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Catheterization and Cardiovascular Interventions 89:78–92 (2017)

Circumflex Coronary Artery Injury After Mitral Valve Surgery: A Report of Four Cases and Comprehensive Review of the Literature

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As the LCx is closely related to the mitral valve annulus, it is susceptible to perioperative injury. Various underlying mechanisms, predisposing factors, and therapeutic strategies have been suggested but disagreement exists. Using a MeSH terms-based PubMed search, 44 cases of mitral valve surgery-related LCx injury were detected, including our 4 cases. We provide a comprehensive review of current knowledge regarding mitral valve surgery-related left circumflex coronary artery (LCx) injury. Preoperative coronary angiography was performed in 55% ($n = 24$). Coronary abnormalities were present in 11% ($n = 5$). Coronary dominance was reported in 73% ($n = 32$), predominantly showing left (69%, $n = 22$) or balanced (19%, $n = 6$) circulations. Right coronary dominance was present in 12% ($n = 4$). Ischemia was detected in the perioperative or early postoperative phase in 86% ($n = 30$). Delayed symptoms were present in 14% ($n = 5$). Echocardiography demonstrated new regional wall motion abnormalities in 80% ($n = 24$), but was negative in 20% ($n = 6$) despite coronary compromise. Electrocardiography showed myocardial ischemia in 97% ($n = 34$), including regional ST-segment elevations in 68% ($n = 23$). Primary treatment was surgical in 42% ($n = 15$) and percutaneous in 58% ($n = 21$), reporting success ratios of 87% ($n = 13$) and 81% ($n = 17$), respectively. We confirm an augmented risk of mitral valve surgery-related LCx injury in balanced or left-dominant coronary circulations. Preoperative knowledge of coronary anatomy does not preclude LCx injury. An anomalous LCx arising from the right coronary cusp was identified as a possible specific high-risk entity. Electrocardiographic monitoring and intraoperative echocardiography remain paramount to ensure a timely diagnosis and treatment.

Key words: acute myocardial infarction; valvular surgery; percutaneous coronary intervention; coronary artery disease; coronary bypass grafts; mitral valve disease

INTRODUCTION

Mitral valve repair has become the treatment of choice in patients with severe mitral valve regurgitation, with reported superiority over valve replacement in terms of operative mortality, late survival, valve-related complications, preservation of mitral valve function, and left ventricular performance [1]. Since the left circumflex coronary artery (LCx) runs in very close proximity to the mitral annulus, it is susceptible to injury during mitral valve surgery. We performed a PubMed literature search using the MeSH terms "mitral valve annuloplasty," "mitral valve surgery," "mitral valve repair," "myocardial infarction," and "circumflex coronary artery" in various combinations. References in appropriate articles were also screened for cases that were not found using the original search criteria (Fig. 1). Together with the 4 cases reported in this manuscript, we found a total of 44 cases of mitral valve surgery-related LCx injury, considering a variety of possible underlying mechanisms, predisposing factors, and different therapeutic strategies (Table I). No large case series exist and there is no consensus as to which subset of patients is at increased risk. We

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Received 12 November 2015; Revision accepted 17 January 2016

DOI: 10.1002/ccd.26449
Published online 19 February 2016 in Wiley Online Library (wileyonlinelibrary.com)

provide a comprehensive review of the literature, discussing current knowledge on predisposing risk factors and available therapeutic strategies.

CASE SERIES

Case 1

A 71-year-old female was referred because of progressive exertional dyspnea. The electrocardiogram (ECG) showed normal sinus rhythm with a right bundle branch block and transthoracic echocardiography (TTE) revealed a normal left ventricular ejection fraction with moderate mitral regurgitation. There were no signs of heart failure and pulmonary artery pressure at rest was normal. However, exercise TTE revealed a severe dynamic mitral regurgitation with occurrence of severe pulmonary arterial hypertension of 55 mm Hg at a moderate exercise of 75 W. Coronary angiography excluded atherosclerotic disease and demonstrated a left dominant coronary circulation with an anomalous LCx originating from the right coronary cusp, with a retroaortic course (Fig. 2A). After heart team discussion, a minimally invasive annuloplasty was performed using the ThruPort access system (Edwards Lifesciences, Irvine, CA) with implantation of a slightly undersized Annuloflo ring size 26 (Sorin, Saluggia, Italy), providing an optimal result. During cardiopulmonary bypass (CPB) weaning, however, repolarization abnormalities over the inferior leads were noticed, and transoesophageal echocardiography (TOE) confirmed marked akinesia of the inferoposterior wall, not present in the preoperative assessment. Urgent coronary angiography showed a total occlusion of the proximal LCx, successfully treated with a primary percutaneous coronary intervention (pPCI) and implantation of a drug-eluting stent (Fig. 2B and C). Since wire and balloon passage were relatively easy, acute tissue retraction was thought to be the underlying mechanism of coronary occlusion, rather than an encircling fixation suture. Further recovery was uneventful with an optimal clinical result at 1 year follow-up.

Case 2

A 74-year-old male with a known small ventricular septum defect (VSD) was initially referred because of progressive exertional dyspnea New York Heart Association (NYHA) class III, progressive degenerative mitral valve regurgitation grade 3/4 and moderate pulmonary arterial hypertension. Preoperative cardiac catheterization showed a balanced coronary circulation without coronary artery disease (Fig. 2D). A successful mitral valve annuloplasty was performed with implantation of a Carpentier-Edwards 30 mm physio II-ring (Edwards Lifesciences, Irvine, CA) and closure of the VSD. The immediate postoperative period was uneventful. Later in the recovery course, the patient complained of dizziness on exertion, and orthostatic hypotension was diagnosed during cardiac rehabilitation. Eighteen months after index surgery, he was admitted because of progressive exertional angina Canadian Cardiovascular Society (CCS)-class 3, and coronary angiography showed a retracted LCx, with a significant stenosis on the mid-section. The patient remained symptom-free after PCI with implantation of a bare metal stent (Fig. 2E and F).

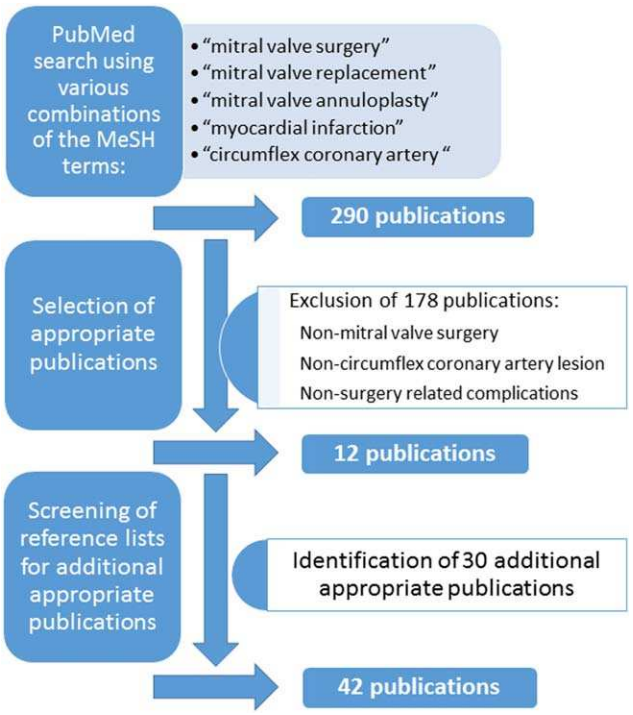

Fig. 1. Flow chart outlining the PubMed search. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Case 3

A 62-year-old male patient with hyperlipidemia and a mitral valve prolapse secondary to Barlow's disease was referred for valvular surgery because of asymptomatic mitral valve regurgitation grade 4/4 with progressive left ventricular dilatation and moderate pulmonary hypertension. Preoperative cardiac catheterization showed a balanced coronary circulation without obstructive coronary artery disease. Successful mitral valve replacement (MVR) was performed with implantation of a St. Jude's Medical 33 mm prosthetic heart valve (St. Jude Medical, St. Paul, MN). Immediately after arrival at the intensive care unit (ICU), the patient developed ventricular fibrillation and became hemodynamically unstable. After successful reanimation, TOE confirmed new marked

TABLE I. Overview of Reported Cases with Left Circumflex Coronary Artery Injury Related to Mitral Valve Surgery

Author	Sex	Age	Preoperative coronary angiogram	Coronary dominance	Type of surgery	Time of onset	Clinical manifestation	ECG	Echocardiographic abnormalities	Reported etiology	Treatment
Danielson et al. (1967)[2]	NA	NA	NA	NA	MVR (3M Starr-Edwards)	NA	NA	NA	NA	NA	NA
Danielson et al. (1967)[2]	NA	NA	NA	NA	MVR (2M Starr-Edwards)	NA	NA	NA	NA	NA	NA
Danielson et al. (1967)[2]	NA	NA	NA	NA	MVR (2M Starr-Edwards)	NA	NA	NA	NA	NA	NA
Virmani et al. (1982)[3]	NA	NA	NA	Balanced	MVR	NA	NA	NA	NA	Suture obliteration	NA
Virmani et al. (1982)[3]	NA	NA	NA	Left	MVR	NA	NA	NA	NA	Suture obliteration	NA
Virmani et al. (1982)[3]	NA	NA	NA	Left	Annuloplasty (Carpentier-Edwards)	NA	NA	NA	NA	Suture obliteration	NA
Morin et al. (1982)[4]	M	43	NA	NA	MVR (St Jude Medical 31 mm)	ECG 1 hr postoperative	NA	Inferoposterior ischemia-injury	NA	Ligation of anomalous LCx	NA (postmortem diagnosis)
Tavilla et al. (1998)[5]	M	60	Normal	Left	Annuloplasty (Carpentier-Edwards 34 mm) + large quadrangular posterior leaflet resection (sliding leaflet technique)	During CPB weaning	Stable	Inferoposterior ischemia-injury	Segmental wall motion abnormalities	Retraction after surgery	Removal annuloplasty + MVR
Speziale et al. (1998)[6]	NA	NA	Anomalous LCX from right coronary sinus	Left	MVR (CarboMedics 27 mm mechanical valve) + TVP (De Vega)	NA	NA	NA	NA	NA	NA
Mulpur et al. (2000)[7]	F	71	Normal	Right	MVR (Carpentier-Edwards)	14 y post-MVR	Asymptomatic	NA	NA	Vascular malformation	Ligation and resection during redo MVR
Assaqqat et al. (2003)[8]	F	9	NA	Left	MVR (CarboMedics 23 mm mechanical valve)	Immediately postoperative	NA	ST elevation inferior leads	Segmental wall motion abnormalities	NA	Successful PCI
Mantilla et al. (2004)[9]	M	66	Normal	Left	Annuloplasty (Carpentier-Edwards 28mm) + quadrangular posterior leaflet resection	At ICU arrival after CPB weaning	Cardiogenic shock	ST elevation inferolateral leads	Inferolateral ST-segment elevation	Possible coronary retraction	Successful PCI
Sangha et al. (2004)[10]	M	76	Normal	Left	MVR (St Jude Medical 33 mm mechanical valve)	At ICU arrival after CPB weaning	Hypotension and ventricular ectopy	ST elevation inferolateral leads	No segmental wall motion abnormalities	Possible coronary retraction	Successful PCI
Hassan et al. (2004)[11]	M	36	NA	Left	MVR (CarboMedics 29 mm mechanical valve)	Immediately postoperative	NA	Inferoposterior ischemia-injury	Segmental wall motion abnormalities	NA	Successful PCI
Nakajima et al. (2005)[12]	M	68	Normal	Left	MVR + maze procedure (cryoablation)	During CPB weaning	Ventricular tachycardia/fibrillation with hemodynamic collaps	ST elevation pattern	Segmental wall motion abnormalities	NA	Emergency CABG
Meursing et al. (2006)[13]	F	27	NA	Left	Annulus spearing aortic root replacement + quadrangular P2 resection with posterior annulus plication (McGoon) + annuloplasty (Cosgrove 34 mm)	2 hr after CPB weaning	Stable	ST elevation inferior leads	Segmental wall motion abnormalities at postoperative day 1	Possible coronary retraction (dynamic stenosis)	Nonsuccessful PCI at postoperative day 1(no balloon passage possible due to acute angle)

Catheterization and Cardiovascular Interventions DOI 10.1002/ccd.
Published on behalf of The Society for Cardiovascular Angiography and Interventions (SCAI).

TABLE I. *Continued*

Author	Sex	Age	Preoperative coronary angiogram	Coronary dominance	Type of surgery	Time of onset	Clinical manifestation	ECG	Echocardiographic abnormalities	Reported etiology	Treatment
Wykrzykowska et al. (2006)[14]	M	61	Normal	Left	P3 leaflet resection + Annuloplasty (Carpentier-Edwards 28 mm physio-ring)	Postoperative (not specified)	Ventricular tachycardia with hemodynamic collapse	Inferolateral T wave abnormalities	Segmental wall motion abnormalities	Coronary retraction vs external compression	Successful PCI
Wykrzykowska et al. (2006)[14]	F	48	Normal	Right	posterior cleft leaflet repair + Annuloplasty (St Jude Medical 28 mm ring)	6 months follow-up: decreased LVEF and reoccurrence MR 3+	Difficult inotropic weaning + runs SVT	Runs of SVT	Global wall motion abnormalities	Occlusion LCx	Redo mitral valve annuloplasty
Raza et al. (2006)[15]	M	75	Normal	NA	P2 resection + Annuloplasty (Cosgrove 34 mm) + maze procedure (cryoablation)	During chest closure after CPB weaning	Hypotension	ST elevation inferolateral leads	Segmental wall motion abnormalities	Extramural hematoma compressing LCx	Successful PCI
Zegdi et al. (2007)[16]	NA	35	NA	Balanced	Valvular resection, annular plication and sliding plasty for P2 prolapse	NA	NA	NA	NA	NA	CABG 10 days post-index surgery
Acar et al. (2007)[17]	NA	NA	NA	Left	Mitral valve repair with extensive annular decalcification	Perioperative	Hemodynamic instability	Regional ST elevation	Segmental wall motion abnormalities	NA	Saphenous vein grafting
Acar et al. (2007)[17]	NA	NA	NA	Left	Mitral valve repair with extensive annular decalcification	Perioperative	Hemodynamic instability	Regional ST elevation	Segmental wall motion abnormalities	NA	Saphenous vein grafting
Acar et al. (2007)[17]	NA	NA	NA	Left	Mitral valve repair with quadrangular posterior leaflet resection	Perioperative	Hemodynamic instability	Regional ST elevation	Segmental wall motion abnormalities	NA	Saphenous vein grafting
Aubert et al. (2008)[18]	M	44	NA	NA	Small posterior quadrangular resection + annular plication and leaflet suture + Annuloplasty (Carpentier-Edwards 32 mm physio-ring)	After CPB weaning	Stable	Posterolateral ST elevation	No segmental wall motion abnormalities	NA	Successful PCI
Ender et al. (2008)[19]	M	43	Normal	NA	P2 chordal repair + Annuloplasty (Carpentier-Edwards 36 mm physio-ring)	After CPB weaning	Stable	ST elevation inferior leads	Segmental wall motion abnormalities	Coronary retraction	Correction of 4 ring sutures
Grande et al. (2008)[20]	M	60	Normal	Right	Posterior quadrangular resection + annular plication + Annuloplasty (Carpentier-Edwards 32 mm ring)	After CPB weaning before ICU transfer	Vfib	ST elevation lateral wall	Segmental wall motion abnormalities	NA	Successful PCI
Gomes W. (2008)[21]	NA	NA	NA	NA	Annuloplasty	Perioperative	NA	Posterolateral ST elevation	Segmental wall motion abnormalities	Coronary kinking	Perioperative MVR (xenograft bioprosthesis)

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TABLE I. *Continued*

Author	Sex	Age	Preoperative coronary angiogram	Coronary dominance	Type of surgery	Time of onset	Clinical manifestation	ECG	Echocardiographic abnormalities	Reported etiology	Treatment
Gomes W. (2008)[21]	NA	NA	NA	NA	Annuloplasty	Perioperative	NA	Posterolateral ST elevation	Segmental wall motion abnormalities	Coronary kinking	Perioperative relocation of annular sutures
Vivas et al. (2009)[22]	F	69	Anomalous LCX from right coronary sinus (retroartic)	NA	Annuloplasty (Carpentier-Edwards 32 mm physio-ring)	3 hr after surgery	Hemodynamic instability	ST elevation inferolateral leads	Global wall motion abnormalities	Extramural hematoma compressing LCx	Nonsuccessful PCI (guidewire passage impossible) + emergency CABG
Calafiore et al. (2010)[23]	F	74	Normal	Balanced	Mitral valve repair (endocarditis) with longitudinal P2 plication + TVP (De Vega)	At ICU arrival after CPB weaning	Stable	Lateral ischemia	No segmental wall motion abnormalities	Occlusion LCx	Nonsuccessful PCI (guidewire passage impossible) + emergency CABG
Vaishnava et al. (2011)[24]	M	52	Anomalous LCX from right coronary sinus	Left	AVR (21 mm bi-leaflet mechanical valve) + MVR (bi-leaflet mechanical valve)	2 hr after arrival at intensive care unit	Stable	Anterior wall ST segment depression	No segmental wall motion abnormalities	Compression between two mechanical valves	Successful CABG
Varela et al. (2011)[25]	M	37	Normal	Right	Mitral valve repair (suture repair P2) + 63 mm posterior annuloplasty band (Medtronic)	After CPB weaning before ICU transfer	Vfib	Regional ST-segment elevation	Initially segmental, later diffuse wall motion abnormalities	Retraction based LCx occlusion	Successful PCI
Varela et al. (2011)[25]	F	42	Normal	Left	MVR (27 mm CarboMetrics prosthesis) + TVP (De Vega) + pericardectomy	at ICU arrival after CPB weaning	monomorphic VT with stable hemodynamics	ST elevation inferior leads	Segmental wall motion abnormalities	occlusion LCx	Successful PCI
Sheth et al. (2011)[26]	M	82	Nonsignificant 50% mid RCA lesion	Left	Redo MVR (29 mm St Jude porcine bioprosthesis)	6 d after surgery	VT induced cardiac arrest	ST elevation inferoposterior leads	NA	Free perforation of Lcx	Successful PCI with covered stent placement
Postorino et al. (2011)[27]	M	NA	NA	NA	Mitral valve repair	NA	NA	ST elevation inferior leads	NA	NA	Successful PCI
Somekh et al. (2012)[28]	F	73	Normal	Left	A2 chordal repair + Annuloplasty (Carpentier-Edwards 26 mm physio-ring)+ Cox maze III procedure	during CPB weaning	NA	ST elevation inferior leads	No segmental wall motion abnormalities	Possible coronary ligation	PCI and surgical revision with MVR after 2 weeks
Schyma et al. (2012)[29]	F	70	NA	NA	AVR + MVR	3 hr after surgery	Cardiogenic shock	ECG changes reported	NA	LCx retraction with functional stenosis	Nonsuccessful emergency surgery (postmortem diagnosis of acute ischemic ventricular rupture)

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TABLE I. *Continued*

Author	Sex	Age	Preoperative coronary angiogram	Coronary dominance	Type of surgery	Time of onset	Clinical manifestation	ECG	Echocardiographic abnormalities	Reported etiology	Treatment
Banayan et al. (2012)[30]	M	50	Nonsignificant 40% mid LAD lesion	Left	Mitral valve repair (endocarditis) + anuloplasty (St Jude Medical 29 mm ring)	At the end of the procedure, before CPB weaning	Stable	Inferolateral ST-segment elevations	Infero-postero-lateral akinesis	Occlusion LCx	Nonsuccessful PCI (guidewire passage impossible) + conservative management
Banayan et al. (2012)[30]	M	80	Normal	Left	MVR with extensive anular decalcification (29 mm St Jude Medical Epic bioprosthesis)	4 days after surgery	nsVT, evolving towards sustained VT	Generalized ST-segment depression	Septal dyskinesia	Free perforation of Lcx	Successful PCI with implantation of a covered stent
Folkmann et al. (2014)[31]	M	62	Normal	Left	MVR (29 mm ATS Mitral 500)	At the end of the procedure after CPB weaning	Stable	AV-sequential pacing rhytm	Segmental lateral wall dysfunction	Occlusion LCx	Successful PCI
Hiltrop et al. (this article)	F	71	Anomalous LCX from right coronary sinus (retroartic)	Left	Annuloplasty (26 mm ring)	At ICU arrival after CPB weaning	Stable	ST segment depression inferior leads	Segmental wall motion abnormalities	Retraction after surgery	Successful PCI
Hiltrop et al. (this article)	M	75	Normal	Balanced	Annuloplasty (Carpentier-Edwards 30 mm physio II-ring)	Angina 18 months after surgery	CCS class 3 angina	ECG changes during exercise	No segmental wall motion abnormalities	Retraction after surgery	Successful PCI
Hiltrop et al. (this article)	M	62	Normal	Balanced	MVR (St Jude Medical 33 mm mechanical valve)	At ICU arrival after CPB weaning	Hemodynamic instability with ventricular fibrillation	Inferolateral ST-segment elevations	Inferolateral hypokinesia	Retraction after surgery (relative undersized prosthesis size?)	Successful CABG
Hiltrop et al. (this article)	M	53	NA	Balanced	MVR (St Jude Medical 33 mm mechanical valve)	At ICU arrival after CPB weaning	Hemodynamic instability with ventricular fibrilation	Inferolateral ST-segment elevations	NA	Retraction after surgery	Successful CABG (patient died because of hypoxemic encephalopathy)

CAD = coronary artery disease; LCx = left circumflex coronary artery; F = female; M = male; NA = not available; MVR = mitral valve replacement; CPB = cardiopulmonary bypass; TVP = tricuspid valve annuloplasty; PCI = percutaneuos coronary intervention; ICU = intensive care unit; CABG = coronary artery bypass grafting; SVT = supraventricular tachycardia; VT = ventricular tachycardia; VFib = ventricular fibrillation.

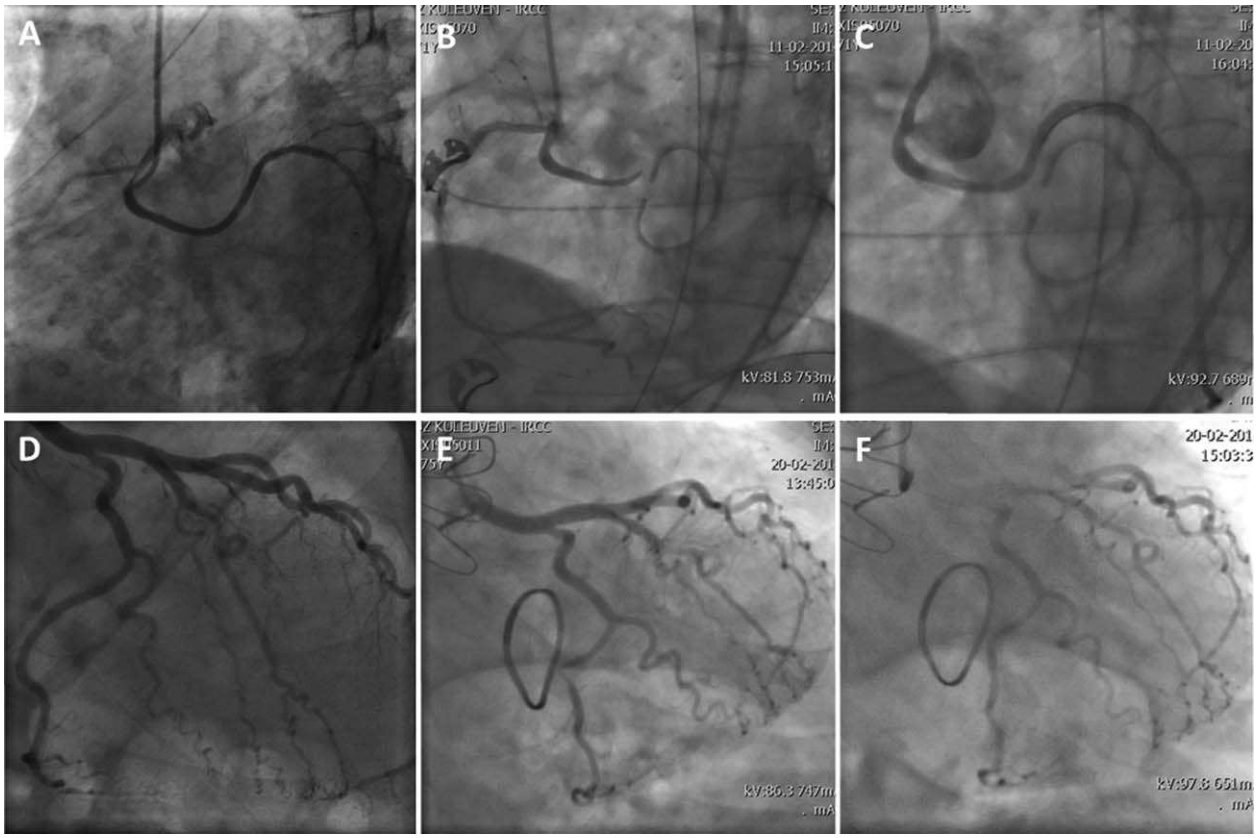

Fig. 2. Preoperative coronary angiography in patient 1 showing an anomalous LCx originating from the right coronary cusp with a retroaortic course (panel A). Postoperative coronary angiography showing a total occlusion of the proximal LCx (panel B). Flow was successfully restored after implantation of a drug-eluting stent (panel C). Preoperative coronary angiography in patient 2 showing a balanced coronary circulation without coronary atherosclerotic disease (panel D). Postoperative coronary angiography demonstrating a retracted LCx with a focal stenosis at the mid portion of the posterior mitral valve annulus (panel E), successfully treated by PCI with restoration of TIMI 3 flow (panel F).

hypokinesia of the inferolateral wall. As LCx injury was suspected, the patient underwent emergency surgical revision, confirming LCx occlusion, which was successfully treated with venous bypass grafting. Because of severe dilatation of the mitral valve annulus, the largest available valve prosthesis (33 mm) was still relatively undersized, causing an important reduction in annular circumference after MVR. This was considered to be the mechanism of tissue retraction in this case. After successful revascularization, however, the patient remained hemodynamically unstable with multiple episodes of ventricular fibrillation and prolonged reanimation, necessitating a therapeutic upgrade with extracorporeal membrane oxygenation treatment. The patient died several days later due to severe hypoxemic encephalopathy.

Case 4

A 53-year-old male patient without relevant medical history was referred because of streptococcus agalactiae mitral valve endocarditis. TOE demonstrated a large mobile mass (20 × 17 mm) attached to the posterior mitral valve leaflet with suspected leaflet perforation and severe mitral regurgitation grade 4/4. The patient experienced visual impairment due to septic embolization. Because of progressive hemodynamic deterioration, the documentation of a large mobile mass with distal embolization and inadequate infection control, semiurgent mitral valve replacement was performed with implantation of a St. Jude Medical 33 mm mechanical heart valve. In the immediate postoperative period, myocardial ischemia was demonstrated with ST-segment elevation in the inferior leads. Urgent coronary angiography confirmed an occluded LCx. The patient underwent emergency surgical revision with sequential venous bypass grafting of the first and second inferolateral branch of the LCx. Further recovery was uneventful. Because of local abscess formation in close relation to the mitral valve annulus, the heart valve prosthesis had to be implanted in a slightly supra

annular position, probably closer to the LCx, explaining tissue retraction and secondary LCx obstruction in this case.

DISCUSSION

The LCx runs in the left atrioventricular groove and lies in close relation to the posterior portion of the mitral valve annulus (Fig. 3). Coronary artery injury is a known but rare complication of mitral valve surgery, with a reported frequency of 0.5–1.8%, occurring after mitral valve replacement as well as mitral valve annuloplasty, even in centers with significant experience in mitral valve surgery [1,2]. Reported frequencies could represent an underestimation because of publication bias, while early recognition with appropriate intervention is paramount but continues to pose a challenge.

We presented four patients with LCx injury after mitral valve surgery. The first patient had a left dominant coronary circulation and an anomalous LCx with a retroaortic course, originating from the right aortic sinus and suffered abrupt vessel closure, probably because of tissue retraction. The other patients all had a balanced coronary circulation. The second patient experienced angina 18 months after surgery, secondary to vessel retraction creating a functional stenosis of the proximal LCx. He was successfully treated with PCI. The third patient underwent MVR because of severe Barlow's disease and experienced abrupt vessel closure, probably because of tissue retraction after valve implantation due to relative prosthesis undersizing because of severe mitral valve annulus dilatation. Emergency CABG was successful but the patient died because of severe hypoxemic encephalopathy. The mechanism of LCx injury in the fourth patient was thought to be a supra annular implantation position due to local abscess formation in the mitral valve annulus, changing traction forces of the fixation sutures on surrounding tissue. Emergency CABG was successful.

Using a PubMed search, we identified 44 cases of mitral valve repair/replacement associated myocardial ischemia (Table I) [2–31]. Since no large registries exist and previous reports disagree regarding possible risk factors, symptoms, diagnostic signs, and available therapeutic strategies, we performed a comprehensive analysis summarizing current knowledge based on all available cases.

Importance of Coronary Artery Anatomy: Coronary Dominance and Coronary Artery Anomalies

In the 70% ($n = 31$) of cases providing details on gender, 32% of patients ($n = 10$) were female and 68% were male ($n = 21$). Findings from preoperative coronary angiography were reported in 55% ($n = 24$) of all published cases, of which 79% ($n = 19$) had normal preoperative coronary angiograms. Based on preoperative or postoperative (investigating coronary ischemia) coronary angiography, dominance was reported in 73% of cases ($n = 32$). The vast majority of these patients had a left dominant (69%, $n = 22$) or a balanced (19%, $n = 6$) coronary circulation, which was also the case in our 4 patients (Table I). Right coronary dominance was reported in 4 patients (12%) to date, correlating well with the prevalence of right coronary dominance in previous reports, but does not preclude LCx injury [32,33] (Fig. 4).

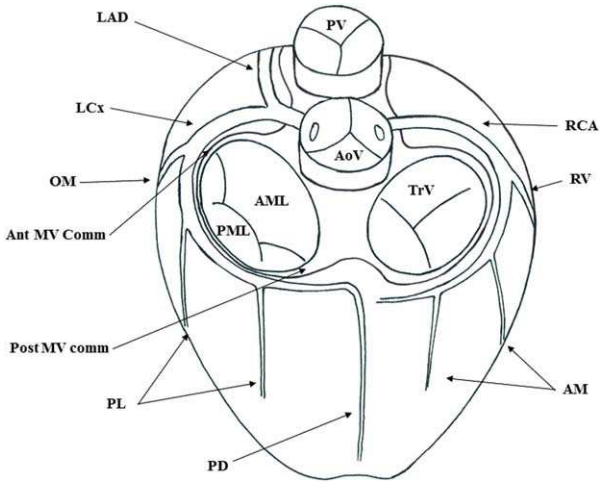

Fig. 3. Anatomical diagram demonstrating the close relation of the LCx and the posterior portion of the mitral valve annulus in a left dominant coronary circulation. Abbreviations: AM: acute marginal branches; Ant MV Comm: anterior mitral valve commissure; AML: anterior mitral valve leaflet; AoV: aortic valve; LAD: left anterior descending coronary artery; LCx: left circumflex coronary artery; OM: obtuse marginal branch; PD: posterior descending coronary artery; PL: posterolateral branches; PML: posterior mitral valve leaflet; Post MV Comm: posterior mitral valve commissure; PV: pulmonary valve; RCA: right coronary artery; RV: right ventricular branch; TrV: tricuspid valve. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

The risk of LCx injury has been reported to be augmented in a codominant or left-dominant coronary anatomy [6]. This was supported by findings from anatomical studies, documenting that the distance between the mitral valve annulus and the LCx could be as little as 1 mm [34]. Pessa et al. previously described 5 relative points at the posterior portion of the mitral valve annulus, numbered from 1 to 5 in an anticlockwise direction, describing the distance between the mitral valve annulus and the LCx. Number 1 is at the level of the anterior commissure, number 5 at the level of the posterior commissure, and the other 3 points are

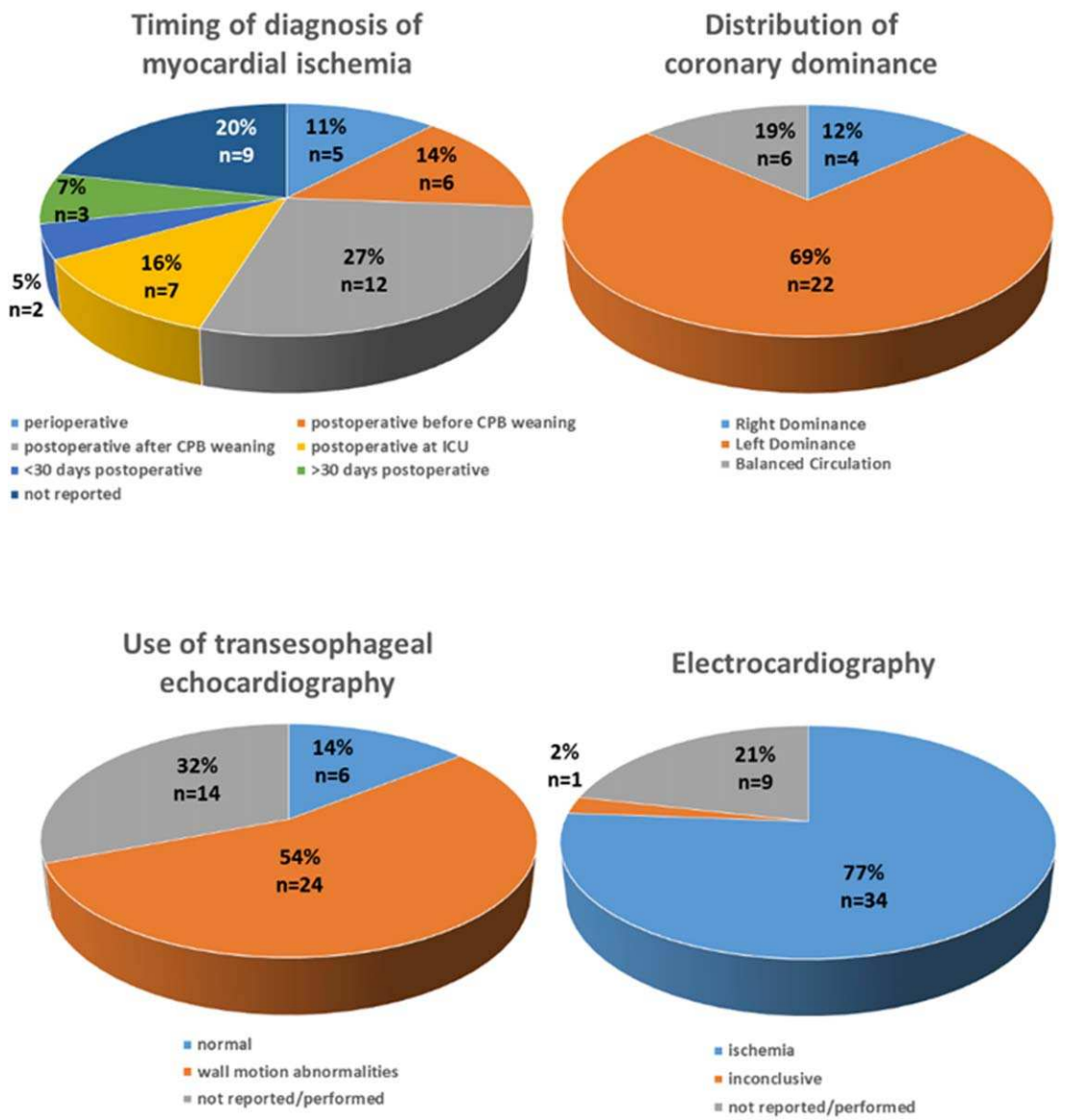

Fig. 4. Chart demonstrating timing of ischemia diagnosis, distribution of coronary dominance, and overall echocardiographic and electrocardiographic findings.

located at equidistance from these 2 extremes [32]. Virmani et al. reported distances of 3–7.5 mm between the LCx and mitral annulus in balanced or left-dominant circulations compared to a distance of always above 5 mm (on average 8.4 mm) in right-dominant circulations [4]. Cornu et al. confirmed this pattern showing that in right-dominant coronary circulations, the LCx lies at an 8 mm average distance from point 1 and a 5 mm average distance from point 4, while in a balanced network, the LCx lies at a 4.5 mm average distance from point 1 and at a 3.5 mm average distance from point 2 [34]. These findings were later confirmed by Kaklikkaya and Yeginoglu, reporting that the shortest distance between the LCx and the mitral valve annulus was 5.1 mm in right-dominant circulations, whereas in balanced systems, it was 3 mm and as little as 2.3 mm in left-dominant circulations. They also identified the proximal one-third of the LCx as the area at greatest risk [35].

In one anatomic study, however, the authors propose that the susceptibility to iatrogenic injury of the LCx is not related to the pattern of coronary dominance [32]. In right-dominant coronary circulations, they reported a much smaller mean average distance between the LCx and the mitral valve annulus at point 1 of 3.99 mm, compared to 8.0 mm and 8.4 mm previously reported by Cornu and Virmani, respectively, or 5.1 mm as reported by Kaklikkaya and Yeginoglu. However, since

only two hearts in this anatomic study had a left-dominant circulation, it is arguably very difficult to make any conclusion regarding coronary artery dominance and the risk of perioperative LCx injury based upon this small study.

Coronary artery anomalies are generally detected in approximately 1% of diagnostic angiograms and include anomalous origins, anomalous distributions, abnormal connections between a coronary artery, and another blood vessel or cardiac chamber and abnormalities as part of a complex congenital disorder [33,36]. In our case series, however, overall prevalence of coronary abnormalities was 11% ($n = 5$), with all 5 patients having an anomalous LCx originating from the right coronary cusp, and a documented retroaortic course in 2 of these patients. A LCx originating from the right aortic cusp is the most common anomaly encountered, with a reported incidence of 0.67% in diagnostic coronary angiographies. It is usually an incidental finding without clinical consequence [36,37]. A retroaortic course of the anomalous LCx is also benign unless there is concomitant atherosclerotic coronary artery disease, but has implications in patients scheduled for mitral valve surgery, since misidentification of the vessel can have serious adverse consequences [5,7,38]. Mitral valve surgery-related injury of an anomalous LCx arising from the right coronary cusp has been reported in 4 patients prior to our manuscript. One patient had a mitral valve replacement with a St Jude Medical 31 mm prosthesis, and died because of accidental ligation of the LCx by one of the fixation sutures [5]. The second patient had a mitral valve replacement with a CarboMedics 27 mm prosthesis (Sorin CarboMedics, Austin, TX) and a De Vega tricuspid annuloplasty, causing LCx compression by the ring of the valve prosthesis [7]. Another patient had aortic and mitral valve replacements with Starr-Edwards prostheses, with coronary compression between the rings [24]. The last patient was treated with mitral valve annuloplasty and suffered LCx occlusion because of external compression by an extramural hematoma, and was treated with emergency CABG [22]. Our first patient underwent minimally invasive annuloplasty with implantation of an undersized 26 mm ring, causing occlusion of the proximal LCx, most probably caused by tissue retraction, and was successfully treated with PCI. Given the marked overrepresentation of an anomalous LCx originating from the right coronary cusp in the literature, this coronary anomaly may represent a specific entity with an increased risk for mitral valve surgery-related LCx injury. However, as only 44 cases have been reported to date, publication bias cannot be excluded and further investigations are required.

Tavilla and Pacini already suggested that preoperative coronary angiography should be mandatory in all patients scheduled for elective mitral valve surgery, evaluating coronary dominance and the course of the LCx [6]. On reviewing all published cases, we have observed that preoperative knowledge of coronary anatomy did not preclude patients from suffering perioperative LCx injury. Nevertheless, all patients suffering a perioperative LCx injury with a preoperative unknown coronary anatomy had a left-dominant circulation. Based upon these observations and considering the reported distribution of coronary dominance in the literature, the increased risk of LCx injury in co-dominant or left-dominant coronary systems seems obvious. Preoperative knowledge of coronary anatomy can therefore be argued to be of importance in an attempt to reduce the risk of perioperative LCx injury. Furthermore, as part of the preoperative surgical planning, measuring the distance between the circumflex artery and the mitral valve annulus using noninvasive imaging techniques, could guide surgeons to further prevent this complication. Multidetector computed tomography (MDCT) provides excellent spatial resolution, is safer than coronary angiography, and has been suggested as a valuable alternative to coronary angiography in this context. It not only allows assessment of atherosclerotic coronary artery disease and identification of coronary artery anomalies but also provides detailed information of extraluminal structures. [15,36,38] (Fig. 5)

Diagnosis and Clinical Presentation of Perioperative LCx Injury

Clinical presentation of perioperative LCx injury can be very diverse, ranging from silent ischemia to overt hemodynamic shock. Reported manifestations include asymptomatic ischemic ECG changes, new regional wall motion abnormalities (RWMA), refractory arrhythmias, hypotension, difficulty in cardiopulmonary bypass (CPB) weaning, and marked hemodynamic shock (Table II) [20,30]. Early recognition of this potentially fatal complication is paramount to preserve myocardial viability and left ventricular function. Difficulty in prompt diagnosis might delay coronary angiography, precluding early diagnosis, and accurate treatment.

Information regarding time of onset of ischemia and diagnosis was available in 80% of patients ($n = 35$). Myocardial compromise was diagnosed early in 86% ($n = 30$), either perioperatively in 37% ($n = 11$) or during the very first hours of the postoperative phase in 63% ($n = 19$), most frequently during CPB weaning. Only 5 cases (14%) have been reported with mitral

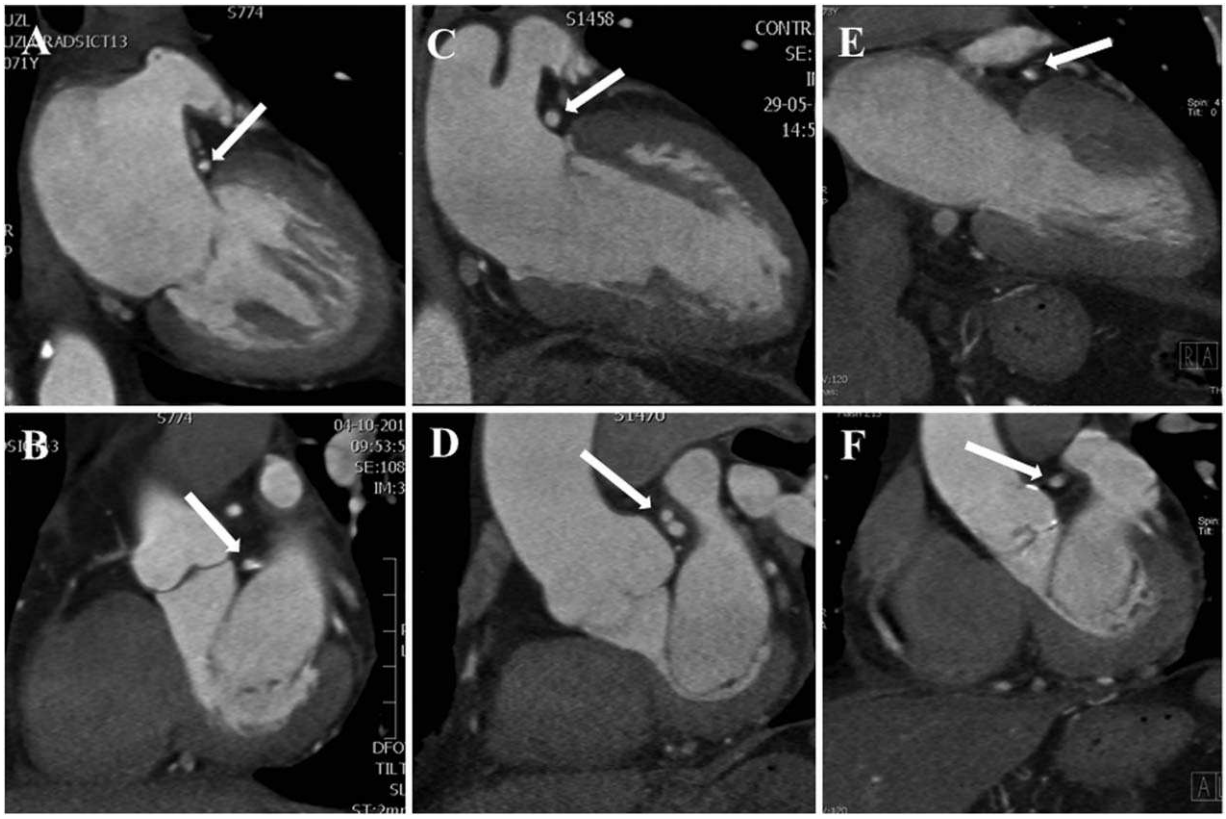

Fig. 5. Long- and short-axis views of a coronary computed tomography scan in a patient with an anomalous LCx originating from the RCA with a retroaortic course (panels A and B) and a patient with a normal left dominant coronary circulation (panels C and D) showing the close relation of the LCx and the anterior mitral valve commissure (arrow). Long- and short-axis views in a right dominant circulation (panels E and F) demonstrate that the course of the LCx (arrow) runs at a greater distance from the mitral valve annulus.

TABLE II. Summary of Clinical Manifestations of Perioperative Circumflex Coronary Artery Injury

Ventricular fibrillation
Sustained or nonsustained ventricular tachycardia
Ventricular ectopy
Supraventricular tachycardia
Difficulty in weaning from cardiopulmonary bypass or inotropics
Cardiogenic shock
Hypotension
Angina
Asymptomatic

valve surgery-related myocardial ischemia at a marked time interval from the index procedure (Fig. 4).

Intraoperative TOE has been reported to be a helpful tool during mitral valve surgery, decreasing mortality rates by detecting myocardial compromise and RWMA in an early phase [13]. Use of echocardiography, perioperatively and/or at the time of ischemia diagnosis, was reported in 68% of cases ($n = 30$), and new or dynamic RWMA were detected in 80% ($n = 24$). In 20% of cases ($n = 6$), echocardiography did not demonstrate any new RWMA despite coronary compromise. Use of echocardiography and its potential findings was not reported in 32% of patients ($n = 14$), leaving an opportunity for improving perioperative care in mitral valve surgery patients, aiming at early detection of this possibly fatal perioperative complication. As described by Ender et al., the LCx can be differentiated from the coronary sinus based on its strong echodense wall and its progressively smaller size along its course [19]. They also described the feasibility and usefulness of monitoring a color Doppler-signal of the LCx to secure coronary patency during and after the procedure in patients with a known left-dominant or balanced coronary circulation [39].

ECG findings were reported in 79% ($n = 35$), demonstrating myocardial ischemia in 97% of patients ($n = 34$). Regional ST-segment elevations were present in 68% of these patients ($n = 23$). The ECG could not be interpreted for ischemia because of ventricular pacing in 2% ($n = 1$). Alongside myocardial ischemia, a

variety of arrhythmias have also been reported in association with mitral valve surgery-related LCx injury (Table II). The very high rate of ECG abnormalities and the ease by which this information can be obtained highlight the importance of peri- and postoperative ECG monitoring in surgical heart valve patients, especially when unexpected clinical or echocardiographic signs are present. Registration of a full 12-lead ECG at the moment of ICU arrival after cardiac surgery should be routine clinical practice. ST-segment changes, however, are often observed in the operating room during mitral valve surgery, are often transient and attributed to intracardiac air causing intracoronary air embolization. Since none of the signs are pathognomonic for LCx injury, close attention for ECG and echocardiographic changes in the perioperative and early postoperative period therefore remains imperative for early recognition. Persistent or recurrent dynamic ST changes, associated with RWMA should therefore alert the surgeon or ICU physician for possible LCx injury and myocardial compromise, and should be followed by urgent coronary angiography to detect the location and possible mechanism of coronary injury. Unexpected or unexplained alterations should be interpreted with a high index of suspicion and the threshold to seek further advice should be low.

Mechanisms of Coronary Artery Injury

Various mechanisms explaining coronary injury have been postulated. Sometimes, however, there is no clear explanation. The following mechanisms have been suggested: occlusion of the artery by entrapment with a completely encircling fixation suture; obliteration of the artery caused by a suture passing through; coronary perforation; thrombotic occlusion due to laceration of the endothelium; vascular distortion caused by tissue retraction causing a dynamic or fixed occlusion, often reported after reconstruction of larger quadrangular valvular resections; laceration of the artery resulting in localized hemorrhage or subintimal hematoma leading to external compression; external compression by the annuloplasty ring and coronary spasm [2,13,14,18,20,30].

Procedure-Related Issues

The risk of perioperative myocardial infarction was 1.7% for isolated MVR according to the 2010 Society of Thoracic Surgeons database, as compared to 2.2% for mitral valve repair [30]. Inadequate myocardial protection, air embolism, and coronary spasm have been reported as contributing factors, but the role of coronary artery injury is likely under-reported.

Several publications reported LCx injury during minimally invasive mitral valve surgery, suggesting a possible increased risk of LCx injury with this technique compared to a conventional approach [16,20,39]. This hypothesis was also addressed by Banayan et al., but could not be supported by objective evidence [30,40,41]. Although the risk for coronary artery injury could be increased in reoperations because of higher procedural complexity, no evidence for this relationship exists in the literature [30]. Other procedure-related factors that could influence mitral valve-related LCx injury include extensive decalcification of annular calcium, aggressive leaflet resections, the use of non-undersized annuloplasty rings and concomitant procedures including internal suture closure of the left atrial appendage and surgical atrial fibrillation ablation [42,43]. We would also like to propose extensive dilatation of the native mitral valve annulus with the risk of an important annular circumference reduction and tissue distortion after surgery and local abscess formation or other regional factors necessitating an adaptation of the optimal anatomical implantation position as possible factors increasing the risk of perioperative LCx injury.

Therapeutic Strategies

Therapeutic options after prompt diagnosis consist of surgical or percutaneous treatment. At this moment, there is no evidence supporting superiority of one option over the other. Favorable results of both strategies should however be interpreted with care since this could represent a publication bias.

In 20% of cases ($n = 8$), the therapeutic strategy was not reported. In the other cases, 42% ($n = 15$) were managed using a surgical approach first, while 58% ($n = 21$) were treated using primary PCI.

Surgical treatment consists of emergency bypass grafting or correction of sutures when a clear mechanistic cause, amenable for correction, can be identified. Results after surgery are excellent with a reported success ratio of 87% ($n = 13$). One patient died during emergency surgery because of a ventricular rupture and another patient died in the early postoperative period because of severe hypoxemic encephalopathy, related to prolonged reanimation and hemodynamic instability after surgery, despite successful revascularization. In 2 cases, the annuloplasty was removed and successful mitral valve replacement was performed [21,22]. In 1 case, perioperative distortion of a normal circumflex artery after mitral valve annuloplasty was reported, which was successfully treated by immediate reoperation and correction of four sutures [19]. PCI reports a slightly higher failure

rate: 81% of patients ($n = 17$) were treated successfully, while this strategy failed in 19% ($n = 4$). Two patients (50%) in the failed PCI group were referred for emergency surgical revascularization while 2 other were managed conservatively. One patient (5%) needed surgical revision 14 days after initially successful PCI because of a coronary perforation with fistulous communication from the stented segment of the LCx into the left atrium [28].

Because of the complexity of the problem, a multidisciplinary discussion is advisable to select the optimal patient and lesion specific therapy in every individual patient. In hemodynamically stable patients, the percutaneous approach has been suggested as the preferred first-line treatment, while unstable patients could benefit more from emergency surgical revision [16]. Timing of diagnosis may also help decide upon the preferred strategy. If the occlusion is diagnosed intraoperatively, emergency coronary bypass grafting or suture correction can reduce the possibility of serious myocardial necrosis, while PCI may be better suited if the diagnosis is made in the immediate postoperative period [20]. Clearly, complete vessel ligation poses the most challenging problem and will often not be amenable by PCI, necessitating the need for a surgical approach.

The use of a hybrid room, capable of performing combined surgical and percutaneous procedures, could allow optimal identification of the exact location of stenosis due to suture injury, and allow selection of the most appropriate treatment, being either surgical or interventional [15].

Intravascular ultrasound (IVUS) imaging has been reported to be of additional value in clarifying the nature of a coronary lesion. In effect, intravascular imaging (using IVUS or optical coherence tomography (OCT)) provides additional anatomic information and, after balloon treatment and stent implantation, helps in the evaluation and optimization of procedural success [11,15,20].

The main limitation of our report is the small sample size of the patient population, related to the small number of reported cases. Coronary artery injury related to cardiac surgery is probably underreported in literature. Injury of a small LCx can easily remain undetected and present without clinical consequences. This should be taken into account when interpreting these results. Publication bias might be an additional problem and should be taken into account when interpreting success ratios of reported strategies. Larger registries are needed to further investigate true prevalence of mitral valve surgery-related coronary artery injury and to detect factors determining true high-risk patients.

CONCLUSION

As the LCx runs in close proximity to the posterior portion of the mitral valve annulus, vascular compromise related to mitral valve surgery can be a significant and potentially fatal complication, requiring close attention during the perioperative and early postoperative period. Preoperative knowledge of coronary anatomy is useful as a preventive measure to identify true high-risk patients, although right coronary dominance does not preclude LCx injury. The true significance of anomalous LCx as a specific high-risk entity should be further investigated. Increased awareness of this potentially lethal complication and meticulous technique should further help avoid LCx injury in patients undergoing mitral valve surgery. Monitoring of ECG and use of intraoperative TOE looking for new RWMA is paramount to ensure a timely diagnosis of this complication. This allows for the organization of immediate coronary angiography to detect the location of injury and guide the best therapeutic strategy for restoration of coronary perfusion. Therapeutic strategies include surgical and interventional procedures, depending on patient and lesion-specific characteristics, both reporting good final results.

ACKNOWLEDGMENTS

The authors would like to thank Tom Adriaenssens, MD, PhD and Paul Herijgers, MD, PhD (University Hospitals Leuven, Department of Cardiovascular Diseases and Cardiac Surgery respectively) for their constructive remarks and help in the preparation of this manuscript.

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