Intra-procedural arrhythmia during cardiac catheterization: A systematic review of literature

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Abstract

BACKGROUND
Cardiac catheterization is among the most performed medical procedures in the modern era. There were sporadic reports indicating that cardiac arrhythmias are common during cardiac catheterization, and there are risks of developing serious and potentially life-threatening arrhythmias, such as sustained ventricular tachycardia (VT), ventricular fibrillation (VF) and high-grade conduction disturbances such as complete heart block (CHB), requiring immediate interventions. However, there is lack of systematic overview of these conditions.

AIM
To systematically review existing literature and gain better understanding of the incidence of cardiac arrhythmias during cardiac catheterization, and their impact on outcomes, as well as potential approaches to minimize this risk.

METHODS
We applied a combination of terms potentially used in reports describing various cardiac arrhythmias during common cardiac catheterization procedures to systematically search PubMed, EMBASE and Cochrane databases, as well as references of full-length articles.

RESULTS
During right heart catheterization (RHC), the incidence of atrial arrhythmias (premature atrial complexes, atrial fibrillation and flutter) was low (< 1%); these arrhythmias were usually transient and self-limited. RHC associated with the development of a new RBBB at a rate of 0.1%-0.3% in individuals with normal conduction system but up to 6.3% in individuals with pre-existing left bundle branch block. These patients may require temporary pacing due to transient CHB. Isolated premature ventricular complexes or non-sustained VT are common during RHC (up to 20% of cases). Sustained ventricular arrhythmias (VT and/or VF) requiring either withdrawal of catheter or cardioversion occurred infrequently (1%-1.3%). During left heart catheterizations (LHC), the incidence of ventricular arrhythmias has declined significantly over the last few decades, from
Cardiac catheterization procedures performed in the cardiac catheterization laboratory (CCL) often include right heart catheterization (RHC); left heart catheterization (LHC); and coronary angiography with or without intra-coronary interventions. Cardiac catheterization is one of the most commonly performed procedures in the modern healthcare system. In 2014, there were more than 1 million inpatient diagnostic cardiac catheterizations and 480000 coronary angiography performed in the United States alone[1]. Given the nature of the intracardiac or intracoronary instrumentation as part of the cardiac catheterization procedure, cardiac arrhythmias are common and often unavoidable. We systematically reviewed the published literature to provide a comprehensive overview of the incidence rates, impact on outcomes and potential approaches to minimize the risk of cardiac arrhythmias during cardiac catheterization procedures.

Catheter-induced cardiac arrhythmias during RHC may occur as soon as the catheter tip enters the right atrium, and while advancing through the right atrium, right ventricle, right ventricular outflow tract and the pulmonary artery. Observed arrhythmias include supraventricular arrhythmias [premature atrial contraction, supraventricular tachycardias (SVTs, including atrial fibrillation (AF), atrial flutter)], ventricular arrhythmias, premature ventricular contractions (PVCs), non-sustained or sustained ventricular tachycardia (NSVT or VT) and ventricular fibrillation (VF), as well as various conduction disturbances, such as right bundle branch block (RBBB).
and complete heart block (CHB), especially in the setting of pre-existing left bundle branch block (LBBB)\(^2\,^3\).

LHC studies typically include measuring the left ventricular pressures and performing left ventriculography with catheters crossing the aortic valve and positioned in the left ventricle, in addition to performing coronary artery angiography. Depending on the coronary angiographic findings, a percutaneous coronary intervention (PCI) may subsequently be performed. In addition, intravascular imaging such as intravascular ultrasound (IVUS) or optimal coherence tomography (OCT) may be used to examine coronary artery anatomy. Fractional flow reserve (FFR) may be applied to assess the hemodynamic significance of a coronary artery stenosis. This review summarizes arrhythmic complications of these procedures. Recently developed structural heart interventional procedures, i.e., transcatheter valvular therapies for valvular disease, often involve rapid pacing and have a potential to cause significant injury to the conduction system. Arrhythmias associated with structural heart interventions are not included in this review.

**MATERIALS AND METHODS**

We screened the titles and abstracts of studies against predefined terms, using PubMed, EMBASE and Cochrane databases (Table 1). The title and available abstracts of all returned articles were reviewed to identify relevant articles for a full-length review and follow-up of their references. We synthesized the following review according to the procedure and arrhythmia types. Meta-analysis was not performed due to the tremendous heterogeneity in inclusion criteria, equipment used in cardiac catheterization, and the arrhythmia definitions among reported studies.

**RESULTS**

**Cardiac arrhythmic during RHC**

RHC may be performed in the CCL, at the bedside of intensive care unit (ICU) or in the operating room. The majority of published studies on arrhythmias during RHC were about RHC procedures performed in the ICU or operating room settings. There have been no head-to-head comparisons about the incidence rates of significant arrhythmias or conduction disturbances during RHC performed in the ICU, operating room and CCL settings. The differences of arrhythmias occurring during RHC using different types or sizes (5 French vs 7 French) of balloon tipped catheters was not studied either.

**Catheter-induced conduction disturbance during RHC**

Right sided conduction disturbances, whether transient or permanent were observed infrequently (less than 1%) during RHC, which rarely resulted in the requirement of permanent pacemakers\(^6\,^9\). Damen et al\(^2\) reported 2 catheter-induced RBBB during 1400 RHCs (0.14%). Ranu et al\(^8\) retrospectively reviewed charts of 349 patients who underwent RHC and discovered that only 1 patient developed CHB (0.3%) required the removal of the pulmonary artery catheter and insertion of a temporary transvenous pacing wire for 36 hours until the patient recovered normal conduction. CHB could occur during RHC in patients with pre-existing LBBB\(^4\,^9\). In the setting of pre-existing LBBB, Damen found 1 out of 16 patients with LBBB experienced transient CHB requiring temporary pacing (6.3%)\(^2\). Morris et al\(^10\) reported 82 procedures in the ICU setting, during which 7 French balloon-tipped flow directed catheters were used in patients with LBBB, and there was no occurrence of CHB. Based on this, the investigators recommended against routine placement of temporary transvenous pacing wires during RHC in patients with LBBB. The incidence of conduction disturbances during RHC which is performed routinely in the CCL for heart failure, pulmonary hypertension or cardiogenic shock has not been well documented.

**Catheter-induced ventricular arrhythmia during RHC**

During RHC, both advancing and withdrawing the balloon tipped catheter through the right atrium, right ventricle or pulmonary artery (PA) may cause arrhythmias\(^2\,^4\,^6\). Since the initial report of the improved design of the flexible, balloon-tipped, flow-directed catheter for RHC or a PA catheter placement by Swan and Ganz, it has been universally adopted in clinical practice. In Swan et al\(^4\)’s initial experience and some subsequent experiences in the CCL, the risk of ventricular arrhythmia was minimal. However, during RHC or PA catheter placement at the bedside in the ICU or OR settings, there were higher rates of various degrees of
ventricular arrhythmias such as singlet PVCs, runs of couplets, consecutive PVCs, VT (non-sustained or sustained) and VF, as high as 85% in some reports (Table 2). All the published reports on ventricular arrhythmias related to RHC were single center studies with either retrospective or prospective designs. There are no uniform definitions in reporting the types of arrhythmias. Table 2 provides the most complete list of published data on the incidence of ventricular arrhythmias during RHC. Most of the observations confirmed that ventricular arrhythmias observed during RHC are generally short-lived and self-limited[17].

Severe life-threatening arrhythmias, such as sustained VT and VF can occur during RHC but are very rare[19]. Wennewold et al[10] reported that only 2 VT and 2 VF episodes occurred during more than four thousand RHC (< 0.1%) performed from 1947 to 1963 (before the design of balloon tipped Swan-Ganz catheter). The incidence of sustained VT or VF, requiring anti-arrhythmia treatment either by medication or cardioversion, is relatively low (0.26%[11, 1%,15%[11], 4.7%[25-28]). Bergmann et al[10] reported that no episodes of VT and 1 episode of VF requiring defibrillation occurred out of 380 RHCs (0.3%) performed for patients with severe aortic stenosis undergoing transcatheter aortic valve replacement. However, Gwak et al[13] reported a 2% incidence rates for VT or VF episodes requiring either withdrawal of the catheter or defibrillation, in their prospective observation of 100 PA catheter placements in the OR for liver allograft transplant recipients.

Cardiac arrhythmias during LHC, coronary angiography and intervention

Ventricular arrhythmias during LHC: Much attention was paid to the occurrence of malignant ventricular arrhythmias – VF, VT and ventricular arrest/asystole (VA) during the early decades of coronary artery angiography (CAG). There were many reports from experienced single centers as well as multicenter registries detailing ventricular arrhythmias. Table 3 provides a comprehensive list of published reports of incidence rates of malignant ventricular arrhythmias during CAG. Gau et al[29] reported an unusually high incidence rate of VF (12%) in their single center study of 75 cases of selective CAG. Excluding this outlier, the median reported incidence rates of ventricular arrhythmias during diagnostic CAG is 0.9% with a range of 0.1% to 1.7%. Taken together the published data reported total of 163090 cases with 1260 incidences of malignant ventricular arrhythmias that resulted in an accumulated incidence rate of 0.77%. In the period of 1960s, ventricular arrhythmias occurred at the rate of 1.1% in CAG in the reported series (134 incidences in 11747 cases); in the 1970s, the rate was 1.0% (738 events in 73097 cases); in the 1980s, 0.8% (216 events in 26231 cases); and in the 1990s, 0.6% (136 events in 24142 cases). More recently, there were two reports from the same institute in China that included more than 18365 and 27798 diagnostic CAG respectively, using 4 or 5 French catheters. Due to the potential overlap of cases in these two reports, only the later report which included the larger sample size was included in our cumulative calculation. The incidence rate of VF was reported to be 0.1%. The temporal trends show that the incidence rates of malignant ventricular arrhythmias during diagnostic CAG have steadily declined from 1.1% to as low as 0.1% in contemporary practice (Table 3). Figure 1 provides a graphic view of the trend of reported incidence rates of VT/VF.

Percutaneous transluminal coronary angioplasty (PTCA) or percutaneous coronary intervention (PCI) has become the most commonly used approach to revascularize obstructive coronary artery disease both in stable ischemic conditions and acute myocardial infarctions. Ventricular arrhythmias are commonly encountered during PCI. In an early study of 1500 PTCA cases, Dorros et al[30] reported an incidence rate of
Table 2: List of studies reported the incidence rate of ventricular arrhythmia during right heart catheterization

| Year | Number RHC | Types of arrhythmia | Incidence rate, n (%) | Setting | Study design | Procedural Outcomes | Ref. |
|------|------------|---------------------|-----------------------|---------|--------------|---------------------|------|
| 1979 | 73         | VA (> 1 PVCs in 4 beats) | 27 (36.9) | OR     | Prospective | All self-limited   | Shaw et al[58] |
|      |            | VA not treatment     | 36 (16.4)           | ICU    | Prospective  | 3 VTs: Treatment    | Sise et al[52] |
|      |            | VA required treatment| 33 (10)             |        | Observational|                    |      |
| 1981 | 320        | PVCs VT             | 5 (1)                |        |              |                    |      |
|      |            |                     |                      |        |              |                    |      |
| 1981 | 60         | PVCs VT             | 29 (48)             | ICU    | Retrospective| 2 VTs: Treatment    | Sprung et al[61]|
|      |            |                     |                      |        | Observational| 1 VF: Mortality     |      |
|      |            | Lidocaine           | 8/53 (15)           | OR     | Prospective  | All self-limited    |      |
|      |            | Placebo             | 10/54 (19)          |        | Randomized   | 2 VF: Mortality     |      |
| 1982 | 150        | Advanced VA         | 80 (53)             | ICU    | Prospective  | 3 VTs: Treatment    | Sprung et al[57,58]|
|      |            | NSVT (6-30 cPVCs)   | 45 (30)             |        | Observational|                    |      |
|      |            | VT (> 30 cPVCs)     | 5 (3)               |        |             |                    |      |
|      |            | VF                  | 2 (1.3)             |        |             |                    |      |
| 1983 | 67         | Advanced VA         | 42 (63)             | ICU    | Prospective  | All self-limited    | Sprung et al[59]|
|      |            | Lidocaine ppx placebo| 18/31 (58)        | OR     | Randomized   |                    |      |
|      |            | Placebo             | 24/36 (67)          |        |              |                    |      |
| 1983 | 528        | PVCs VT             | 58 (11)             | ICU    | Prospective  | 8 VTs: Meds        | Boyd et al[21] |
|      |            | VF                  | 8 (1.5)             |        | Observational|                    |      |
|      |            |                     | 0                   |        |              |                    |      |
| 1985 | 56         | Advanced VA         | 7 (12.5)            | ICU    | Prospective  | All self-limited    |      |
|      |            |                     |                      |        | Observational|                    |      |
| 1985 | 250        | PVCs VT             | 162/250 (64.8)      | OR     | Observational| All self-limited    | Damen et al[14]|
|      |            | VF (VT > 3 cPVC > 100 bpm) | 11/250 (4.4) |        |              |                    |      |
|      |            |                     | 0                   |        |              |                    |      |
| 1986 | 1400       | Overall PVCs        | 880/1400 (62.9)     | OR     | Prospective  | All self-limited    | Damen et al[5] |
|      |            | VT (> 3 cPVC > 100 bpm) | 838/1400 (59.9)   |        | Observational|                    |      |
|      |            | VF                  | 42/1400 (3)         |        |              |                    |      |
| 1986 | 142        | Overall Benign      | 64 (45)             | ICU    | Prospective  | All self-limited    | Patel et al[59]|
|      |            |                     | 24 (16.9)           |        | Observational|                    |      |
|      |            | Malignant†          | 40 (28.1)           |        |              |                    |      |
| 1989 | 68         | Overall Benign      | 55 (80.8)           | OR     | Prospective  | All self-limited    | Keusch et al[62] |
|      |            |                     | 30 (44.1)           |        | Observational|                    |      |
|      |            | Malignant†          | 25 (36.8)           |        |              |                    |      |
| 2007 | 100        | PAC insertion       | 70 (70)             | OR     | Prospective  | All self-limited    | Gwak et al[21] |
|      |            | Overall Benign      | 33 (33)             |        | Observational|                    |      |
|      |            | Malignant‡          | 37 (37)             |        |              |                    |      |
| 2012 | 139        | Overall Benign      | 76/139 (54.7)       | OR     | Prospective  | All self-limited    | Pipanmekaporin et al[28] |
|      |            |                     | 58 (41.7)           |        | Randomized   |                    |      |
|      |            | Severe (≥ 3 PVCs)   | 28 (20.1)           |        |              |                    |      |
| 2013 | 380        | VT                  | 0                   | Hybrid CCL | Retrospective| DCCV                | Bergmann et al[19] |
|      |            | VF                  | 1 (0.26)            |        | Observational|                    |      |
| 2017 | 174        | Overall             | 149/174 (85.6)      | OR     | Prospective  | All self-limited    | Satol et al[23] |
Multiple PVCs ≥ 2 78/174 (44.8)  
Observational

1Malignant definition: Premature ventricular contractions (PVCs) with couples or > 3 consecutive PVCs.
2Malignant definition: PVC couples, or ≥ 3 consecutive PVCs with heart rate > 120 bpm.
3Malignant definition: ≥ 3 consecutive PVCs with heart rate > 100 bp.
4RHC: Right heart catheterization; VA: Ventricular arrest (asystole); OR: Operating room; ICU: Intensive care units (including medical ICU, surgical ICU and cardiac ICU); PVC: Premature ventricular contractions; VT: Ventricular tachycardia; PAC: Pulmonary artery catheter; VF: Ventricular fibrillation; CCL: Cardiac catheterization laboratory; cPVCs: Consecutive PVCs; DCCV: Direct current cardioversion; NSVT: Non-sustained VT.

1.6% of VF and 0.5% of sustained VT required intervention. Subsequent reports of the rate of ventricular arrhythmias from both single center experiences and registries ranged from 0.84% to 4.3%. Addala et al. have so far reported the largest single center cohort, with more than 19000 PTCA cases and 164 events of VF (0.84%). Based on the published data (255 events in 23882 PTCA cases), the cumulative incidence rates of VF/VT during PTCA in patients with stable or unstable angina was calculated to be 1.1%. Mehta et al. and Har et al. both reported a higher incidence of VF during primary PCI for ST-elevation myocardial infarction (STEMI). 4.3% and 4.1% respectively (Table 3). Available data in the literature suggests that the incidence rates of ventricular arrhythmias during PCI in patients with stable and acute coronary artery disease have been relatively constant in the past two decades of practice. NCDR CathPCI registry and ACTION registry did not collect information about intra-procedural arrhythmias during diagnostic CAG and PCI until the newest version of data collection form (version 5) for CathPCI registry was implemented in July 2018. Without timely termination, malignant ventricular arrhythmias could be life-threatening. Intrinsic build-in telemetry monitoring by trained staff in CCL has proven to be effective. In the reported series, the episodes of VT/VF during diagnostic LHC and CAG left minimal impact on long term outcomes. Gau et al. reported that all 9 episodes of VF in their first 75 CAG experiences (12% incidence rate) were successfully defibrillated without impacts on outcomes. Others reported the same successful immediate restoration of normal rhythm from intra-procedural VF/VT episodes without adverse sequelae during the hospitalization. The prognosis of patients with stable coronary artery disease was more governed by the status of CAD and left ventricular dysfunction and other comorbidities, rather than the occurrence of VT/VF during the procedure.

Whether ventricular arrhythmias in the setting of acute myocardial infarctions have an impact on outcomes has been a controversial question. Mehta et al. reported that the occurrence of VT/VF during primary PCI did not influence PCI success, hospital or one-year outcomes, compared to patients who did not have intra-procedural ventricular arrhythmias. However, Har et al. recently found that, compared to patients without ventricular arrhythmias, the occurrence of intra-procedural VF/VT requiring cardioversion during primary PCI for STEMI was associated with increased early post-MI mortality (12.0% vs 0.5% in-hospital mortality, and 24.1% vs 3.6% of 30 days mortality); but not late mortality.

**Atrial tachy-arrhythmia in LHC and coronary interventions:** Bourassa et al. reported a 0.17% atrial tachy-arrhythmia (AF and SVT) in 5250 CAG cases in their single center study. Balloon inflation during PTCA was found to increase P wave dispersions and as well as the maximum duration of P waves, which may result in increased risk of AF. There are no recent studies reporting atrial tachy-arrhythmias during LHC and coronary interventions.

**FFR measurement and intravascular imaging related arrhythmias:** Park et al. reported their first intracoronary adenosine-induced AF during FFR measurement. The patient required hospitalization, and amiodarone administration which led to sinus conversion, and a medical regimen for thromboembolic event prophylaxis. More seriously, there were a total of 7 cases of intracoronary adenosine induced VF during FFR have been reported in the literature. Various doses (from 96 mcg to 360 mcg and 480 mcg) of intracoronary adenosine boluses were delivered right before the VF occurred. Shah et al. reported the incidence rate of VF during FFR was 0.9% (3 cases in 326 FFR cases). They postulated that the large volume of adenosine/saline solute injection (up to 30 cc/injection) might have contributed to the induction of VF by causing ischemia. By increasing the adenosine concentration and reducing the volume of injection with a similarly high dose of adenosine, Shah reported the avoidance of VF. The overall rate of intracoronary adenosine-induced VT/VF during FFR measurement is unknown. There is no reported case of intravenous adenosine induced VF. Intracoronary papaverine is also used to induce maximum hyperemia in FFR measurement. It was well known that use of intracoronary papaverine during FFR may prolong QT interval and induce polymorphic VT and VF. The risk of...
Figure 1  Graphic view of reported incidence rates of ventricular tachycardia / ventricular fibrillation during coronary angiography. Gau et al[29] reported in 1970, an outlier with high incidence of ventricular fibrillation (VF) in their early experience of 75 cases of coronary angiography (CAG). Excluding the outlier, other reported VF/ventricular tachycardia (VT) incidence rates were consistently low with median 0.9%, (range 0.1% to 1.7%). Total reported CAG cases excluding the 75 cases in Gau et al[29] were 163015, and total VF/VT cases 1251, with the incidence rate of 0.8%. VF: Ventricular fibrillation; VT: Ventricular tachycardia.

polymorphic VT (torsade de pointes) and VF has been reported to be around 1.2%-1.3%[48,50].

The potential risk of cardiac arrhythmias, especially malignant ventricular arrhythmias associated with intravascular imaging such as IVUS and OCT, has been reported to be 1.1% (5 out of 468 cases). VF rate was reported in a multicenter evaluation of the safety of OCT[51]. However, transient chest pain and electrocardiographic changes (QRS widening/ST segment depression/elevation) have been observed in 47.6% cases[52].

Brady-arrhythmias and conduction disturbances during LHC and coronary angiography: The risk of conduction disturbances is low during procedures performed via femoral artery approach and higher when using a radial artery approach. One study reported the incidence of symptomatic sinus bradycardia in patients undergoing trans-radial coronary angiography to be as high as 4.3%[53]. In almost all cases, the heart rate returned to normal with adjustment of catheter or atropine administration without residual consequences[53,54]. The etiology of this phenomenon is unclear. Perhaps catheter stimulation or stretch of subclavian, brachiocephalic arteries or ascending aorta may induce a vasovagal reaction.

**DISCUSSION**

**Arrhythmias during right heart catheterization**

Conduction disturbances were recognized during the very early practice of intracardiac catheterization[27]. It was anticipated that advancing catheters through the ventricle, would irritate the right bundle branch and its fascicular branches and might lead to transient or even permanent injuries. Fortunately the incidence of conduction abnormalities as well as ventricular arrhythmias is low and the long term implications are relatively negligible.

Pre-disposing risk factors associated with the increased incidence of ventricular arrhythmias, in particular the risk of VT or VF requiring intervention during RHC, include myocardial infarctions, septic shock[59], pre-existing cardiac conditions[59], use of a guidewire to assist PA catheter advancement[60], prolonged procedural time and presence of valvular diseases[32,60]. Recent studies suggested that positioning the patient in the head-up and right lateral position while passing right heart catheters would allow the catheter to easily enter the right ventricular outflow tract and thereby, reduce the incidence of severe arrhythmias[32,57]. Intravenous lidocaine
| Year | VF (%) | VT (%) | VA (%) | Overall (%) | Procedure types | Study designs (incidence/ total subjects) | Ref. |
|------|--------|--------|--------|-------------|-----------------|------------------------------------------|------|
| 1967 | 1.3    | N/R    | N/R    | 1.3         | N/R CAG         | Single center (Sones) 84/6400            | McGuire et al[85] |
| 1968 | 1.33   | N/R    | N/R    | 1.33        | N/R CAG         | Meta-analysis (5/535; 22/1500)           | Takaro et al[86] |
| 1968 | 0.7    | 0      | 0      | 0.7         | N/R CAG         | Multicenter, CASS registry 23/3312       | Ross et al[87] |
| 1970 | 12     | 0      | 0      | 12          | N/R CAG         | Single center 9/75                       | Gau et al[88] |
| 1972 | 0.22   | 0      | 0      | 0.22%       | CAG             | Single center 1/445                      | Green et al[89] |
| 1973 | 1.281  | 1.28   | N/R    | N/R CAG     | Multicenter, survey; 600/46904            | Adams et al[90] |
| 1975 | 1.14   | 0      | 0      | 1.14        | N/R CAG         | Single center, 4/351                     | Shah et al[91] |
| 1976 | 0.36   | 0.11   | 0.32   | 0.19        | CAG             | Single center 19/5250 VF; 6/5250 VT; 17/5250 VA | Bourassa et al[92] |
| 1976 | 1.01   | N/R    | N/R    | 1.01        | CAG             | Single center 11/1094                    | Nitter-Hauge et al[93] |
| 1976 | 1.5    | N/R    | N/R    | 1.5         | CAG             | Single center 22/1500                    | Pridie et al[94] |
| 1979 | 0.63   | 0      | 0      | 0.63        | 4.3 CAG         | Multicenter registry 48/7555            | Davis et al[95] |
| 1979 | 0.11   | 0      | 0      | 0.11        | 0 CAG           | Single center 10/10000                   | Vijay et al[96] |
| 1983 | 1.6    | 0.5    | 0      | 2.1         | N/R PTCA        | Registry 24/1500 VF; 8/1500 VT          | Dorros et al[97] |
| 1984 | 0.52   | N/R    | N/R    | 0.5         | CAG             | Single center 39/7915                    | Nishimura et al[98] |
| 1985 | 1.7    | 1.7    | N/R    | 1.7         | N/R CAG         | Single center 66/3906                    | Lehmann et al[99] |
| 1985 | 0.784  | 0.78   | N/R    | 0.78        | N/R CAG         | Single center 63/8081                    | Murdock et al[100] |
| 1987 | 1.28   | N/R    | N/R    | 1.28        | N/R CAG         | Single center 26/2025                    | Arrowood et al[101] |
| 1989 | 0.27   | 0      | 0.03   | 0.3         | 0 CAG           | Single center 11/3656                    | Armstrong et al[102] |
| 1989 | 1.71   | 0      | 0      | 1.7         | N/R CAG         | Single center 11/648                     | Lehmann et al[103] |
| 1990 | 1      | 1.0    | N/R    | 1.0         | N/R CAG         | Single center, 2 cohorts                 | Misra et al[104] |
| 1990 | 0.4    | 0.4    | N/R    | 0.4         | N/R CAG         | Renografin-76 (20/2000) vs Isovue-370    | Epstein et al[105] |
| 1990 | 0.54   | 0.54   | N/R    | 0.54        | N/R CAG         | Multicenter, CASS registry (108/20142)   | Epstein et al[106] |
| 1991 | 2.06   | 2.06   | N/R    | 2.06        | N/R PTCA        | Single center, (19/922)                  | Brennan et al[107] |
| 1991 | 0.4    | 0.8    | 0      | 1.2         | 0 PTCA          | Single center, double blinded, RCT       | Lembo et al[108] |
|      | 0.7    | 2.0    | 0      | 2.7         | 0 PTCA          | Diatrizoate (15/551, 2.7%)               |               |
| 2002 | 2.1    | 0      | 0      | 2.1         | N/R PTCA        | Single center 19/905                     | Huang et al[109] |
| 2004 | 4.3    | 4.3    | N/R    | 4.3         | N/R PTCA        | Multicenter, PTCA (133/3065, PAMI study, STEMI) | Mehta et al[110] |
Atrial tachy-arrhythmia in LHC and coronary interventions

Contrary to RHC, LHC is performed via a retrograde approach. There is no direct contact of instruments with atrial structures. Direct stimulation of the atrium causing arrhythmia is rare during LHC and coronary interventions. Thus, the findings of our recent multicenter study[31,40,41] and mechanical stimulations of myocardial tissue due to catheter and wires, contribute to the occurrence of ventricular arrhythmias. These malignant ventricular arrhythmias are also the topic of many case reports throughout recent decades. Understanding their potential causes, contributing factors, and approaches to minimize the risk as well as preparing to manage them when they occur are one of the core subjects of training in the interventional cardiology community.

Causes and contributing factors of ventricular arrhythmias during LHC and approaches to minimize the risk

The more than 10 folds decrease in incidence rate of malignant ventricular arrhythmias during CAG and LHC is the result of half a century’s clinical and translational research. It is generally accepted that ischemic changes of myocardium, toxicities of contrast medium[68-69], and mechanical stimulations of myocardial tissue by catheter and wires, contribute to the occurrence of ventricular arrhythmias. Individual patients’ vulnerability or susceptibilities to ventricular arrhythmias, often influenced by electrolyte derangement, pre-existing prolongation of QT interval, small caliber coronary arteries, or the severities and acuities of coronary artery disease, also play important roles. Furthermore, the operators’ experience and approach in performing the LHC and coronary intervention also dictate outcomes (Table 4).

Arrhythmias during left heart catheterization

The belief that the selective injection of contrast medium into coronary arteries would result in asymmetrical hypoxia, electrical imbalance, and invariably ventricular arrhythmias was disproved by the pioneer of coronary arteriography, Dr. Sones Jr[60,62]. However, the fear of fatal ventricular arrhythmias related to coronary angiography persists. Due to the proximity of catheters, wires and other equipment to the ventricular walls during LHC, ventricular arrhythmias will unavoidably occur despite the advancement of techniques, reagents and equipment. Direct stimulation with wires and catheters of the ventricular myocardial tissues may disturb local electric activities and introduce myocardial contractions which lead to PVCs in singlets, couples or runs continuously for various lengths. Therefore, advancing equipment into the left ventricular chamber leading to frequent PVCs, non-sustained ventricular tachycardia (NSVT) with cPVCs ≥ 3 beats or ventricular tachycardia (cPVCs ≥ 30 beats) are common, up to 80% in our catheterization laboratory at New York Presbyterian Queens (Shaik et al manuscript in preparation). These ventricular arrhythmias are usually terminated by catheter manipulations (withdrawal, repositioning etc.) without significant impact on hemodynamics. Malignant ventricular arrhythmias, such as sustained VT, VF and ventricular arrest or standstill could occur but are much less common. These malignant ventricular arrhythmias usually cause hemodynamic compromise and require immediate interventions, i.e. chest wall compression, cardioversion and possibly the administration of a pharmacological agent. These malignant ventricular arrhythmias are also the topic of many case reports throughout recent decades. Understanding their potential causes, contributing factors, and approaches to minimize the risk as well as preparing to manage them when they occur are one of the core subjects of training in the interventional cardiology community.

| Year | VT/VF Rate | VT/VF Rate | VT/VF Rate | VT/VF Rate | Procedure | Institution |
|------|------------|------------|------------|------------|------------|-------------|
| 2005 | 0.84       | N/R        | 0.84       | N/R        | PTCA       | Single center, (164/19497) |
| 2008 | 0.08       | 0.05       | 0.13       | N/R        | CAG        | Single center 24/18365 |
| 2009 | 0.1        | N/R        | 0.1        | N/R        | CAG        | Single center 27/2798 (radial 0.076%, femoral 0.147%) |
| 2017 | 4.1        | N/R        | 4.1        | N/R        | PCI        | Multicenter, APPROACH trial, 138/3614 STEMI |

Summary
- Total reported CAG cases: 163090; total of 1260 with overall VT/VF/VA rate 0.77% for diagnostic CAG.
- Total reported non-AMI PTCA cases: 2388; total of 255 VT/VF with VT/VF rate 1.1% for PTCA.

1Ventricular fibrillation and sustained ventricular arrhythmias were reported together. VF: Ventricular fibrillation; VT: Ventricular tachycardia; VA: Ventricular arrest (asystole); CAG: Coronary arteriography or angiography; PTCA: Percutaneous transluminal coronary angioplasty; PCI: Percutaneous coronary intervention; RCT: Randomized controlled trial; STEMI: ST segment elevation myocardial infarction. N/R: Not reported.
Table 4 Known risk factors for ventricular tachycardia / ventricular fibrillation during coronary angiography and percutaneous coronary intervention and approaches to mitigate the risk

| Risk factors                                                                 | Approaches to mitigate risk                                                                 |
|------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------|
| Catheter wedging coronary ostium, damping pressure causes ischemia and stagnation of contrast medium[33]. | 1 Smaller caliber catheter to avoid damping                                                   |
|                                                                              | 2 Catheters with sideholes to avoid damping                                                   |
|                                                                              | 3 Dis-engage catheter, clear contrast before next injection to minimize ischemia               |
|                                                                              | 4 Avoid prolonged injection or large amount CM injection                                      |
| Contrast medium toxicity [34, 97]                                             | 1 Use non-ionic, low osmolar contrast                                                         |
| Non-ionic CM has lower risk than ionic CM                                    | 2 Eliminating calcium-binding additive in CM                                                 |
| Low osmolarity CM has lower risk than high osmolarity CM                     | 3 Use electrolytes optimized CM                                                               |
| Calcium-binding additive in CM increase the risk of VT/VF                   | 1 Meticulously manipulating equipment                                                         |
| Catheter or wire tip irritation of LV [89]                                   | 2 More practice                                                                              |
| High risk in RCA and bypass graft CAG [99]                                  | Pay more attention to avoid or minimize ischemia during procedure                            |
| Direct injection into conus branch leading to VF [102, 103]                 | Early recognition of conus branch engagement and avoid injection or abort injection          |
| Increased risk of VF/VT in patients with severe CAD and cardiomyopathy      | 1 Pre-procedural workup to understand the risk                                                |
|                                                                              | 2 Meticulous procedural technique                                                             |
|                                                                              | 3 Operators training and competency                                                           |
|                                                                              | 4 Close monitoring                                                                            |
|                                                                              | 5 Early reperfusion therapy                                                                   |
| Acute myocardial infarction and primary PCI patients have high risk of VF/VT| 6 Consider mechanic circulatory support for AMI patients with cardiogenic shock or extensive CAD with severely reduced EF (high risk patients with high risk CAD) |

CM: Contrast medium; VT: Ventricular tachycardia; VF: Ventricular fibrillation; LV: Left ventricular; CAG: Coronary angiography; CAD: Coronary artery disease; RCA: Right coronary artery; PCI: Percutaneous coronary intervention; EF: Ejection fraction.

literature review are not surprising.

**FFR measurement and intravascular imaging related arrhythmias during LHC and coronary interventions**

In symptomatic patients with moderate coronary artery stenosis, guidelines supported by robust clinical evidence recommend the use of FFR to guide the clinical decision making process[67]. The risk of arrhythmias during FFR measurement involves instrumentation of the coronary arteries with guidewires, catheters and contrast medium, as well as the pro-arrhythmic effects[68] of adenosine, which is the most commonly used agent to induce maximum hyperemia[69]. Intravenous infusion of adenosine at 140 mcg/kg/min or intracoronary bolus injection at the doses of 60 mcg, 120 mcg, up to 480 mcg, are generally safe and well tolerated, largely owing to its very short half-life. Adenosine induced transient sinus bradycardia, AV block, and sinus tachycardia are common and expected physiologic effects on the heart rhythm. Adenosine-induced arrhythmias and conduction disturbance are short-lived and self-limited without the need of special treatment. The current gold standard for FFR studies is to use intravenous adenosine to induce hyperemia, especially when taking into consideration the reported risk of severe ventricular arrhythmias which using intracoronary adenosine and papaverine. However, head-to-head safety data is not available.

Because OCT involves high volume contrast injections to disperse blood components during image acquisition the incidence of ventricular arrhythmias is higher. This may cause chest pain, electrocardiographic changes and even ventricular arrhythmias – all three of which have been reported in the literature. There are no particular concerns regarding IVUS studies causing ventricular arrhythmias.

**Brady-arrhythmias and conduction disturbances during LHC and coronary angiography**

Brady-arrhythmias have been recognized since the very early experiences and are relatively common during LHC and coronary angiography[70]. Direct toxicity of contrast medium and stimulation of chemoreceptors, other vasovagal reactions induced by pain and anxiety, etc. were the proposed mechanisms of these
Arrhythmias. Lately, with the growing popularities of trans-radial catheterization, coiling of the catheters and direct stimulation of the aortic arch and carotid sinus receptors was also noted to cause sinus bradycardia. An infrequent yet significant conduction disturbance associated with LHC and CAG is LBBB and/or CHB. As opposed to the right bundle, the trunk of the left bundle is generally short and immediately divides into two fascicles. The left bundle branch is also broadly distributed over the left septal surface in a diffuse fanlike structure. To some extent, these anatomic features of the left bundle protect it from mechanical damage during catheter instrumentation of the left ventricle. Some patients, however, may have anatomic variations, which include a left bundle that extends undivided for 20 mm or more, making the left bundle vulnerable. Shimamoto et al. reported 3 patients, without any known conduction abnormalities or evidence of infarction prior to LHC, who developed LBBB, without a change in heart rate during coronary angiography. Of these patients, only one eventually developed a permanent LBBB and none had significant complications. The recognition of the possibility of developing LBBB is particularly important when patients have pre-existing right bundle branch and/or fascicular blocks, which could potentially require permanent pacemaker implantation if persistent CHB occurs. Furthermore, the His bundle travels through the membranous septum in immediate proximity to the posterior sinus of Valsalva and runs just under the left ventricular endocardium. It is thus, anatomically vulnerable to mechanical trauma during LHC and CAG. A single touch of these structures by the catheter tip may cause intra-His bundle injury resulting in CHB.

Understanding the risk factors for development of brady-arrhythmias and conduction disturbances during LHC and CAG helps the operator to be prepared should these arrhythmias occur and compromise hemodynamics, which will require either administration of atropine and other drugs, and/or emergent transvenous pacing. However, given the low incidence as well as relatively rapid recovery in most of the cases, prophylactic temporary transvenous pacing as performed earlier in practice is no longer recommended. In recent years, there has been a growing interest in using coronary catheters and guidewires for left ventricular pacing in order to reduce resource utilization and avoid the risks of transvenous wire placement.

In conclusion, diagnostic RHC, LHC, CAG, and coronary interventions are the most commonly performed invasive cardiac procedures. This systematic literature review demonstrated a 0.14%-0.3% incidence of transient RBBB during RHC in normal individuals, with a significantly higher risk of CHB (up to 6.3%) requiring temporary or permanent pacing for individuals with pre-existing LBBB. Isolated PVCs or nonsustained VT which do not require specific treatment are common (approximately 20% incidence rate in most of the reports) during RHC. Potentially life-threatening ventricular arrhythmias (sustained VT and/or VF) requiring either withdrawal of catheter or cardioversion also occur but at much lower rates (1%-1.3%). The incidence rate of diagnostic LHC and CAG causing arrhythmias has reduced 10 fold in the last half century from 1.1% to 0.1% (in modern era) due to an improved procedural techniques, better training, improved contrast medium, and equipment. Coronary interventions as well as hemodynamic assessment with FFR and intracoronary imaging (especially OCT) continue to carry an increased risk of introducing malignant arrhythmias with up to 1% incidence rate of VF requiring shocks. Rigorous and constant monitoring, and readiness to intervene are essential for the modern cardiac catheterization facility.

**ARTICLE HIGHLIGHTS**

**Research background**
Cardiac Catheterization is one of the most commonly performed procedures in the modern health care system. Given the nature of intracardiac and intracoronary manipulation of catheters during the procedure, arrhythmias are not uncommon. Understanding the incidence, risk factors and strategies to mitigate the risk bears clinical significance.

**Research motivation**
There are sporadic reports on the topics of intra-procedural arrhythmias during cardiac catheterization. We systematically reviewed published literature, analyzed the incidence rate, temporal trends, and predictors of atrial and ventricular arrhythmias during left and right heart cardiac catheterization. We also discussed factors and approaches to reduce arrhythmias and improve the safety of the procedures.

**Research objectives**
The goal of this study is to provide a comprehensive overview of the incidence rates and impact on short- and long-term outcomes of arrhythmias during cardiac catheterization, as well as
understand approaches to minimize the risk of malignant arrhythmias during cardiac catheterization.

**Research methods**
We systematically searched PubMed, EMBASE and Cochrane databases with a combination of comprehensive terms related to cardiac catheterization procedures and various cardiac arrhythmias, then carefully reviewed and synthesized the data by types of procedure and arrhythmias.

**Research results**
We found a 0.14-0.3% incidence of transient right bundle branch block during right heart catheterization (RHC) in normal individuals, and a significantly higher risk of complete heart block (up to 6.3%) requiring temporary or permanent pacing for individuals with pre-existing left bundle branch block (LBBB). Isolated premature ventricular contraction or non-sustained ventricular tachycardia (VT) which do not require specific treatment are common (approximately 20% incidence rate) during RHC. Potentially life-threatening ventricular arrhythmias (sustained VT and/or ventricular fibrillation) requiring either withdrawal of catheter or cardioversion also occur but at lower rates (1.0%-1.3%). The incidence rate of diagnostic left heart catheterization and coronary angiography causing arrhythmias has significantly reduced from 1.1% to 0.1% in the last half century. However, invasive coronary intervention and hemodynamic assessment including optical computed tomography and fractional flow reserve continue to possess a significantly higher risk.

**Research conclusions**
Cardiac arrhythmias are common during cardiac catheterization. While the majority of arrhythmias are benign and self-limited, complete heart block in the presence of pre-existing LBBB and ventricular tachycardia during RHC could be consequential requiring interventions. As the improvement of reagents, equipment and techniques, the incidence rate of serious arrhythmias such as ventricular tachycardia/fibrillation during LHC has significantly decreased, but it continues to require constant intra-procedural monitoring and readiness to intervene.

**Research perspectives**
As cardiac catheterization procedure continues to serve as essential diagnostic and therapeutic tool for patients, intra-procedural cardiac arrhythmias occur at relatively low incidence rates. Understanding the types of arrhythmias, associated risk factors and the strategies to monitor and mitigate the risk continue to be essential for patient safety and procedure success. It continues to require close surveillance and exploration of best practice to minimize the risk.

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**REFERENCES**

1. Benjamin EJ, Muntner P, Alonso A, Bittencourt MS, Callaway CW, Carson AP, Chamberlain AM, Chang AR, Cheng S, Dai SR, Delling FN, Djousse L, Elkind MSV, Ferguson JF, Fornage M, Jordan LC, Khan SS, Kissela BM, Knutson KL, Kwan TW, Lackland DT, Lewis TT, Lichtman JH, Longenecker CT, Loop MS, Lutsey PL, Martin SS, Matsushita K, Moran AE, Mussolino ME, O'Flaherty M, Parsley A, Perak AM, Rosamond WD, Roth GA, Sampson UKA, Satou GM, Schroeder EB, Shah SH, Spartanu NL, Stokes A, Tirschwell DL, Tsao CW, Turakhia MP, VanWagner LB, Wilkins JT, Wong SS, Virani SS; American Heart Association Council on Epidemiology and Prevention Statistics Committee and Stroke Statistics Subcommittee. Heart Disease and Stroke Statistics-2019 Update: A Report From the American Heart Association. Circulation 2019; 139: e56-e528 [PMID: 30700139 DOI: 10.1161/CIR.0000000000006591]

2. Damen J, Bolton D. A prospective analysis of 1,400 pulmonary artery catheterizations in patients undergoing cardiac surgery. Acta Anaesthesiol Scand 1986, 30: 386-392 [PMID: 3766094 DOI: 10.1111/j.1399-6576.1986.0034.3]

3. Wennenvelt A, Christiansen I, Lindeneg O. Complications in 4,413 catheterizations of the right side of the heart. Am Heart J 1965; 69: 173-180 [PMID: 14256692 DOI: 10.1016/0002-8703(65)90034-7]

4. Patton RD, Bordia A, Ballantyne F, Ryan GF, Goldstein S, Heinele RA. Bundle-of-He's recording of complete heart block during cardiac catheterization: electrophysiologic documentation of bilateral bundle branch block. Am Heart J 1971; 81: 108-113 [PMID: 5996961 DOI: 10.1016/0002-8703(71)90060-3]

5. Simonson E. Transient right bundle branch block produced by heart catheterization in man. Am Heart J 1951; 41: 217-224 [PMID: 14818934 DOI: 10.1016/0002-8703(51)90101-9]

6. Abernethy WS. Complete heart block caused by the Swan-Ganz catheter. Chest 1974; 65: 349 [PMID: 4813842 DOI: 10.1378/chest.65.3.349]

7. Luck JC, Engel TR. Transient right bundle branch block with “Swan-Ganz” catheterization. Am Heart J 1976; 92: 263-264 [PMID: 941840 DOI: 10.1016/0002-8703(76)80265-7]

8. Ranu H, Smith K, Nimako K, Sheth A, Madden BP. A retrospective review to evaluate the safety of right
heart catheterization via the internal jugular vein in the assessment of pulmonary hypertension. Clin Cardiol 2010; 33: 303-306 [PMID: 20513069 DOI: 10.1002/clc.20770]

9 Stein PD, Mahur VS, Herman MV, Levine HD. Complete heart block induced during cardiac catheterization of patients with pre-existent bundle-branch block. The hazard of bilateral bundle-branch block. Circulation 1966; 34: 783-791 [PMID: 5925651 DOI: 10.1161/01.cir.34.5.783]

10 Morris D, Mulvihill D, Lew WY. Risk of developing complete heart block during bedside pulmonary artery catheterization in patients with left bundle-branch block. Arch Intern Med 1987; 147: 2005-2010 [PMID: 3675106 DOI: 10.1001/archinte.1987.0037010133209]

11 Cheng TO, Bashour T, Kelser GA. Complete heart block occurring during right-heart catheterization in a patient with left bundle-branch-block and prolonged P-R interval studied by bundle of His recording and atrial pacing. Med Ann Dist Columbia 1972; 41: 742-743 [PMID: 4509129]

12 Fishenfeld J, Desser KB, Benchimonial A, Promisloff S. Case studies: heart block during cardiac catheterization—demonstration by His bundle recording and documentation of concealed retrograde A-V nodal conduction. J Electrocardiol 1974; 7: 265-272 [PMID: 4842391 DOI: 10.1016/0022-0756(74)90033-8]

13 Gwak MS, Kim JA, Kim GS, Choi SJ, Ahn H, Lee JJ, Lee S, Kim M. Incidence of severe ventricular arrhythmias during pulmonary artery catheterization in liver allograft recipients. Liver Transplant 2007; 13: 1455-1454 [PMID: 17920132 DOI: 10.1002/ltx2.13000]

14 Damen J. Ventricular arrhythmias during insertion and removal of pulmonary artery catheters. Chest 1985; 88: 190-193 [PMID: 4017671 DOI: 10.1378/chest.88.2.190]

15 Swan HJ, Ganz W, Forrester J, Marcus H, Diamond G, Chonette D. Catheterization of the heart in man with use of a flow-directed balloon-tipped catheter. N Engl J Med 1970; 283: 447-451 [PMID: 5434111 DOI: 10.1056/NEJM197007282830902]

16 Steele P, Davies H. The Swan-Ganz catheter in the cardiac laboratory. Br Heart J 1973; 35: 647-650 [PMID: 4712471 DOI: 10.1136/hrt.35.5.647]

17 Sprung CL, Pozen RG, Rozanski JI, Pinero JR, Eastier BR, Castellanos A. Advanced ventricular arrhythmias during bedside pulmonary artery catheterization. Am J Med 1982; 72: 203-208 [PMID: 7058332 DOI: 10.1016/0002-9345(82)90117-7]

18 Cairns JA, Holder D. Letter: Ventricular fibrillation due to passage of a Swan-Ganz catheter. Am J Cardiol 1975; 35: 589 [PMID: 1119409 DOI: 10.1001/0002-9149.75.9.8046-2]

19 Bergmann L, Grobwendt T, Kahliert P, Konorza T, Wendi D, Thielmann M, Heusch G, Peters J, Kottenberg E. Arrhythmogenic risk of pulmonary artery catheterisation in patients with severe aortic stenosis undergoing transcatheter aortic valve implantation. Anesthesiologia 2013; 68: 46-51 [PMID: 23121437 DOI: 10.1111/anac.12069]

20 Sise MJ, Hollingsworth P, Brimm JE, Peters RM, Virgilio RW, Shackford SR. Complications of the flow-directed pulmonary artery catheter: A prospective analysis in 219 patients. Crit Care Med 1981; 9: 315-318 [PMID: 7214960 DOI: 10.1097/00003246-198104000-00006]

21 Boyd KD, Thomas SJ, Gold J, Boyd AD. A prospective study of complications of pulmonary artery catheterizations in 500 consecutive patients. Chest 1983; 84: 245-249 [PMID: 6884097 DOI: 10.1378/chest.84.3.245]

22 Iberti TJ, Benjamin E, Gruppi L, Raskin JM. Ventricular arrhythmias during pulmonary artery catheterization in the intensive care unit. Prospective study. Am J Med 1985; 78: 451-454 [PMID: 3976703 DOI: 10.1016/0002-9345(85)90337-7]

23 Satoh H, Miyata Y, Hayasaka T, Wada T, Hayashi Y. An analysis of the factors producing multiple ventricular arrhythmias during pulmonary artery catheterization. Am J Cardiol Anas 2017; 20: 141-144 [PMID: 28393771 DOI: 10.4103/aca.ACA_18_17]

24 Southworth JL, McKusick VA, Pierce EC, 2nd, Rawson FL Jr, Hayashi Y. Ventricular fibrillation precipitated by cardiac catheterization; complete recovery of the patient after 45 minutes. J Am Med Assoc 1950; 413: 717-720 [PMID: 15421803 DOI: 10.1001/jama.1950.0291034009003]

25 Voukydis PC, Cohen SI. Catheter-induced arrhythmias. Am Heart J 1974; 88: 588-592 [PMID: 4420638 DOI: 10.1016/0002-8703(74)90242-7]

26 Michel J, Johnson AD, Bridges WC, Lehman JH, Grey F, Field L, Green DM. Catheterization arrhythmias. Am J Med 1950; 8: 526-527 [PMID: 15410741 DOI: 10.1001/0002-9345(50)90242-4]

27 Michel J, Johnson AD, Bridges WC, Lehmann JH, Gray F, Field L, Green DM. Arrhythmias during intracardiac catheterization. Circulation 1950; 2: 240-244 [PMID: 15427211 DOI: 10.1161/01.cir.2.2.240]

28 Pipanmekaporn T, Bunchungmongkol N, Pin on P, Pungsaowawong Y. Impact of patients' positions on the incidence of arrhythmias during pulmonary artery catheterization. J Cardiovasc Anesth 2012; 26: 391-394 [PMID: 22209175 DOI: 10.1053/j.jvca.2011.10.013]

29 Gau GT, Oakley CM, Rahimtoo SL, Raphael MJ, Steiner RE. Selective coronary arteriography. A review of 18 months' experience. Clin Radiol 1970; 21: 275-286 [PMID: 5433646 DOI: 10.1016/0361-813X(70)90045-4]

30 Dorros G, Cowley MJ, Simpson J, Bentivoglio LG, Block PC, Bourassa M, Detre K, Gosselin AJ, Grunzig AR, Kelsey SF, Kent KM, Mullin SM, Myler RK, Passamani ER, Stertzer SH, Williams DO. Percutaneous transluminal coronary angioplasty: report of complications from the National Heart, Lung, and Blood Institute PTCA Registry. Circulation 1983; 67: 723-730 [PMID: 6218938 DOI: 10.1161/01.cir.67.4.723]

31 Addala S, Kahlm JK, Mocca TF, Harjai K, Pellizon G, Ochoa A, O'Neil WW. Outcome of ventricular fibrillation developing during percutaneous coronary interventions in 19,497 patients without cardiogenic shock. Am J Cardiol 2005; 96: 764-765 [PMID: 16169355 DOI: 10.1016/j.amjcard.2005.04.057]

32 Brennan E, Mahur PR, Ashawian VJ. Incidence and presumed etiology of ventricular fibrillation during coronary angioplasty. Am J Cardiol 1991; 67: 769-770 [PMID: 2006630 DOI: 10.1016/0002-9149(91)90539-w]

33 Lembo NJ, King SB, Roubin GS, Black AJ, Douglas JS. Effects of nonionic versus ionic contrast media on complications of percutaneous transluminal coronary angioplasty. Am J Cardiol 1991; 67: 1046-1050 [PMID: 2024591 DOI: 10.1016/0002-9149(91)90863-G]

34 Huang J, Skinner JL, Rogers JM, Smith WM, Holman WL, Ideker RE. The effects of acute and chronic amiodarone on activation patterns and defibrillation threshold during ventricular fibrillation in dogs. J Am Coll Cardiol 2002; 37: 385-383 [PMID: 12106947 DOI: 10.1016/S0735-1097(02)01942-3]

35 Mehta RH, Harjai KJ, Grines L, Stone GW, Boura J, Cox D, O'Neill W, Grines CL. Primary Angioplasty in Myocardial Infarction (PAMI) Investigators. Sustained ventricular tachycardia or fibrillation in the cardiac catheterization laboratory among patients receiving primary percutaneous coronary intervention: WJC https://www.wjgnet.com June 26, 2020 Volume 12 Issue 6
Incidence, predictors, and outcomes. *J Am Coll Cardiol* 2004; 43: 1765-1772 [PMID: 15149097 DOI: 10.1016/j.jacc.2003.09.072]

Har B, Veenehuysen G, Galbraith D, Southern D, Wilton S and Knudtson M. Ventricular Arrhythmia at Primary PCI for ST-elevation myocardial infarction predicts 30-day but not long-term mortality. *JACC* 2017; 69: supp 243 [DOI: 10.1016/S0735-1097(17)3362-X]

Bourassa MG. Noble J. Complication rate of coronary arteriography. A review of 5250 cases studied by a percutaneous femoral technique. *Circulation* 1976; 53: 106-114 [PMID: 1244231 DOI: 10.1161/01.cv.53.1.106]

Vijay NK, Schoomaker FW. Percutaneous preformed single catheter coronary arteriography and its complications--10,000 cases. *Cathet Cardiovasc Diag* 1979; 5: 179-185 [PMID: 487421 DOI: 10.1002/ccd.1810050213]

Nishimura RA, Holmes DR, McFarland TM, Smith HC, Bove AA. Ventricular arrhythmias during coronary angiography in patients with angina pectoris or chest pain syndromes. *Am J Cardiol* 1984; 53: 1496-1499 [PMID: 6311752 DOI: 10.1016/0002-9149(84)90566-2]

Epstein AE, Davis KB, Kay GN, Blumb VJ, Rogers WJ. Significance of ventricular tachyarrhythmias complicating cardiac catheterization: a CASS Registry Study. *Am J Heart* 1990; 119: 494-502 [PMID: 2178371 DOI: 10.1016/0002-8703(89)90270-6]

Ozmen F, Atalar E, Aytemir K, Özer N, Açıl T, Ovınc K, Akşıkely S, Kes S. Effect of balloon-induced acute ischaemia on P wave dispersion during percutaneous transluminal coronary angioplasty. *Europace* 2001; 3: 299-303 [PMID: 11678388 DOI: 10.1016/europ.2001.08.007]

Park E, Price A, Vidovich M. Adenosine-induced atrial fibrillation during fractional flow reserve measurement. *Cathet Cardiovasc Diag* 2012; 19: 650-651 [PMID: 2224932 DOI: 10.1002/ccd.20121]

Patel HR, Shah P, Bajaj S, Virk H, Bikkina M, Shamoof F. Intracoronary adenosine induced ventricular arrhythmias during fractional flow reserve (FFR) measurement: case series and literature review. *Cardiovasc Interv Ther* 2017; 32: 374-380 [PMID: 27577946 DOI: 10.1007/s12928-016-0427-8]

Khan ZA, Akbar G, Saeed W, Malik S, Khan F, Sardar MR. Ventricular fibrillation with intracoronary adenosine during fractional flow reserve assessment. *Cardiovasc Revasc Med* 2016; 17: 487-489 [PMID: 27477304 DOI: 10.1016/j.carrev.2016.07.004]

Shah AH, Chan W, Seidelin PH. Ventricular Fibrillation Precipitated by Intracoronary Adenosine During Fractional Flow Reserve Assessment - A Cautionary Tale. *Heart Lung Circ* 2015; 24: e173-e175 [PMID: 26166173 DOI: 10.1016/j.hlc.2015.05.012]

Nakayama M, Tanaka N, Sakoda K, Hokama Y, Hoshino K, Kimura Y, Ogawa M, Yamashita J, Kobori Y, Uchiyama T, Aizawa Y, Yamashina A, Papaverine-induced polymorphic ventricular tachycardia during coronary flow reserve study of patients with moderate coronary artery disease. *Circ J* 2015; 79: 530-536 [PMID: 25746536 DOI: 10.1255/circj.CJ-14-1118]

Nakayama M, Saito A, Kitazawa H, Takahashi M, Sato M, Fuse K, Okabe M, Hoshino K, Tanaka N, Yamashina A, Aizawa Y. Papaverine-induced polymorphic ventricular tachycardia in relation to QTU and giant T-U waves in four cases. *Intern Med* 2012; 51: 351-356 [PMID: 22333368 DOI: 10.2169/internmed.51.6567]

Talman CL, Winniford MD, Rossen JD, Simonetti I, Kienzle MG, Marcus ML. Polymorphous ventricular tachycardia: a side effect of intracoronary papaverine. *J Am Coll Cardiol* 1990; 15: 275-278 [PMID: 2299607 DOI: 10.1016/0735-1097(90)90845-8]

Kern NJ, Deligonul U, Serota H, Gudapati C, Buckingham T. Ventricular arrhythmia due to intracoronary papaverine: analysis of QT intervals and coronary vasodilatory reserve. *Cathet Cardiovasc Diag* 1990; 19: 229-236 [PMID: 2334953 DOI: 10.1002/ccd.1810940202]

Okabe Y, Otowa K, Mitamura Y, Murai H, Usui S, Kaneko S, Takamura K. Evaluation of the risk factors for ventricular arrhythmias secondary to QT prolongation induced by papaverine injection during coronary flow reserve studies using a 4 Fr angi-catheter. *Eur J Cardiovasc Prev Rehabil* 2009; 16: 217-221 [PMID: 18610276 DOI: 10.1177/1074284709336134]

Tearney GJ, Proctor DN, Kaul S, Wackers FJ, Ahlstrom L, Khandheria BK, Ho SY, Higano S, Gregoire V, Schaff HV, Meier B, Lloyd T, Davis RS, Udvadia J, Takahashi I, Lee D, Yock PG. Ventricular arrhythmias during fractional flow reserve assessment: a report from the International Working Group for Intravascular Optical Coherence Tomography (IWG-IVOCT). Consensus standards for acquisition, measurement, and reporting of intravascular optical coherence tomography studies: a report from the International Working Group for Intravascular Optical Coherence Tomography Standardization and Validation. *J Am Coll Cardiol* 2012; 59: 1058-1072 [PMID: 22421299 DOI: 10.1016/j.jacc.2011.09.079]

Yurtdag M, Kaya Y, Gündilli E. Transradial approach in the diagnosis and treatment of coronary artery disease: a 2-center experience. *Turk J Med Sci* 2014; 44: 666-673 [PMID: 25551940 DOI: 10.3906/sag-1212-93]

Gedela M, Kumar V, Shaikh KA, Stys A, Stys T. Bradycardia during Transradial Cardiac Catheterization due to Catheter Manipulation: Resolved by Catheter Removal. *Case Rep Vasc Med* 2017; 2017: 8538149 [PMID: 28348915 DOI: 10.1155/2017/8538149]

Patel C, Laboy V, Venus B, Mathru M, Wier D. Acute complications of pulmonary artery catheter insertion in critically ill patients. *Crit Care Med* 1986; 14: 195-197 [PMID: 3943335 DOI: 10.1097/00003246-198601000-00005]

Sprung CL, Jacobs LJ, Caralia PV, Karfp M. Ventricular arrhythmias during Swan-Ganz catheterization of the critically ill. *Chest* 1981; 79: 413-415 [PMID: 7229695 DOI: 10.1378/chest.79.4.413]

Keusch DJ, Winters S, Thys DM. The patient's position influences the incidence of dysrhythmias during pulmonary artery catheterization. *Anesthesiology* 1989; 70: 582-584 [PMID: 2929995 DOI: 10.1097/00000542-198904000-00004]

Shaw TJ. The Swan-Ganz pulmonary artery catheter. Incidence of complications, with particular reference to ventricular dysrhythmias, and their prevention. *Anaesthesia* 1979; 34: 651-656 [PMID: 517718 DOI: 10.1111/j.1365-2044.1979.tb04268.x]
Circulation, McKinnon CM, Rösch J, Judkins MP. Complications of selective percutaneous transfemoral angiography. *Circulation* 1968; 5: 213-221 [PMID: 5640580 DOI: 10.1016/0002-8703(68)90062-8].

Ryan TJ. The coronary angiogram and its seminal contributions to cardiovascular medicine over five decades. *Circulation* 2002; 106: 722-726 [PMID: 12163439 DOI: 10.1161/01.cir.0000214919.12686.d4].

Ryan TJ. The coronary angiogram and its seminal contributions to cardiovascular medicine over five decades. *Trans Am Clín Climatol Assoc* 2002; 113: 261-271 [PMID: 12603714 DOI: 10.1161/01.CIR.0000024109.12686.d4].

Leverstad K, Vatne K, Brodal U, Laake B, Simonsen S, Aakhus T. Safety of the nonionic contrast medium omnipaque in coronary angiography. *Cardiovasc Intervent Radiol* 1989; 12: 98-100 [PMID: 2500247 DOI: 10.1007/bf02577398].

Missri J, Jeresaty RM. Ventricular fibrillation during coronary angiography: reduced incidence with nonionic contrast media. *Cathet Cardiovasc Diagn* 1990; 19: 4-7 [PMID: 2306765 DOI: 10.1002/cd.18109101].

Jacobsen EA, Pedersen HK, Klow NE, Refsum H. Cardiac electrophysiology, arrhythmogenic mechanisms and roentgen contrast media. *Acta Radiol Suppl* 1995; 399: 105-114 [PMID: 8610504 DOI: 10.1177/024818519503963913].

Murdoch DK, Johnson SA, Loeb HS, Scanlon PJ. Ventricular fibrillation during coronary angiography: reduced incidence in man with contrast media lacking calcium binding additives. *Catheter Cardiovasc Diagn* 1985; 11: 153-159 [PMID: 3921258 DOI: 10.1002/cd.181010296].

Tomino PA, De Bruyne B, Pijs NH, Siebert U, Ikeno F, van ’t Veer M, Kluss V, Manoharan G, Engstrom T, Oldroyd KG, Ver Lee PN, MacCarthy PA, Fearon WF; FAME Study Investigators. Fractional flow reserve versus angiography for guiding percutaneous coronary intervention. *N Engl J Med* 2009; 360: 213-224 [PMID: 19144937 DOI: 10.1056/NEJMoa080761].

Mallet ML. Proarrhythmic effects of adenosine: a review of the literature. *Emerg Med J* 2004; 21: 408-410 [PMID: 15208219 DOI: 10.1136/emj.2004.016048].

Pijs NH, Sels JW. Functional measurement of coronary stenosis. *J Am Coll Cardiol* 2012; 59: 1045-1057 [PMID: 22432198 DOI: 10.1016/j.jacc.2011.09.077].

Fink RJ, Merrick B, Lowe HM. Mechanism of the bradycardia during coronary angiography. *Am J Cardiol* 1975; 35: 17-22 [PMID: 1109243 DOI: 10.1016/0002-9149(75)90553-6].

Eckberg DL, White CW, Kioschos JM, Abboud FM. Mechanisms mediating bradycardia during coronary angiography. *J Clin Invest* 1974; 54: 1455-1461 [PMID: 4434442 DOI: 10.1172/JCI107893].

Richards KL, Browning JD, Hoekenga DE. Prevention of contrast-induced bradycardia during coronary angiography. *Cathet Cardiovasc Diagn* 1981; 7: 185-190 [PMID: 7028274 DOI: 10.1002/cd.1810070208].

Shimamoto T, Nakata Y, Sumiyoshi M, Ongura S, Takaya J, Sakurai H, Yamaguchi H. Transient left atrioventricular block complicating coronary angiography. *Cathet Cardiovasc Diagn* 1992; 20: 146-149 [PMID: 9559437 DOI: 10.1253/jcj.62.146].

Munsif AN, Schechter E. Complete block below the His bundle induced by left-sided cardiac catheterization in patients without pre-existing conduction abnormalities. *Jpn Circ J* 1998; 62: 146-149 [PMID: 9559437 DOI: 10.1253/jcj.62.146].

Richards KL, Browning JD, Hoekenga DE. Prevention of contrast-induced bradycardia during coronary angiography. *Cathet Cardiovasc Diagn* 1990; 21: 408-410 [PMID: 7028274 DOI: 10.1002/cd.1810070208].

Kuroki M, Ikeda U, Noda T, Hosoda S, Yaginuma T. Complete atrioventricular block induced by left heart catheterization. *Jpn Circ J* 1991; 55: 511-514 [PMID: 1956620 DOI: 10.1253/jcj.32.511].

Murasato Y, Ninomiya K, Imai M, Araki M, Kawasaki I, Iiyashiki H, Abe H, Kuroiwa A. Complete atrioventricular block during left heart catheterization. *Jpn Circ J* 1994; 58: 671-675 [PMID: 7967009 DOI: 10.1253/jcj.58.671].

Brachfeld CA, Marshall J, Volosin KJ, Groh WC. Complete atrioventricular block during cardiac catheterization: two cases reports in patients without pre-existing conduction abnormalities. *Catheter Cardiovasc Diagn* 1990; 20: 126-130 [PMID: 2354513 DOI: 10.1002/cd.1810200213].

McBride W, Hills LD, Lange RA. Complete heart block during retrograde left-sided cardiac catheterization. *Am J Cardiol* 1989; 63: 375-376 [PMID: 2913745 DOI: 10.1016/0002-9149(89)90355-x].

Feit A, Kipperman R, Urseil S, Reddy CV. Complete heart block complicating retrograde left heart catheterization. *Cathet Cardiovasc Diagn* 1990; 20: 131-132 [PMID: 2354513 DOI: 10.1002/cd.1810200214].

Sack JB, MacAlpin R, Gerber R, Gupta VK, Sherman CT, Yeatman L. Complete left heart block complicating retrograde left-heart catheterization of patients with cardiac allografts. *Catheter Cardiovasc Diag* 1992; 26: 219-223 [PMID: 1617715 DOI: 10.1002/cd.1810260311].

Mixon TA, Cross DS, Lawrence ME, Gantt DS, Dehner GJ. Temporary coronary guidewire pacing during percutaneous coronary intervention. *Catheter Cardiovasc Interv* 2004; 61: 494-500; discussion 502-3 [PMID: 15065145 DOI: 10.1002/cdi.20009].

Meier B. Left ventricular pacing for bradycardia in the cardiac catheterization laboratory. *Catheter Cardiovasc Interv* 2004; 62: 31 [PMID: 1503597 DOI: 10.1002/ccd.20033].

Meier B. Emergency pacing during cardiac catheterization: it is all there already. *Catheter Cardiovasc Interv* 2004; 61: 501-502 [PMID: 15065146 DOI: 10.1002/cdi.20033].

Harvey JR, Wyman RM, McKay RG, Baim DS. Use of balloon flotation pacing catheters for prophylactic temporary pacing during diagnostic and therapeutic catheterization procedures. *Am J Cardiol* 1988; 62: 941-948 [PMID: 3021787 DOI: 10.1016/0002-9149(88)90397-7].

McGuire J, Chou TC. Angiography: advantages and hazards. *Am Heart J* 1967; 73: 293-295 [PMID: 6091989 DOI: 10.1016/0002-8703(67)90423-1].

Takaro T, Dart CH, Scott SM, Fish RG, Nelson WM. Coronary arteriography: indications, techniques, complications. *Ann Thorac Surg* 1968; 5: 213-221 [PMID: 5640380 DOI: 10.1016/0003-4975(68)90634-5].

Ross RS, Gorlin R. Cooperative study on cardiac catheterization. Coronary arteriography. *Circulation* 1968; 37: 1167-1173 [PMID: 5640703 DOI: 10.1161/01.circ.37.5s.1167].

Green GS, McKinnon CM, Rösch J, Judkins MP. Complications of selective percutaneous transfemoral coronary arteriography and their prevention. A review of 445 consecutive examinations. *Circulation* 1972; 45: 552-557 [PMID: 5012244 DOI: 10.1161/01.cir.45.3.552].
Shaik FA et al. Arrhythmia during cardiac catheterization

89 Adams DF, Fraser DB, Abrams HL. The complications of coronary arteriography. Circulation 1973; 48: 609-618 [PMID: 4726245 DOI: 10.1161/01.cir.48.3.609]

90 Shah A, Groj J, Fisher VJ. Complications of selective coronary arteriography by the Judkins technique and their prevention. Am Heart J 1975; 90: 353-359 [PMID: 1163425 DOI: 10.1016/0002-8703(75)90325-7]

91 Nitter-Hauge S, Enge I. Complication rates of selective percutaneous transfemoral coronary arteriography. A review of 1094 consecutive examinations. Acta Med Scand 1976; 200: 123-126 [PMID: 785955 DOI: 10.1111/j.0954-6820.1976.tb08206.x]

92 Pridie RB, Booth E, Garrett J, Knight E, Parnell B, Towers MK. Coronary angiography Review of 1500 consecutive cases. Br Heart J 1976; 38: 1200-1203 [PMID: 1008961 DOI: 10.1136/hrt.38.11.1200]

93 Davis K, Kemp HG, Judkins MP, Gosselin AJ, Killip T. Complications of coronary arteriography from the Collaborative Study of Coronary Artery Surgery (CASS). Circulation 1979; 59: 1105-1112 [PMID: 346020 DOI: 10.1161/01.cir.59.6.1105]

94 Lehmann MH. Ventricular fibrillation during coronary arteriography. Am J Cardiol 1985; 55: 248 [PMID: 3966393 DOI: 10.1016/0002-9149(85)90348-0]

95 Murdock DK, Lawless CE, Loeb HS, Furiass JS, Pagano SJ, Scanion PJ. Characterization of ventricular fibrillation during coronary angiography. Am J Cardiol 1985; 55: 249 [PMID: 3966394 DOI: 10.1016/0002-9149(85)90350-9]

96 Arrowood JA, Mullan DF, Kline RA, Engel TR, Kowey PR. Ventricular fibrillation during coronary angiography: the precatheterization QT interval. J Electrocardiol 1987; 20: 255-259 [PMID: 3655597 DOI: 10.1016/0022-0736(87)80024-0]

97 Armstrong SJ, Murphy KP, Wilde P, Hartnell GG. Ventricular fibrillation in coronary angiography: what is the role of contrast medium? Eur Heart J 1989; 10: 892-895 [PMID: 2598945 DOI: 10.1093/oxfordjournals.eurheartj.a059398]

98 Lehmann KG, Chen YC. Reduction of ventricular arrhythmias by atropine during coronary arteriography. Am J Cardiol 1989; 63: 447-451 [PMID: 2916430 DOI: 10.1016/0002-9149(89)90317-2]

99 Huang JL, Ting CT, Chen YT, Chen SA. Mechanisms of ventricular fibrillation during coronary angioplasty: increased incidence for the small orifice caliber of the right coronary artery. Int J Cardiol 2002; 82: 221-228 [PMID: 1191909 DOI: 10.1016/s0167-5273(01)00596-4]

100 Chen J, Gao L, Yao M, Chen J. Ventricular arrhythmia onset during diagnostic coronary angiography with a 5F or 4F universal catheter. Rev Esp Cardiol 2008; 61: 1092-1095 [PMID: 18817680 DOI: 10.1157/13126050]

101 Chen J, Gao LJ, Chen JL, Song HJ. Contemporary analysis of predictors and etiology of ventricular fibrillation during diagnostic coronary angiography. Clin Cardiol 2009; 32: 283-287 [PMID: 19452481 DOI: 10.1002/clc.20394]

102 Nagamoto Y, Fuji Y, Morita Y, Ueda Y, Yamane K, Miyake Y, Fujiwara M, Mito S, Watari Y, Tamekiyo H, Ohmoto T, Murakya Y, Hayashi Y. Ventricular fibrillation followed by the augmentation of Brugada-like electrocardiographic changes caused by ischemia of the conus branch in a patient with coronary artery disease. IHJ Cardiovasc Case Rep (CVCR) 2018; 2: 58-60 [DOI: 10.1016/j.hjccr.2017.12.003]

103 Riede FN, Gutmann M, Meier Y, Leibundgut G. Electrical storm after conus branch occlusion. IHJ Cardiovasc Case Rep (CVCR) 2018; 2: S94-S96 [DOI: 10.1016/j.hjccr.2018.10.003]
