (*white arrows*), as well as OR-clips after vein harvesting for coronary bypass (*right* calf, *arrowheads*). While the vascular anatomy is clearly standing out on the CT images and postprocessings, DSA imaging can be challenging to assess

contrasted vessels, possible alternatives are virtual colonoscopy packages and lung visualization presets, although the results were not convincing. The approach chosen by us, to visualize calcifications and CO_2 vessel contrast, seemed to be the most impressive, although the clinical value of such postprocessing remains unclear.

Compared with other gadolinium/iodine-free contrast imaging modalities, angiography CO_2-CTA has the advantage of a higher spatial resolution at very short imaging times, avoiding the associated artifacts. Compared with ultrasound, the vascular tree is visualized in its entirety, and the method is not operator-dependent, although the technique surely needs to be evaluated against vascular ultrasound, especially for the limb arteries. Future studies, beyond the pilot setting of the study at hand, should encompass duplex ultrasound, as well as contrast free MRI. Likewise, the comparison of 2D–3D imaging is suboptimal in the current setting, prone to projection and calibration errors. Further studies that include a higher number of patients could establish measures less prone to projectional artifacts or miscalibration, such as assessment of stenosis diameters. At the same time, CO_2-CTA is an invasive procedure, and the risks need to be weighed carefully against the benefit of the diagnostic information. The employment of thin angiographic catheters (4F in this study) has been shown to reduce the risk of angiography-related complications [5]. As in all radiological techniques using ionizing radiation, the benefit of a method, such as CT, needs to be weighed against the potential harm of the additional radiation applied. The relatively low viscosity of CO_2 might even allow the use of 3F catheters, further lowering the risk of complications. An antegrade approach for CO_2 injection was chosen, because retrograde CO_2 contrast injection would have resulted in asynchronous CO_2 propagation, and catheter material from a retrograde femoral approach would have inhibited a free contrast flow and potential bolus fragmentation could have occurred. A limitation of aortic pigtail-based CO_2 angiography is the lack of the possibility for superselective CO_2 angiography, which would potentially increase the image quality [9]. Because our cubital approach is suboptimal for superselective catheterization of the lower limb vasculature, a careful evaluation of other approaches, including a comparison to then possible low-volume iodinated contrast examinations (e.g., <10 ml [12, 17]) needs to be included in further study protocols.

Conclusions

High-pitch CO_2 enhanced CTA is feasible and provides diagnostic information in vascular pathologies. In this pilot study, the diagnostic value in the distal vasculature was limited, potentially hinting at an advantage of depicting aortal and ilial pathologies in patients with claudication or post aneurysm repair. The cross-sectional information adds diagnostically exploitable information compared with projectional CO_2 X-ray angiography.

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Conflict of interest Tobias Penzkofer reports travel support from Siemens Healthcare and Philips Healthcare, outside the submitted work. The Department of Diagnostic and Interventional Radiology, RWTH University Hospital Aachen has a research agreement with Siemens Healthcare, Germany. Karin Slebocki, Jochen Grommes, Philipp Bruners, Peter Isfort, Stephane Langer, Christiane K. Kuhl and Andreas H. Mahnken have nothing to disclose. Thomas Schmitz-Rode is inventor of the CO_2 injection device used in the study.

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