Value of Image Fusion in Coronary Angiography for the Detection of Coronary Artery Bypass Grafts

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Background—Coronary angiography is more complex in patients with coronary artery bypass grafts (CABG). Image fusion is a new technology that allows the overlay of a computed tomography (CT) three-dimension (3D) model with fluoroscopic images in real time.

Methods and Results—This single-center prospective study included 66 previous CABG patients undergoing coronary and bypass graft angiography. Image fusion coronary angiographies (fusion group, 20 patients) were compared to conventional coronary angiographies (control group, 46 patients). The fusion group included patients for whom a previous chest CT scan with contrast was available. For patients in this group, aorta and CABG were reconstructed in 3D from CT acquisitions and merged in real time with fluoroscopic images. The following parameters were compared: time needed to localize the CABG; procedure duration; air kerma (AK); dose area product (DAP); and volume of contrast media injected. Results are expressed as median. There were no significant differences between the 2 groups in patient demographics and procedure characteristics (access site, number of bypass to be found, and interventional cardiologist's experience). The time to localize CABG was significantly shorter in the fusion group (7.3 versus 12.4 minutes; $P=0.002$), as well as the procedure duration (20.6 versus 25.6 minutes; $P=0.002$), AK (610 versus 814 mGy; $P=0.02$), DAP (4390 versus 5922.5 cGy·cm^2; $P=0.02$), and volume of iodinated contrast media (85 versus 116 cc; $P=0.002$).

Conclusions—3D image fusion improves the CABG detection in coronary angiography and reduces the time necessary to localize CABG, total procedure time duration, radiation exposure, and volume of contrast media. (*J Am Heart Assoc.* 2016;5:e002233 doi: 10.1161/JAHA.115.002233)

Key Words: cardiovascular imaging • computed tomography • coronary angiography • coronary artery bypass graft • fluoroscopy • fusion imaging • radiation exposure • real-time imaging

Patients with coronary artery bypass grafts (CABGs) often need coronary evaluation by means of coronary angiography, in order to explore recurrence of chest pain, or heart failure, or for preoperative evaluation of cardiac valve replacement or high-risk noncardiac surgery. Indeed, the natural history of native coronary artery disease, and the natural evolution of aortocoronary bypass have been widely described (10–15% of venous grafts are occluded per year,

50% after a period of 10 years).[1–3] Locating a CABG during coronary angiography may be difficult, particularly for venous or radial artery grafts because of the variability in proximal anastomosis location. These procedures last longer and therefore lead to higher levels of radiation exposure,[4] and are more nephrotoxic,[5] in patients with a higher risk of complications (generally elderly, overweight, suffering from polyvascular disease, renal failure, and so on). A cardiac computed tomography (CT) scan system allows for reconstruction in three dimensions (3D) of any structure of interest. It is now possible to fuse this reconstruction in real time with any other form of interventional imaging.[6] This technology improves the two-dimensional (2D) spatial visualization of images from a medical examination by merging, in real time, a 3D model obtained from reconstructed CT images of the structure of interest, with conventional interventional X-ray images. This technology is commonly referred to as image fusion. This new imaging technique, initially described in interventional neuroradiology,[7–10] is now used in abdominal[11] and vascular[12–14] interventional radiology. In cardiology, its

use is limited primarily to atrial fibrillation procedures,[15–18] but also to complex hemodynamic procedures in the context of congenital heart disease.[19–21]

So far, to our knowledge, this technique has never been described during coronary angiography, particularly for location of CABGs. Our study evaluates the contribution of image fusion to reducing the time needed to locate the graft, as well as procedure duration, ionizing radiation exposure level, and amount of iodine contrast agent needed during aortocoronary bypass graft location procedures.

Materials and Methods

We conducted a single-center, controlled, observational, and prospective study, at the University Hospital of Nantes (Nantes, France), from June 2013 to June 2014. All patients with previous single or multiple coronary artery bypasses, who were hospitalized for a coronary angiography during this period were included. The indication for coronary angiography was provided by the patient's attending cardiologist. Patients referred to a planned angioplasty or examined under emergency conditions, as well as minors or adults under guardianship, were excluded. Patients undergoing a contrast-enhanced thoracic CT scan allowing CABG 3D reconstruction were included in the "image fusion" group. The other patients, with no previous recorded or usable CT images were included in the "control" group. The CT scan used for the 3D reconstruction was performed before the coronary angiography, either during a previous or the current hospitalization. If performed during the current hospitalization, most CT scans were performed to look for bypass graft distance from the sternum in patients with previous thoracic surgeries with a novel indication for cardiac surgery. No thoracic CT scan was made specifically for the purposes of this study. Each patient gave oral consent, after having been suitably informed. Comparisons between the image fusion and control groups are possible because having CT scan did not affect the characteristics of the CABG. This study was approved by the French CNIL (Commission Nationale de l'Informatique et des Libertés) and GNEDS (Groupe Nantais d'Ethique dans le Domaine de la Santé) organisations.

Evaluation Criteria

The main evaluation criterion was the length of time needed to find CABG. This duration was calculated in minutes, between the beginning of the CABG search and the opacification of all of the sought bypass grafts. The beginning of this search was orally announced by the physician, most often after the whole native coronary arteries opacification. At this time, a stopwatch was started, under paramedical staff

control present during the angiography. The physician looked for all the CABG reported in each patient, excluding any known occluded bypasses.

The secondary evaluation criteria were as follows: The procedure duration measured using a stopwatch started after insertion of the arterial catheter (allowing the difficulties encountered with arterial puncture to be avoided) and stopped when the physician took off the catheters, after opacification of the native coronary arteries and the CABG sought in the patient. As for all interventional radiology procedures,[22] the parameters, corresponding to the applied irradiation and quantity of contrast agent required, were reported in each group. Thus, the total air kerma (AK) in milliGray (mGy), dose area product (DAP) in centiGray per square centimeters (cGy·cm^2), fluoroscopy time in minutes, total radiation time in minutes, and amount of iodinated contrast agent in milliliters (mL) were reported. The radiation exposure data were measured automatically and uniformly by various systems. The AK corresponds to the kinetic energy deposited per unit mass, in mGy, and the DAP corresponds to the mean dose absorbed in air from the X-ray beam cross-section, multiplied by the surface area of this section, in cGy·cm^2. The number of catheters used was also noted.

In addition, the general demographic data of the population, indication for coronary angiography, access site, number of CABGs to be looked for, and type of CABG for each patient were reported to allow comparison between the 2 groups.

Procedure

All coronary angiographies were performed in our institution in 1 of 2 rooms (Innova 2100 and IGS 520 OR; GE Healthcare, Chalfont St Giles, UK) equipped with a 20×20 cm flat panel detector. These machines are identical in terms of X-ray exposure settings (low dose with a default frame rate of 7.5 frames/s) and radiation protection. The contrast agent used was Hexabrix (Guerbet, Roissy CdG Cedex, France). The coronary angiography procedures were performed by senior physicians from the University Hospital, and their level of experience was noted. Fellows, who had just completed their training in interventional cardiology, were considered to be less experienced than the others. Femoral or radial punctures were chosen based on the interventional cardiologist's decision.
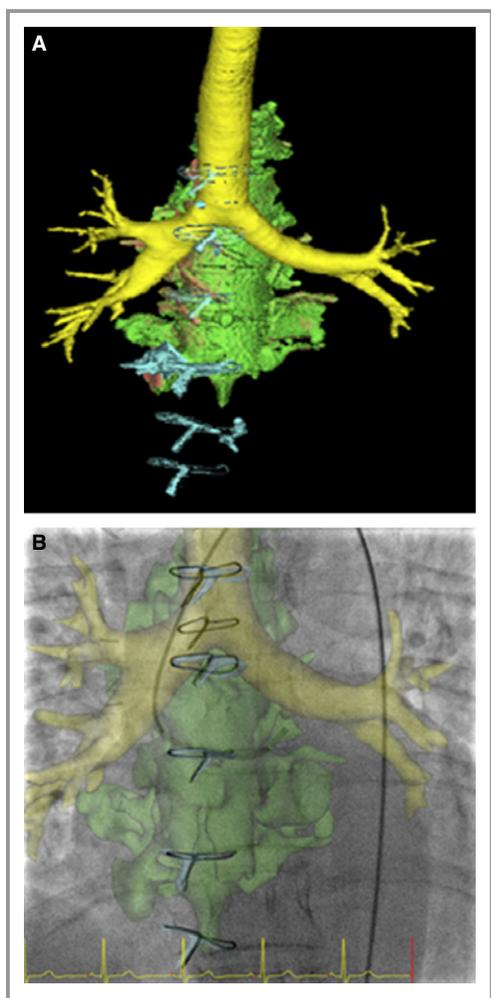
Real-Time 3D Reconstruction and Image Fusion

In the image fusion group, the 3D reconstruction was achieved using injected thoracic CT scans performed in the institution (Light Speed VCT 64; GE Healthcare) available in the Nantes University Hospital network server. There were no

patients coming with a CT from other locations. A 3D reconstruction of the structures of interest was obtained. First, the aorta and CABG were reconstructed in 3D, with the proximal part of the CABG being the most critical element, allowing the interventional cardiologist to achieve improved guidance during the procedure. Then, the steel wires used for sternotomy, the trachea up to the carina and the proximal part of the 2 bronchi, and 3 vertebrae were also reconstructed in 3D (Figure 1A) in order to optimize the real-time positioning of the 3D images onto the angiogram. All of these segmentations were performed before the coronary angiography procedure by a senior radiologist or a resident cardiologist.

The reconstructed 3D images were then initially registered and overlaid over the real-time fluoroscopic images using a dedicated workstation and image fusion software (AW

Workstation with Innova HeartVision; GE Healthcare). The first registration step consisted in aligning the sternotomy wires on both images, as well as the trachea and the vertebrae (Figure 1B; Video S1). Once achieved, the aorta and CABG reconstructions were displayed, and the search for the latter could be initiated (Figure 2; Videos S2 through S4 are examples of 3D reconstruction merged with real-time fluoroscopic). 3D data sets could be displayed and manipulated both from the control room and from table side in the procedure room. It was always necessary to manually adjust

Figure 1. Examples of image reconstruction. A, 3D reconstruction of sternotomy wires, vertebrae and the trachea down to the proximal part of the bronchi. B, 3D reconstruction positioned in real time on the fluoroscopic images. 3D indicates three-dimensional.
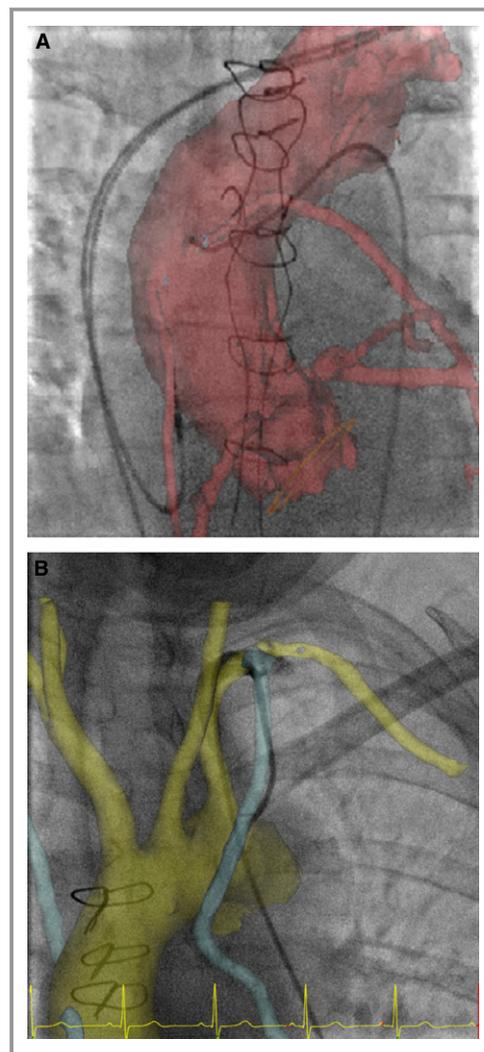
Figure 2. 3D reconstruction merged with the real-time fluoroscopic. A, 3D reconstructions of aorta and CABG positioned in real time, and coronary angiography catheter positioned next to a saphenous CABG. B, 3D reconstructions of aorta and CABG positioned in real time, opacification of the left internal mammary artery during a coronary angiography using the femoral approach. 3D indicates three-dimensional; CABG, coronary artery bypass graft.

the imported 3D reconstruction to that of a more elevated position, despite perfect alignment of the spine and sternum. The accuracy of the image overlay was then visually confirmed through the use of contrast angiograms. This coregistration was synchronized with the movements of the C-arm, so that the projection of the 3D CT-like data set was continuously adjusted according to the movements of the C-arm through various oblique angles.

This entire workflow took ≈10 minutes per examination including 5 minutes for the segmentation step before the procedure and 5 minutes for registration during the examination. Because of the simplicity of the registration step, and the fact that it can be done in the lab outside of an examination, training was fully performed within a few procedures.

Statistical Analysis

As a result of the absence of any published data on this topic, it was not possible to compute the number of subjects required for the study. Continuous data are expressed as median and interquartile range [Q1–Q3] or mean values and SD, and the nominal data as numbers (%). Continuous variables were analyzed with the Mann–Whitney test and the nominal variables were analyzed using the chi-square (χ^2) test or Fisher's exact test. Our initial analysis compared the nominal variables (surgical approach, cardiologist's experience, and so on) and the continuous variables (age, total number of bypass grafts to be found, number of mammary bypasses to be found, and so on) in the 2 groups. The primary and secondary evaluation criteria were then compared between the 2 groups. Finally, the primary evaluation criteria

were indexed according to the number of bypass grafts to be located in each of the 2 groups, in order to remain independent of any differences in terms of the number of bypasses to be located in each of the 2 groups. This indexed data were then compared using the Mann–Whitney test for the quantitative data. A *P* value of less than 0.05 was considered to be statistically significant. Because all the other parameters involved data related to opacification of the native coronary arteries, we did not index these to the number of bypass grafts to be found.

Results

Between June 2013 and June 2014, a total of 66 patients were included in our study, of which 20 were in the image fusion group and 46 were in the standard coronary angiography group. The general characteristics of the population are summarized in Table 1. These are general purpose data, which do not have any influence on the procedure. No significant differences were observed between the image fusion group and the control group, in terms of: age (71±11 versus 71±10 years old, respectively; *P*=0.91), Body mass index (BMI) (28.8±5.9 versus 28.7±4.9, respectively; *P*=0.94), kidney function as assessed by the level of serum creatinine (89.9±19.8 versus 86.8±23.3 µmol/L, respectively; *P*=0.6). There were more angiography procedures for preoperative indications in the fusion group. There were more women in the fusion group comparatively than the control group (35% versus 11%; *P*=0.03).

The data specific to the procedure are summarized in Table 2. There was no significant difference between the 2

Table 1. Patients Demographics

	Group			
	Control	Fusion	Total	*P* Value
Age	71±10	71±11	71±10	0.91
Sex				0.03*
Men	41 (89%)	13 (65%)	54 (82%)	
Women	5 (11%)	7 (35%)	12 (18%)	
BMI, kg/m²	28.7±4.9	28.8±5.9	28.7±5.2	0.94
Creatinine, µmol/L	86.8±23.3	89.9±19.8	87.8±22.2	0.6
Indication				0.008*
Recurrent angina	25 (54%)	5 (25%)	30 (45%)	
Positive ischemia test	9 (20%)	4 (20%)	13 (20%)	
Heart failure	8 (17%)	2 (10%)	10 (15%)	
Preoperative	4 (9%)	9 (45%)	13 (20%)	

Data as mean value (±SD) or a number (percentage). BMI indicates body mass index.

Table 2. Characteristics of the Procedures Used in Both Groups

	Group			P Value
	Control, N (%)	Fusion, N (%)	Total (%)	
Access site				0.17
Right femoral	36 (78)	11 (55)	47 (71)	
Left femoral	2 (4)	1 (5)	3 (5)	
Right radial	2 (4)	2 (10)	4 (6)	
Left radial	6 (13)	6 (30)	12 (19)	
Total	46 (100)	20 (100)	66 (100)	
Number of bypass to be found				0.78
1	7 (15)	3 (15)	10 (15)	
2	14 (30)	9 (45)	23 (35)	
3	18 (39)	7 (35)	25 (38)	
4	6 (13)	1 (5)	7 (11)	
5	1 (2)	0 (0)	1 (2)	
Total	46 (100)	20 (100)	66 (100)	
Number of mammary bypass				0.03*
0	0 (0)	3 (15)	3 (5)	
1	30 (65)	10 (50)	40 (60)	
2	16 (35)	7 (35)	23 (35)	
Total	46 (100)	20 (100)	66 (100)	
Number of bypass implanted on the aorta*				0.94
0	14 (30)	5 (25)	19 (29)	
1	18 (39)	8 (40)	26 (39)	
2	12 (26)	6 (30)	18 (27)	
>2	2 (4)	1 (5)	3 (5)	
Total	46 (100)	20 (100)	66 (100)	
Interventional cardiologist's experience				0.18
CCA/assistant	15 (33)	10 (50)	25 (38)	
Experienced	31 (67)	10 (50)	41 (62)	
Total	46 (100)	20 (100)	66 (100)	

Data as a number (percentage). CCA indicates Assistant Chief Clinical.
*Including saphenous vein and radial artery bypass, including proximal insertion on the aorta.

groups for characteristics that could potentially influence the parameters studied. The total number of bypass grafts to be located was not significantly different between the 2 groups (P=0.78), allowing an unbiased comparison of the 2 groups. The different types of CABG were: mammary CABG and CABG implanted on the aorta including saphenous CABG and CABG using the radial artery. There was no difference for CABG with aortic anastomosis (P=0.94). For mammary CABG, there was a difference: There were more procedures without mammary CABG to be located on the fusion group (P=0.03). The cardiologists' experience, as previously described, was similar

in the 2 groups (P=0.18). There was no significant difference between the 2 groups in terms of access site (P=0.17).

In the image fusion group, the CT scans were mainly performed during a previous hospitalization at our institution (55%). The indications for CT scans were as follows: preoperative assessments of patients undergoing TAVI (transcatheter aortic valve implantation; 35%); assessment of chest pain related to CABG permeability/obstruction; without reaching a conclusion from the CT coronary angiography scan (30%); pulmonary assessment (15%); preoperative assessment of mitral insufficiency surgical repair (10%) and preoperative

assessment of mechanical aortic prosthesis dysfunction (5%); and suspected mediastinitis (5%).

Table 3 summarized the different parameters measured in the 2 groups. The use of image fusion significantly reduces the length of time needed to find a CABG as compared to the time needed in the control group (7.3 [3.8–11.3] versus 12.4 minutes [7.5–19.4], respectively; P=0.002). When compared with a standard angiogram, the use of image fusion reduced significantly: procedure duration (20.6 [14–26.6] versus 25.6 minutes [20.3–40], respectively; P=0.002); AK (610 mGy [356–724] versus 814 mGy [430–1148]; P=0.02); DAP (4390 [3189.5–6055.6] versus 5922.5 cGy·cm^2 [4064–9094.9]; respectively, P=0.02); and amount of iodinated contrast agent (85 [70–98] versus 116 mL [65–148], respectively; P=0.002). For the number of catheters used, the difference between the image fusion and the control groups was not significant (3.05±1.1 versus 3.69±1, respectively; P=0.53).

In order to optimize the comparison between the 2 groups for the main evaluation criterion, the CABG search time was indexed according to the number of bypass grafts expected to be found in each group, thus giving the search time per searched CABG, in each group (Table 4). The use of image fusion significantly reduces the indexed CABG search time per searched CABG (3.08 [1.81–4.6] versus 5.13 [3.03–8.63]; P=0.049).

Discussion

The results of this study clearly highlight the contribution of 3D image fusion to coronary angiography, in terms of CABG search time, procedure length, fluoroscopy time, total radiation time, AK, DAP, as well as the amount of contrast agent required. All of the important parameters involved in an interventional procedure are improved through the use of this easy-to-use technology.

Any medical examination, in particular, an invasive imaging procedure, involves a risk. Over the past 20 years, the number and complexity of interventional cardiology acts has significantly increased. The adverse effects of X-ray radiation on patients and medical staff have been well described for many years.[23–25] Many studies have demonstrated the advantages to be gained by limiting X-ray radiation exposure, and have proposed guidelines to restrict this exposure.[26] Radiation safety is undeniably a major issue in the development of medical imaging.[26,27] Standard means of protection (lead apron, leaded glass goggles, and thyroid shields) provide the operator with incomplete protection, associated with the risk of developing spinal pathologies.[28,29] The main solution to reduce radiation exposure is to decrease the duration of procedures as much as possible. Similarly, the nephrotoxicity of iodinated contrast products is well known, and has been described for many years,[30] and the need for nephrotoxicity

Table 3. Comparison of Procedure Data From the 2 Groups

	Group		
	Control (%)	Fusion (%)	P Value
Search time, min	12.4 [7.5–19.4]	7.3 [3.8–11.3]	0.002*
	46 (100)	20 (100)	
Procedure time, min	25.6 [20.3–40.0]	20.6 [14.0–26.6]	0.002*
	46 (100)	20 (100)	
Total radiation time, min	14 [10.7–21.1]	11.6 [8.1–14.7]	0.01*
	32 (70)	15 (75)	
Fluoroscopy time, min	11.2 [9.1–20.3]	9.6 [6.5–11.9]	0.006*
	46 (100)	20 (100)	
Air kerma, mGy	814 [430–1148]	610 [356–724]	0.02*
	44 (95)	20 (100)	
DAP, cGy·cm^2	5922.5 [4064.0–9094.9]	4390 [3189.5–6055.6]	0.02*
	46 (100)	20 (100)	
Amount of contrast agent, mL	116 [65–148]	85 [70–98]	0.002*
	46 (100)	20 (100)	
No. of catheters	3.69±1	3.05±1.1	0.53
	46 (100)	20 (100)	

Data as median [Q1–Q3] or mean value (±SD) or a number (percentage). DAP indicates dose area product.

Table 4. Comparison of CABG Search Times, When These are Indexed According to the Number of Bypass Grafts to be Found

	Group		
	Control	Fusion	*P* Value
Indexed search time, min	3.08 [1.81–4.6]	5.13 [3.03–8.63]	0.049*

Data as median [Q1–Q3]. CABG indicates coronary artery bypass graft.

prevention has also been well studied.[31,32] Other complications are more specific to cardiac catheterism procedures, such as postangiographic embolism,[33] arterial puncture complications, and hemorrhagic or infectious complications.

Coronary angiography in patients with CABG not only lasts longer, but also leads to higher irradiation and nephrotoxicity than coronary angiography in patients without CABG.[4,5,34,35] In addition, the CABG population is certainly more fragile and at a higher risk of complications related to more comorbidities, such as polyvascular diseases, elderly, overweight, and kidney failure. In this general context of reduction of iatrogenic complications in invasive procedures, the need for improvement in techniques used to search for CABG with coronary angiography has been well discussed for many years. Eisenhauer et al. showed that aortocoronary graft markers have a beneficial impact on the use of postoperative angiography.[36,37] Other, more-recent studies have confirmed this beneficial effect, with a significant reduction in the number of catheters used, amount of contrast agent needed, and fluoroscopy time required, thanks to the use of these markers.[38,39] Unfortunately, the use of such markers impedes the implementation of CT scan assessments, with a poor visualization of the CABG proximal sutures arising from artefacts induced by these markers. They are not favored by surgeons.[40,41] As a consequence, this does not appear to be a useful solution to improvement in CABG searches during coronary angiography.

Image fusion is a new technology that was initially described in neuroradiology.[7] Its use is now flourishing and has an increasing number of fields of application.[42] The general principle is to enhance the content of a 2D examination by overlaying, in real time, 3D information. The 3D model can be produced from different imaging modalities, such as CT, magnetic resonance, or ultrasound images. In cardiology, its use is limited to radiofrequency-based atrial fibrillation ablation procedures[15,16] and to complex rythmological and hemodynamic interventions in congenital heart diseases patients.[19–21] So far, all of these evaluations are limited to feasibility studies or case reports providing a subjective evaluation of the contributions of this technology. However, all of these studies recognize the advantages of this new technology. To our knowledge, this technique had not been described in coronary angiography. This present study is therefore the first prospective study to have objectively evaluated the contribution of image fusion to coronary angiography. By using pre-existing CT scans, this technique does not lead to any additional radiation exposure to patients. Also, in the context of pre-TAVI assessments, although CT scans are frequently performed in CABG patients (to evaluate the CABG distance from the sternum or for additional evaluation of the aortic ring),[43] they do not waive the need for a preoperative coronary angiography. It is thus very helpful, in the particular context of elderly patients with frequent renal dysfunction, to limit the volume of nephrotoxic contrast agent. This study shows that image fusion is a novel, safe, and efficient technique, reducing the iatrogenic complications of procedures involving interventional cardiology, through a reduction in radiation exposure, amount of contrast agent used, and procedure duration.

Several other applications could be of interest. For instance, in patients presenting with a dilation of the ascending aorta, coronary angiography can be challenging. If available, preoperative CT fusion could be used over fluoroscopy to facilitate the procedure in a similar way to what we described. In interventional cardiac catheterization of congenital heart disease as well, the contribution of image fusion may be large. For instance, in our center, image fusion is commonly used for transcatheter pulmonary valve implantation. In transcatheter mitral valve intervention (Mitraclip) as well, image fusion is used to improve the safety of atrial septal punction.

The present study does not conclude on whether or not performing a CT scan, for the specific purpose of image fusion to assist a CABG search, is justified. Further research is needed to evaluate this possibility.

Limitations of the Study

The small number of patients and the single-center design represent potential limitations to the study, given that the small number reduces its statistical relevance. The prospective nature of our study is one of the reasons for this small number of patients.

Conclusion

The use of image fusion to assist CABG detection in coronary angiography leads to a reduction in CABG search time,

fluoroscopy time, use of iodinated contrast agents, ionizing radiation exposure, and duration of procedures. Following these results, the potential of merging reconstructed 3D CT scans with real-time coronary angiography should be fully exploited in interventional cardiology.

Disclosures

None.

References

1. Goldman S, Zadina K, Moritz T, Ovitt T, Sethi G, Copeland JG, Thottapurathu L, Krasnicka B, Ellis N, Anderson RJ, Henderson W; VA Cooperative Study Group #207/297/364. Long-term patency of saphenous vein and left internal mammary artery grafts after coronary artery bypass surgery: results from a Department of Veterans Affairs Cooperative Study. *J Am Coll Cardiol*. 2004;44:2149–2156.

2. Fitzgibbon GM, Kafka HP, Leach AJ, Keon WJ, Hooper GD, Burton JR. Coronary bypass graft fate and patient outcome: angiographic follow-up of 5,065 grafts related to survival and reoperation in 1,388 patients during 25 years. *J Am Coll Cardiol*. 1996;28:616–626.

3. Rodés-Cabau J, Facta A, Larose E, DeLarochellière R, Déry J-P, Nguyen CM, Roy L, Proulx G, Gleeton O, Barbeau G, Noël B, Rouleau J, Boudreault J-R, Bertrand OF. Predictors of aorto-saphenous vein bypass narrowing late after coronary artery bypass grafting. *Am J Cardiol*. 2007;100:640–645.

4. Delewi R, Hoebers LP, Råmunddal T, Henriques JPS, Angerås O, Stewart J, Robertsson L, Wahlin M, Petursson P, Piek JJ, Albertsson P, Matejka G, Omerovic E. Clinical and procedural characteristics associated with higher radiation exposure during percutaneous coronary interventions and coronary angiography. *Circ Cardiovasc Interv*. 2013;6:501–506.

5. Sanmartin M, Cuevas D, Moxica J, Valdes M, Esparza J, Baz JA, Mantilla R, Iñiguez A. Transradial cardiac catheterization in patients with coronary bypass grafts: feasibility analysis and comparison with transfemoral approach. *Catheter Cardiovasc Interv*. 2006;67:580–584.

6. Markelj P, Tomaževič D, Likar B, Pernuš F. A review of 3D/2D registration methods for image-guided interventions. *Med Image Anal*. 2012;16:642–661.

7. Powell MF, DiNobile D, Reddy AS. C-arm fluoroscopic cone beam CT for guidance of minimally invasive spine interventions. *Pain Physician*. 2010;13:51–59.

8. Wallace MJ, Kuo MD, Glaiberman C, Binkert CA, Orth RC, Soulez G; Technology Assessment Committee of the Society of Interventional Radiology. Three-dimensional C-arm cone-beam CT: applications in the interventional suite. *J Vasc Interv Radiol*. 2008;19:799–813.

9. Racadio JM, Babic D, Homan R, Rampton JW, Patel MN, Racadio JM, Johnson ND. Live 3D guidance in the interventional radiology suite. *AJR Am J Roentgenol*. 2007;189:W357–W364.

10. Daly MJ, Siewerdsen JH, Moseley DJ, Jaffray DA, Irish JC. Intraoperative cone-beam CT for guidance of head and neck surgery: assessment of dose and image quality using a C-arm prototype. *Med Phys*. 2006;33:3767–3780.

11. Meyer BC, Frericks BB, Albrecht T, Wolf K-J, Wacker FK. Contrast-enhanced abdominal angiographic CT for intra-abdominal tumor embolization: a new tool for vessel and soft tissue visualization. *Cardiovasc Intervent Radiol*. 2007;30:743–749.

12. Eide KR, Ødegård A, Myhre HO, Haraldseth O. Initial observations of endovascular aneurysm repair using Dyna-CT. *J Endovasc Ther*. 2007;14:50–53.

13. Kobeiter H, Nahum J, Becquemin J-P. Zero-contrast thoracic endovascular aortic repair using image fusion. *Circulation*. 2011;124:e280–e282.

14. Tacher V, Lin M, Desgranges P, Deux J-F, Grünhagen T, Becquemin J-P, Luciani A, Rahmouni A, Kobeiter H. Image guidance for endovascular repair of complex aortic aneurysms: comparison of two-dimensional and three-dimensional angiography and image fusion. *J Vasc Interv Radiol*. 2013;24:1698–1706.

15. Knecht S, Skali H, O'Neill MD, Wright M, Matsuo S, Chaudhry GM, Haffajee CI, Nault I, Gijsbers GHM, Sacher F, Laurent F, Montaudon M, Corneloup O, Hocini M, Haïssaguerre M, Orlov MV, Jaïs P. Computed tomography–fluoroscopy overlay evaluation during catheter ablation of left atrial arrhythmia. *Europace*. 2008;10:931–938.

16. Li JH, Haim M, Movassaghi B, Mendel JB, Chaudhry GM, Haffajee CI, Orlov MV. Segmentation and registration of three-dimensional rotational angiogram on live fluoroscopy to guide atrial fibrillation ablation: a new online imaging tool. *Heart Rhythm*. 2009;6:231–237.

17. Nölker G, Gutleben KJ, Marschang H, Ritscher G, Asbach S, Marrouche N, Brachmann J, Sinha AM. Three-dimensional left atrial and esophagus reconstruction using cardiac C-arm computed tomography with image integration into fluoroscopic views for ablation of atrial fibrillation: accuracy of a novel modality in comparison with multislice computed tomography. *Heart Rhythm*. 2008;5:1651–1657.

18. Sra J, Krum D, Malloy A, Vass M, Belanger B, Soubelet E, Vaillant R, Akhtar M. Registration of three-dimensional left atrial computed tomographic images with projection images obtained using fluoroscopy. *Circulation*. 2005;112:3763–3768.

19. Fagan T, Kay J, Carroll J, Neubauer A. 3-D guidance of complex pulmonary artery stent placement using reconstructed rotational angiography with live overlay. *Catheter Cardiovasc Interv*. 2012;79:414–421.

20. Glatz AC, Zhu X, Gillespie MJ, Hanna BD, Rome JJ. Use of angiographic CT imaging in the cardiac catheterization laboratory for congenital heart disease. *JACC Cardiovasc Imaging*. 2010;3:1149–1157.

21. Glöckler M, Koch A, Greim V, Shabaiek A, Rüffer A, Cesnjevar R, Achenbach S, Dittrich S. The value of flat-detector computed tomography during catheterisation of congenital heart disease. *Eur Radiol*. 2011;21:2511–2520.

22. Decree No. 2003-270 of 24 March 2003 on the protection of persons exposed to ionizing radiation for medical and forensic purposes and amending the Public Health Code (Second Part: Decrees in Council of State). 2003.

23. Wagner LK, Eifel PJ, Geise RA. Potential biological effects following high X-ray dose interventional procedures. *J Vasc Interv Radiol*. 1994;5:71–84.

24. Balter S, Hopewell JW, Miller DL, Wagner LK, Zelefsky MJ. Fluoroscopically guided interventional procedures: a review of radiation effects on patients' skin and hair. *Radiology*. 2010;254:326–341.

25. Delichas M, Psarrakos K, Molyvda-Athanassopoulou E, Giannoglou G, Sioundas A, Hatziioannou K, Papanastassiou E. Radiation exposure to cardiologists performing interventional cardiology procedures. *Eur J Radiol*. 2003;48:268–273.

26. Kuon E, Glaser C, Dahm JB. Effective techniques for reduction of radiation dosage to patients undergoing invasive cardiac procedures. *Br J Radiol*. 2003;76:406–413.

27. Cousins C, Miller DL, Bernardi G, Rehani MM, Schofield P, Vañó E, Einstein AJ, Geiger B, Heintz P, Padovani R, Sim K-H; International Commission on Radiological Protection. ICRP PUBLICATION 120: radiological protection in cardiology. *Ann ICRP*. 2013;42:1–125.

28. Goldstein JA, Balter S, Cowley M, Hodgson J, Klein LW; Interventional Committee of the Society of Cardiovascular Interventions. Occupational hazards of interventional cardiologists: prevalence of orthopedic health problems in contemporary practice. *Catheter Cardiovasc Interv*. 2004;63:407–411.

29. Ross AM, Segal J, Borenstein D, Jenkins E, Cho S. Prevalence of spinal disc disease among interventional cardiologists. *Am J Cardiol*. 1997;79:68–70.

30. Weisbord SD. Iodinated contrast media and the kidney. *Rev Cardiovasc Med*. 2008;9(suppl 1):S14–S23.

31. Reddan D, Laville M, Garovic VD. Contrast-induced nephropathy and its prevention: what do we really know from evidence-based findings? *J Nephrol*. 2009;22:333–351.

32. Bagshaw SM, Culleton BF. Contrast-induced nephropathy: epidemiology and prevention. *Minerva Cardioangiol*. 2006;54:109–129.

33. Gress DR. The problem with asymptomatic cerebral embolic complications in vascular procedures: what if they are not asymptomatic? *J Am Coll Cardiol*. 2012;60:1614–1616.

34. Boatman DM, Saeed B, Varghese I, Peters CT, Daye J, Haider A, Roesle M, Banerjee S, Brilakis ES. Prior coronary artery bypass graft surgery patients undergoing diagnostic coronary angiography have multiple uncontrolled coronary artery disease risk factors and high risk for cardiovascular events. *Heart Vessels*. 2009;24:241–246.

35. Lin A, Brennan P, Sadick N, Kovoor P, Lewis S, Robinson JW. Optimisation of coronary angiography exposures requires a multifactorial approach and careful procedural definition. *Br J Radiol*. 2013;86:20120028.

36. Eisenhauer MD, Collier E III, Eisenhauer TL, Cambier PA. Beneficial impact of aorto-coronary graft markers on post-operative angiography. *Cathet Cardiovasc Diagn*. 1997;40:249–253; discussion 254.

37. Eisenhauer MMD, Malik CJA, Coyle CLC, Arendt MMA. Impact of aorto-coronary graft markers on subsequent graft patency: a retrospective review. *Cathet Cardiovasc Diagn*. 1997;42:259–261.

38. Varghese I, Boatman DM, Peters CT, Daye J, Haider A, Roesle M, Banerjee S, Brilakis ES. Impact on contrast, fluoroscopy, and catheter utilization from knowing the coronary artery bypass graft anatomy before diagnostic coronary angiography. *Am J Cardiol*. 2008;101:1729–1732.

39. Peterson LR, McKenzie CR, Ludbrook PA, Sundt TM III, Eichling JO, Schardan-Watson G, Tiefenbrunn AJ. Value of saphenous vein graft markers during subsequent diagnostic cardiac catheterization. *Ann Thorac Surg*. 1999;68:2263–2266.

40. Clark DA. Circumferential aorto-coronary bypass markers revisited. *Cathet Cardiovasc Diagn*. 1997;42:262.

41. Eisenhauer MD. Aortocoronary graft markers and subsequent catheterization. *Ann Thorac Surg*. 2000;69:1645–1646.

42. Abi-Jaoudeh N, Kruecker J, Kadoury S, Kobeiter H, Venkatesan AM, Levy E, Wood BJ. Multimodality image fusion-guided procedures: technique, accuracy, and applications. *Cardiovasc Intervent Radiol*. 2012;35:986–998.

43. Schoenhagen P, Tuzcu EM, Kapadia SR, Desai MY, Svensson LG. Three-dimensional imaging of the aortic valve and aortic root with computed tomography: new standards in an era of transcatheter valve repair/implantation. *Eur Heart J*. 2009;30:2079–2086.