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Systematic Review/Meta-analysis

Right Ventricular Outflow Tract Obstruction in Adults: A Systematic Review and Meta-analysis

Yu Hao Zeng, MD,[a] Alexander Calderone, MD,[a] Nicolas Rousseau-Saine, MD, FRCPC,[a] Mahsa Elmi-Sarabi, PhD,[a] Stéphanie Jarry, MSc,[a] Étienne J. Couture, MD, FRCPC,[b] Matthew P. Aldred, MBBS, FANZCA,[a] Jean-Francois Dorval, MD, FRCPC,[c] Yoan Lamarche, MD, MSc, FRCSC,[d,e] Lachlan F. Miles, MBBS, PhD, FANZCA,[f] William Beaubien-Souligny, MD, PhD, FRCPC,[g] and André Y. Denault, MD, PhD, FRCPC[a,e]

[a] *Department of Anesthesiology, Montreal Heart Institute, Université de Montréal, Montreal, Quebec, Canada*

[b] *Department of Anesthesiology and Department of Medicine, Division of Intensive Care Medicine, Quebec Heart & Lung Institute, Quebec, Quebec, Canada*

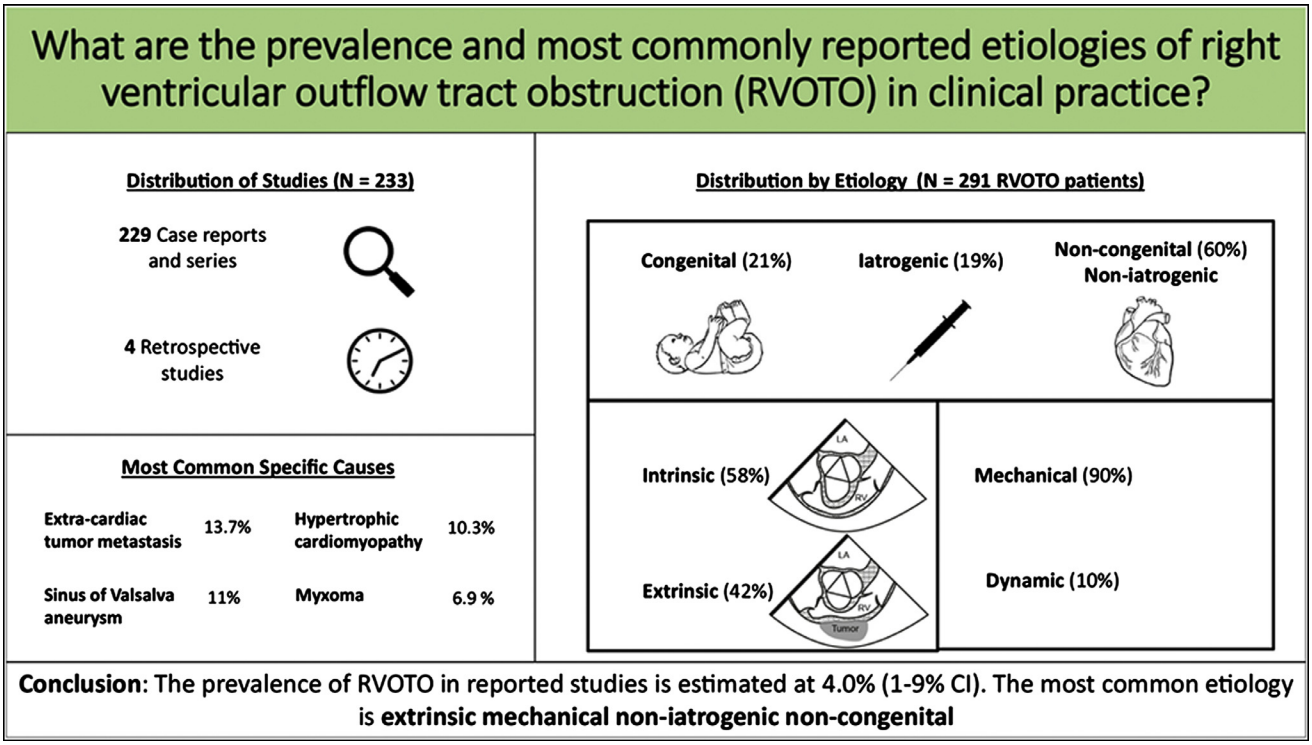
[c] *Department of Cardiology, Montreal Heart Institute, Université de Montréal, Montreal, Quebec, Canada*

[d] *Department of Cardiac Surgery, Montreal Heart Institute, Université de Montréal, Montreal, Quebec, Canada*

[e] *Critical Care Division, Montreal Heart Institute, Université de Montréal, Montreal, Quebec, Canada*

[f] *Department of Critical Care, The University of Melbourne, Melbourne, Victoria, Australia and Department of Anaesthesia, Austin Health, Melbourne, Australia*

[g] *Department of Medicine, Nephrology Division, Centre Hospitalier de l'Université de Montréal, Montreal, Quebec, Canada*



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ABSTRACT

Background: Right ventricular outflow tract obstruction (RVOTO) is a cause of hemodynamic instability that can occur in several situations, including cardiac surgery, lung transplantation, and thoracic surgery, and in critically ill patients. The timely diagnosis of RVOTO is important because it requires specific considerations, including the adverse effects of positive inotropes, and depending on the etiology, the requirement for urgent surgical intervention.

Methods: The objective of this systematic review and meta-analysis was to determine the prevalence of RVOTO in adult patients, and the distribution of all reported cases by etiology.

Results: Of 233 available reports, there were 229 case reports or series, and 4 retrospective cohort studies, with one study also reporting a prospective cohort. Of 291 reported cases of RVOTO, 61 (21%) were congenital, 56 (19%) were iatrogenic, and 174 (60%) were neither congenital nor iatrogenic (including intracardiac tumour). The mechanism of RVOTO was an intrinsic obstruction in 169 cases (58%), and an extrinsic obstruction in 122 cases (42%). A mechanical obstruction causing RVOTO was present in 262 cases (90%), and 29 cases of dynamic RVOTO (10%) were reported. In the 5 included cohorts, with a total of 1122 patients, the overall prevalence was estimated to be 4.0% (1%-9%).

Conclusions: RVOTO, though rare, remains clinically important, and therefore, multicentre studies are warranted to better understand the prevalence, causes, and consequences of RVOTO.

RÉSUMÉ

Contexte : L'obstruction de la chambre de chasse du ventricule droit (OCCVD) est une cause d'instabilité hémodynamique qui peut survenir dans plusieurs situations, y compris une chirurgie cardiaque, une transplantation pulmonaire ou une chirurgie thoracique, ou encore chez des patients en phase critique. Il est important que le diagnostic d'OCCVD soit posé rapidement, car d'une part cette affection exige la prise en compte d'éléments particuliers, y compris les effets indésirables des agents inotropes positifs et, d'autre part, en fonction de l'étiologie, une intervention chirurgicale d'urgence pourrait être nécessaire.

Méthodologie : L'objectif de cette revue systématique associée à une méta-analyse était de déterminer la prévalence de l'OCCVD chez les patients adultes ainsi que la distribution de tous les cas rapportés en fonction de leur étiologie.

Résultats : Sur les 233 rapports disponibles, on comptait 229 études ou séries de cas, et quatre études de cohortes rétrospectives, dont une qui présentait également les résultats d'une cohorte prospective. Sur 291 cas d'OCCVD rapportés, 61 (21 %) étaient d'origine congénitale, 56 (19 %) étaient d'origine iatrogène et 174 (60 %) avaient une origine qui n'était ni congénitale ni iatrogène (dont une tumeur intracardiaque). Le mécanisme de l'OCCVD était une obstruction intrinsèque dans 169 cas (58 %), et une obstruction extrinsèque dans 122 cas (42 %). Une obstruction mécanique causant l'OCCVD était présente dans 262 cas (90 %), et 29 cas d'OCCVD dynamique (10 %) ont été rapportés. Dans les 5 cohortes incluses, comptant au total 1 122 patients, la prévalence globale était estimée à 4,0 % (de 1 % à 9 %).

Conclusions : L'OCCVD, malgré sa rareté, n'en est pas moins importante sur le plan clinique; la réalisation d'études multicentriques serait donc justifiée pour permettre de mieux comprendre la prévalence, les causes et les conséquences de cette affection.

Right ventricular (RV) dysfunction is associated with significant morbidity and mortality, particularly in cardiac surgery.[1-4] These associations could be related to several factors, including venous congestion and cardio-intestinal syndrome.[5,6] An uncommon mechanism of RV dysfunction and elevated right atrial pressure is RV outflow tract obstruction (RVOTO). It is diagnosed by the presence of a systolic pressure gradient between the main pulmonary artery (PA) and the RV outflow tract (RVOT). This obstruction has been defined as hemodynamically significant when the maximal systolic pressure gradient between the RV and the PA is greater than 25 mm Hg.[7] This condition requires urgent treatment when it results in decreased end-organ perfusion from both reduced cardiac output and increased venous congestion.

The diagnosis can be made by imaging (computed tomography [CT] or magnetic resonance), transthoracic echocardiography (TTE), transesophageal echocardiography (TEE), epicardial intraoperative echocardiography, or cardiac catheterization. It can be both diagnosed and monitored continuously using a PA catheter with an RV port capable of simultaneously transducing the RV and PA pressures.[8] There are several etiologies of RVOTO, which can be classified according to their pathophysiological mechanism; some of these are congenital,[9] whereas others are iatrogenic.[10] The mechanism of RVOTO also can be differentiated depending on the location of the obstruction, whether intrinsic[11] or extrinsic[12] to the RVOT, and on the persistence of the phenomenon relative to the timing of the cardiac cycle (dynamic during systole or diastole only or persistent throughout the cardiac cycle).[13]

To our knowledge, no comprehensive review of the prevalence or etiology of RVOTO in adults has been published. We therefore performed a narrative review in order to answer important, related questions: (i) What is the prevalence of RVOTO in the adult population? (ii) What is the distribution of cases of RVOTO according to etiology? and (iii) How can we define RVOTO?

Methods

Study eligibility and search strategy

To be eligible for inclusion, articles had to report at least one case of RVOTO in adult patients and describe its etiology. Only full published reports in English or French were considered. Articles that represented a combination of both pediatric and adult populations were excluded if the authors did not specify the age of the patients with RVOTO.

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Ethics Statement: No consent was required for this study.

Corresponding author: Dr André Y. Denault, Montreal Heart Institute, 5000 Belanger Street, Montreal, Quebec H1T 1C8, Canada. Tel.: +1-514 376-3330; fax: +1-514 376-1355.

E-mail: andre.denault@umontreal.ca

See page 1162 for disclosure information.

Supravalvular and valvular causes of obstruction were excluded from the analysis, and only sub-valvular causes were cumulated. The articles were retrieved via a PubMed search (last accessed on August 15, 2020) with the following keywords: "RVOTO" or "right ventricle outflow tract obstruction" or "right ventricle outflow tract stenosis" with "cardiac surgery" and "adult" in [all fields] or medical subject headings. An advanced search was conducted from the initial simple search by manually modifying the medical subject heading terms to maximize the number of relevant studies found. The PubMed search query and results are detailed in Supplemental Appendix S1. Secondary sources were obtained by manually screening the bibliographies of all articles. Instances in which the primary and secondary sources were used as citations in other articles were examined individually to screen for additional articles.

Data extraction

The etiologies of RVOTO were divided into 3 categories: 1, congenital—caused by a disease or physical abnormality that has been present since birth; 2, iatrogenic—caused by a medical intervention or procedure; 3, non-congenital/non-iatrogenic—caused by a disease or physical abnormality that has not been present since birth and not caused by a medical intervention or procedure. Within each category, the obstruction was classified as either mechanical, if the dimensions of the RVOT remained constant during the cardiac cycle, or dynamic, if the dimensions of the RVOT changed during the cardiac cycle. The cause of obstruction was also classified according to its location. It was defined as "intrinsic"[11] if the origin of the RVOTO arose within the anatomic structure of the RVOT itself, as in hypertrophic cardiomyopathy. It was defined as "extrinsic" if the cause of RVOTO was not related to the normal anatomy of the RVOT, as in an aneurysm of the sinus of Valsalva whereby the RVOT was externally compressed. The number of patients with RVOTO, along with the diagnostic method and moment of diagnosis, were also extracted from each article.

The initial database search and classification of articles were performed by one of the authors (Y.Z.). The entire research methodology was redone a second time by another author (A. C.) in order to identify any discrepancies and articles that may have been missed by the initial review. Differences in etiology classification and in exclusion or inclusion of articles were flagged, and then reviewed by a third author (A.D.). Once these were resolved, a final review was performed by the second author (A.C.). Cohort studies were verified and validated by a fourth author (W.B.). The quality of the retrospective studies used in the meta-analysis was assessed using the National Heart, Lung, and Blood Institute Study Quality Assessment Tools.

Analysis

Data about the prevalence of RVOTO collected from cohort studies were used to conduct a meta-analysis of proportions using the arcsine transformation. Given that there was important clinical and methodological heterogeneity among studies, we calculated pooled proportions and 95% confidence intervals (CIs) using a random effects model. We used inverse variance to weigh each study in the pooled analysis and assessed statistical heterogeneity using I^2 values. We considered a P value < 0.05 to be statistically significant. A subgroup analysis was performed by grouping studies depending on whether they were designed to include only patients at high risk for RVOTO (special population) vs any type of surgery patients. We performed all analyses with R version 3.6.1 (R Core team, Vienna, Austria) using the *metaprop* command from the R package meta version 4.13.[14]

Results

Results from the literature search

Our PubMed search identified a total of 1013 articles on human subjects written in English or French. Of the 1013 articles retrieved, 890 were excluded for one or more of the following reasons: there was no mention of the prevalence or etiology of RVOTO; the articles described an obstruction of either the left ventricular outflow tract or the RV inflow tract; the articles described cases of pulmonary stenosis or obstruction that occurred in a location outside of the RVOT; and the study subjects came from a pediatric population or a mixed adult−pediatric population in which differentiation was impossible.

Following the exclusion process, 124 primary articles in total were retained. A total of 109 articles were retrieved from the bibliographic examination of the 124 retained studies, as well as reverse citation of these primary and secondary sources, resulting in a total of 233 studies, summarized in Supplemental Table S1.[10,15-246] Supplemental Figure S1 describes the search process in a flow diagram.

Description of studies

A total of 291 patients with RVOTO in 233 studies have been reported so far in the medical literature. These patients were retrieved from 209 case reports (89.7%), 20 case series (8.6%), and 4 retrospective studies (1.7%). All case reports and series described an etiology of RVOTO that fell within our predefined classification. All retrospective studies focused on the prevalence of RVOTO, and one report combined a retrospective and a prospective cohort.[122] In these 4 retrospective studies, the populations consisted of a mix of adult and pediatric patients, but the adult cases were distinguished from the pediatric cases.[76,102,164,237]

Table 1 summarizes the etiology distribution and mechanism of reported cases of RVOTO. A total of 174 cases (60%) were non-congenital and non-iatrogenic; 61 (21%) were congenital; and 56 (19%) were iatrogenic. The mechanism of RVOTO was intrinsic in 169 cases (58%) and extrinsic in 122 cases (42%). A mechanical obstruction causing the RVOTO was present in 262 cases (90%), and only 29 cases of dynamic RVOTO (10%) were reported. The subcategories of each types are detailed in Supplemental Table S2.

The non-congenital and non-iatrogenic cases are summarized in Supplemental Table S3. As noted, most of this class of RVOTO cases were related to 71 (41%) primary cardiac tumours, 40 (23%) extracardiac tumours including metastasis or compression, or 32 (18%) cases of

Table 1. Etiology distribution and mechanism of reported right ventricular outflow tract obstruction cases (n = 291)

	Non-congenital and non-iatrogenic (n = 174; 60%)		Congenital (n = 61;21%)		Iatrogenic (n = 56;19%)	
	Intrinsic	Extrinsic	Intrinsic	Extrinsic	Intrinsic	Extrinsic
Mechanical(n = 262)	76 (43.7)	94 (54)	58 (95.1)	1 (1.6)	9 (16)	24 (42.9)
Dynamic(n = 29)	3 (1.7)	1 (0.6)	2 (3.3)	0 (0)	21(38)	2 (3.6)

Values are n (%).

sinus of Valsalva aneurysms (18%). The most common primary cardiac tumours reported were myxomas and PA or trunk neoplasms, representing 28% and 25% of all primary tumours in reported cases, respectively. The most common extracardiac tumours reported were renal cell carcinoma, representing 12.5% of extracardiac tumour compressions.

Congenital cases are described in Supplemental Table S4. Of these 61 cases, 30 (49%) were due to cases of hypertrophic cardiomyopathy, and 15 (25%) were related to a double-chambered right ventricle.

The iatrogenic cases are summarized in Supplemental Table S5. The most common causes were dynamic systolic obliteration associated with vasoactive/ionotropic agent use during surgery in 11 patients, and RVOTO after lung transplantation in 9 patients. Dynamic RVOTO was observed in only 29 cases, much less frequently than mechanical obstruction. Eleven cases of obstruction were worsened by the administration of inotropes or vasoactive agents during surgery,[122] and one occurred during the induction of anesthesia.[223] Most of the other reported cases were observed after lung transplantation (n = 9).[55,61,65,67,70,108,142,231] Two cases occurred as a result of cardiac surgery complications,[134,242] and one case resulted from a postoperative mediastinal hematoma.[66] A single case could be attributed to cardiac catheterization, which iatrogenically precipitated infundibular muscular spasm in a patient with pulmonic stenosis and thus dynamic RVOTO.[10] Six cases were secondary to structures in the heart causing dynamic obstruction solely during systole, with 2 attributed to myxomas,[31,219] 2 due to septal aneurysms,[106,227] and another 2 due to double-chambered right ventricle muscle bundles.[205]

The most frequent overall causes of RVOTO irrespective of etiologic classification are summarized in Table 2. Extracardiac tumour metastasis or compression of the right ventricle was the most common cause found in our study, representing 13.7% of all cases described in this literature review. This cause was followed in frequency by sinus of Valsalva aneurysm (11%), hypertrophic cardiomyopathy (10.3%), myxoma (6.9%), and PA/trunk neoplasm (6.2%). Four reports were made of dual RVOTO and left ventricular outflow tract obstruction.[91,96,133,193]

Definition of RVOTO and diagnostic technique

In the majority of studies analyzed, TTE or TEE (n = 195) were part of the investigational workup for RVOTO. Cardiac catheterization (n = 94) was the second most commonly used investigational modality. Most of the diagnoses were made preoperatively (n = 187). The remaining diagnoses were made intraoperatively (n = 10), during the immediate postoperative period or in the intensive care unit (n = 10), as a contemporaneously distant postoperative diagnosis (n = 25). The majority of studies relied on multiple investigative modalities in order to properly establish the diagnosis of RVOTO (n = 190). Overall, CT scan or CT angiography (n = 79) were more commonly used than cardiac magnetic resonance imaging (n = 57) as complementary forms of investigation to provide confirmation of RVOTO or reveal the extent of the obstruction. In some instances, the investigative workup suggested the diagnosis, or the workup could not be performed and the diagnosis was confirmed on autopsy following the patient's death.[20,27,29,37,57,59,129,243] There were no predetermined echocardiographic diagnostic criteria across the studies. In one study, RVOTO is explicitly defined as a flow velocity of >2.0 m/s (16 mm Hg) on continuous wave Doppler TTE across the RVOT;[102] however, this specific criterion is not universally mentioned in all studies. Intraoperatively, clinically significant RVOTO in the largest study was defined as a gradient >25 mm Hg between the RV and PA systolic pressures, as measured by a PA catheter.[122]

Table 2. Most-frequent overall reported causes of right ventricular outflow obstruction

Etiology and references	Cases, n (% of total cases)
Extracardiac tumour metastasis/compression:	40 (13.7)
19, 23, 27, 29, 32, 37, 40, 45, 49, 52, 54(3), 57, 59(3), 62, 69, 79, 80, 89, 90, 97, 98, 118, 124, 129, 147, 156, 160, 178, 187, 206, 213, 216, 224, 233, 234, 240	
Sinus of Valsalva aneurysm:	32 (11)
21, 35, 39, 41, 46, 56, 60(2), 76, 81, 100, 103, 110, 125, 127, 136, 139, 144, 148, 153, 172, 179, 180, 191, 192, 194, 201, 207, 209, 212, 236, 244	
Hypertrophic cardiomyopathy:	30 (10.3)
51(4), 91, 92, 96, 102(9), 128, 133,152, 164(9), 193, 241	
Myxoma:	20 (6.9)
15, 20, 24, 31, 64, 71, 85, 93, 101, 112, 116, 131, 149, 159, 162, 167, 182, 188, 219, 238	
Pulmonary artery/trunk neoplasm:	18 (6.2)
26(11), 104(2), 111, 130, 137, 161, 225	
Double-chambered right ventricle:	15 (5.2)
88(3), 158(2), 164(2), 181, 190, 203, 205 (2), 214, 228, 245	
Dynamic systolic obliteration associated with vasoactive agent use during surgery:	11 (3.8)
122(11)	

Parenthetical after reference number indicates number of cases within reference.

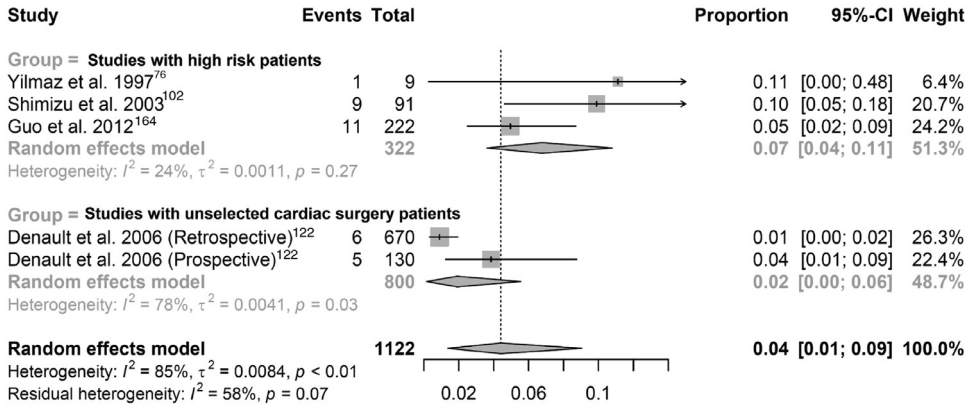

Figure 1. Prevalence of right ventricular outflow tract obstruction in the setting of cardiac surgery. Forest plot of the 4 included studies with 5 cohorts. The prevalence ranged from 1% to 11%, depending on the studied population. Studies were separated based on whether or not they were performed on a specific population. In the 5 included cohorts with a total of 1122 patients, the overall prevalence was estimated to be 4.0% (confidence interval [CI]: 1%-9%). Significant heterogeneity was observed in the included studies (I^2 = 85%).

Prevalence of RVOTO

The prevalence of RVOTO in patients under different conditions was determined in 5 cohorts, with a total number of 1122 patients (Supplemental Table S6). The estimated prevalence from these studies is 4% (1%-9%) with significant statistical heterogeneity (I^2 = 85%; Fig. 1).

In the only study including unselected cardiac surgery patients and using continuous RV and PA pressure monitoring, Denault et al. reported an RVOTO prevalence of 0.9% in the retrospective cohort of 670 patients, and a prevalence of 3.8% in a prospective cohort of 130 patients.[122] The pooled prevalence in these cohorts was 2% (CI: 0%-6%), although significant statistical heterogeneity was found between these cohorts (I^2 = 78%).

The 3 remaining studies had smaller n values, which varied between 9 and 222, and showed the prevalence of RVOTO in particular populations, including patients who had an aneurysm of the sinus of Valsalva (11.1%),[76] patients with hypertrophic cardiomyopathy (9.9%),[102] and patients undergoing corrective surgery for sinus of Valsalva aneurysm (5%).[164] The pooled prevalence in these cohorts, including patients at risk for RVOTO, was 7% (CI: 4%-11%) with moderate statistical heterogeneity (I^2 = 24%).

Methodological quality of studies

The 236 studies included contained diverse methodologies and limitations. A retrospective methodology was used in 235 (99.6%) studies, and only one study (0.4%) used a prospective design exclusively. One of the retrospective studies contained a prospective cohort for validation.[122] Most studies were either case reports or case series (97%), describing 1 to 11 cases. One of the studies was a case series combined with a retrospective cohort; however, for the purpose of our study, it was counted only as a case series.[26] The remaining prospective or retrospective studies reported an n value ranging from 9 to 800. Retrospective studies were evaluated using the National Heart, Lung, and Blood Institute Study Quality Assessment Tools (Supplemental Appendix S2).

Discussion

In this narrative review, we describe 291 patients with RVOTO. In all 233 reports, we determined the cause for RVOTO and classified it by etiology and location. The most commonly reported pathology is neither congenital nor iatrogenic, corresponding to 60% of reported cases. The most common type of RVOTO documented was extrinsic and mechanical, which means it is secondary to a pathology found outside of the RVOT that is physically obstructing the outflow of blood from the RV to the PA. In congenital cases, the most common pathology was hypertrophic cardiomyopathy, in which a thickened myocardium mechanically obstructed the RVOT. Acknowledging that RVOTO is a key pathophysiological finding in several more common congenital cardiopathies characterized by hypoplasia of RV outflow structures (such as a tetralogy of Fallot or certain cases of double outlet right ventricle), it seems likely that this result is in part affected by reporting bias. Indeed, it is more common for physicians to report a rare and unusual case compared to a case presenting as expected. Even though the numbers and proportions should be interpreted with caution, our findings nonetheless reveal that RVOTO can be present in a large variety of congenital heart diseases in an adult population, beyond the most obvious pathologies. With one exception, in which RVOTO happened during induction of anesthesia,[223] most reported cases of iatrogenic RVOTO occurred after either cardiac or thoracic surgery.

The total number of cases of RVOTO during a specific period determines the prevalence. The total number of patients in 4 reported studies is 1122. Given that 3 of these 4 studies focused on specific populations, the prevalence of RVOTO cannot be generalized from these. The remaining study gives a more representative overview of RVOTO in an adult surgery population: Denault et al. reported a cohort of 670 adult patients who underwent intraoperative TEE, and a prospective cohort of 130 patients.[122] In this study, the majority of TEEs were performed in patients in the operating room in a centre specialized for adult cardiac surgery.

There is no clear-cut consensus regarding the definition of RVOTO. The diagnosis can be made with imaging modalities

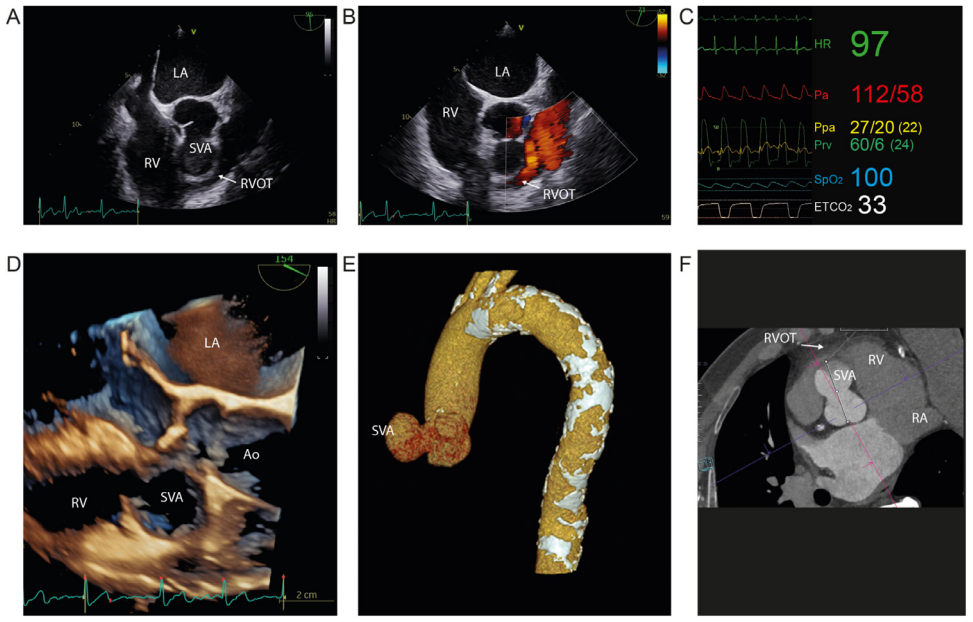

Figure 2. Aneurysm of Valsalva causing right ventricular outflow tract (RVOT) obstruction. (**A**) Mid-esophageal inflow/outflow view with sinus of Valsalva aneurysm (SVA) at the level of the right coronary cusp aneurysm causing an obstruction in the RVOT. (**B**) Note the color Doppler acceleration after the obstruction. (**C**) An intraoperative systolic pressure gradient of 33 mm Hg was observed between the pulmonary artery pressure (Ppa) and the right ventricular pressure (Prv). (**D**) Intraoperative 3-dimensional view of the RVOT. (**E**) Aortic reconstruction and (**F**) computed tomography showing the SVA obstructing the RVOT. (Video 1, view video online.) Ao, aorta; $ETCO_2$, end-tidal carbon dioxide; HR, heart rate; LA, left atrium; Pa, arterial pressure; RA, right atrium; RV, right ventricle; SpO_2, oxygen saturation using pulse oximetry.

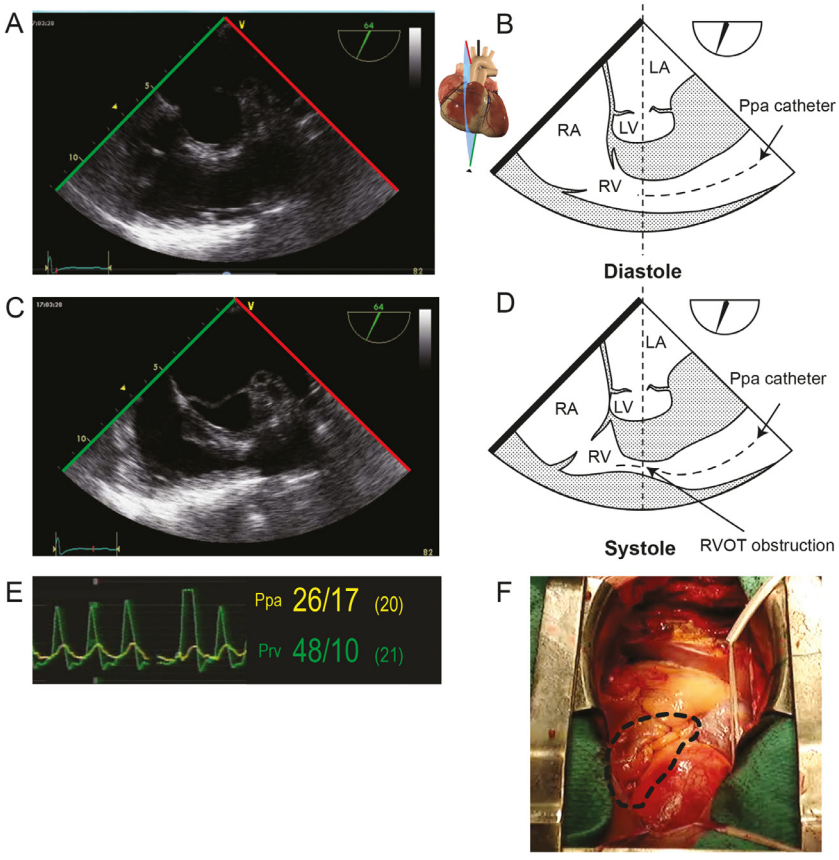

Figure 3. Intrinsic dynamic iatrogenic obstruction of the right ventricular outflow tract (RVOT). Mid-esophageal inflow/outflow views during (**A**, **B**) diastole and (**C**, **D**) systole. Notice the significant decrease in the size of the RVOT tract during systole. (**E**) Systolic pressure gradient of 22 mm Hg between the pulmonary artery pressure (Ppa) and the right ventricular pressure (Prv) across the RVOT. (**F**) Intraoperative aspect of the RVOT obstruction (dotted line). (See Videos 2 and 3, view videos online.) LA, left atrium; LV, left ventricle; RA, right atrium; RV, right ventricle. Reproduced with permission of Taylor and Francis Group, LLC, a division of Informa plc. from Denault et al.[251] © 2018 Taylor and Francis Group.

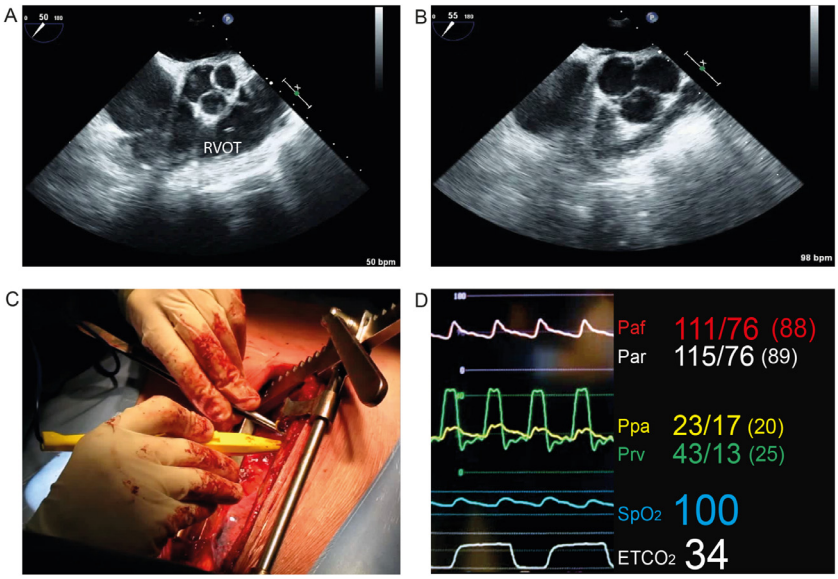

Figure 4. Transient right ventricular outflow tract (RVOT) obstruction during right mammary dissection. Mid-esophageal inflow/outflow view (**A**) before and (**B**) after the beginning of the right mammary dissection. (**C**) The surgical retractor was compressing the RVOT, causing hemodynamic instability and a systolic pressure gradient of 20 mm Hg (**D**) between the pulmonary artery pressure (Ppa) and the right ventricular pressure (Prv). $ETCO_2$, end-tidal carbon dioxide; Paf, femoral arterial pressure; Par, radial arterial pressure; SpO_2, oxygen saturation using pulse oximetry. (Videos 4 and 5, view videos online.)

such as CT, magnetic resonance imaging, TTE, or TEE.[239] Hemodynamic measurements of pressure gradients across the RVOT using catheterization, Doppler echocardiography, or a PA catheter with an RV port can be used (Fig. 2; Video 1, view video online). Dynamic and mechanical RVOTO can be seen in real time intraoperatively (Figs. 3 and 4; Videos 2-5, view videos online). Most of the studies implemented a multimodal approach to confirm and identify the extent of the RVOTO. In the studies we examined, the diagnosis was made during preoperative evaluations, intraoperatively during surgery (Figs. 2-4), postoperatively, in the intensive care unit (Figs. 5-7; Videos 6-9, view videos online) following discharge from surgery, or on autopsy. Hemodynamic measurement of pressure gradients represents the most precise method for RVOTO identification and would allow for identification of the prevalence of this phenomenon when performed in a nonspecific population.

Importance and treatment of RVOTO

It is important to recognize RVOTO and correctly diagnose the underlying pathology in order to implement appropriate management. For example, mechanical RVOTO due to an RV–PA conduit or homograft failure requires specific operative management (either open or percutaneous), as compared to RVOTO due to a dynamic iatrogenic cause. As for a dynamic obstruction, it is typically reported after lung transplantation (Fig. 6). In patients receiving inotropes, the term "suicide RV" has been used to describe the acute onset of dynamic RVOTO.[10,67,231] Kirshbom et al. provided a very convincing hypothesis explaining this phenomenon.[70] Pulmonary allograft candidates often suffer from chronic pulmonary hypertension, leading to structural changes in the heart. As a result, the interventricular septum deviates to the left while the right ventricle dilates and hypertrophies. After lung transplantation, the RV afterload abruptly decreases, and its

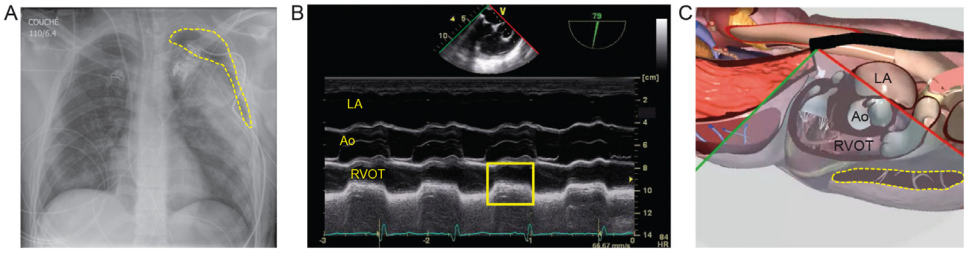

Figure 5. Extrinsic mechanical iatrogenic right ventricular outflow tract (RVOT) obstruction caused by a left-sided tension pneumothorax. (**A**) A left pneumothorax is shown on the chest radiograph. (**B**) Mid-esophageal view of the RVOT on transesophageal echocardiography. A constant diastolic obstruction of the RVOT is present on M-mode. (**C**) The obstruction is caused by compression on the RVOT by the antero-medial portion of the left pneumothorax as shown on the CAE-Vimedix simulator (CAE Healthcare Inc., Montreal, Canada). (See Video 6, view video online.) Ao, aorta; LA, left atrium. Reproduced with permission of Taylor and Francis Group, LLC, a division of Informa plc. from Denault et al.[251] © 2018 Taylor and Francis Group.

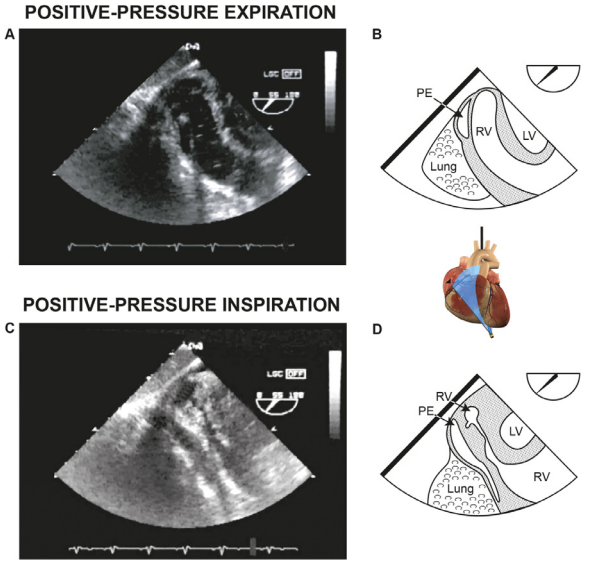

Figure 6. Right ventricular outflow tract (RVOT) obstruction after single lung transplantation. Deep transgastric RVOT views at 55° during (**A, B**) positive-pressure expiration and (**C, D**) inspiration show extrinsic RVOT collapse from positive-pressure ventilation. (See Video 7, view video online.) LV, left ventricle; PE, pericardial effusion; RV, right ventricle. Reproduced with permission of Taylor and Francis Group, LLC, a division of Informa plc. from Denault et al.[251] © 2018 Taylor and Francis Group.

systolic function improves. The septal deviation toward the left resolves, the RV volume decreases, and the hypertrophic right ventricle can predispose to a dynamic RVOTO. This condition can be exacerbated if the patient is exposed to inotropic agents that increase the RV contractility and decrease RV end-systolic volume, further worsening RVOTO. The resulting tachycardia, reduced diastolic filling time, and RV volume could aggravate the RVOTO.[70] In such cases, beta-blockers should be a preferred treatment when RVOTO is noticed, because these medications decrease heart contractility, increase RV volume, and increase diastolic filling time.[247,248] As previously discussed, RVOTO, particularly when dynamic, is likely underdiagnosed in the postoperative cardiac surgery population. This underdiagnosis is a result of the fact that dynamic obstructions are transient (up to 5 minutes), thus rendering their identification difficult without continuous monitoring using a PA catheter, and they are often undetected when using echocardiography alone. Careful positioning of the PA catheter is important because in small patients distal PA position can result in overestimation of an RVOTO (Fig. 8; Video 10, view video online).

The treatment of RVOTO will depend on its etiology. In the case of postsurgical dynamic obstruction, inotrope withdrawal, volume expansion, and the use of beta-blockers or calcium-channel inhibitors should be considered. Mechanical cases will likely require surgical intervention. It is therefore paramount that clinicians be able to detect RVOTO early so

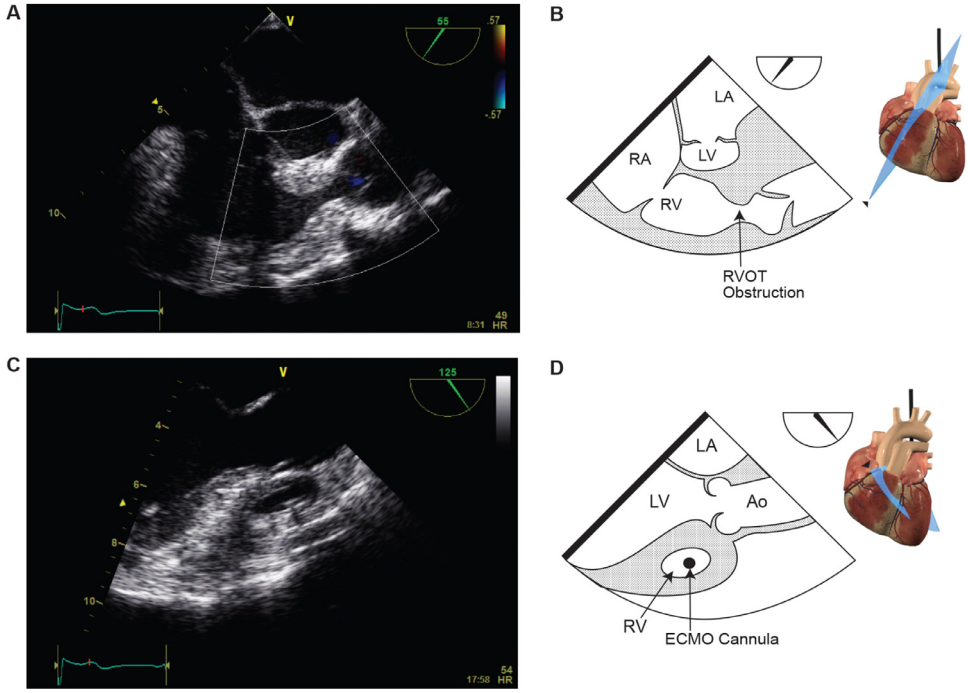

Figure 7. Right ventricular outflow tract (RVOT) obstruction after single lung transplantation. A patient after single lung transplantation requiring extracorporeal membrane oxygenation (ECMO). (**A, B**) The mid-esophageal right ventricular inflow/outflow view shows significant edema causing RVOT obstruction just below the pulmonic valve. (**C, D**) Mid-esophageal long-axis view also shows RVOT obstruction and the ECMO cannula in the RVOT. (See Videos 8 and 9, view videos online.) Ao, aorta; LA, left atrium; LV, left ventricle; RA, right atrium; RV, right ventricle. Courtesy of Dr Jens Lohser from the Vancouver General Hospital; reproduced from Denault et al.[252] with permission of Taylor and Francis Group, LLC, a division of Informa plc. © 2011 Informa Healthcare.

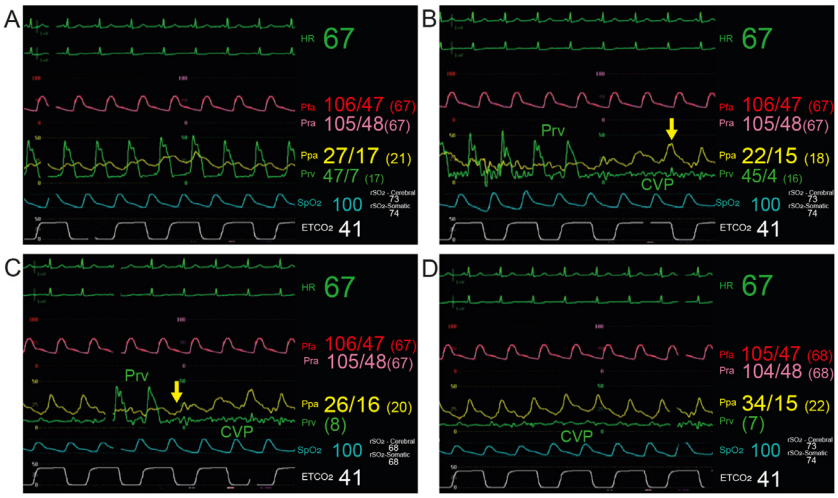

Figure 8. Pseudo right ventricular outflow tract obstruction. Hemodynamic waveforms in a 73-year-old man undergoing revascularization. (**A**) A 20 mm Hg systolic gradient between the right ventricular pressure (Prv) and the pulmonary artery pressure (Ppa) is present. (**B**) Pulling back the pulmonary artery pressure reveals a higher Ppa (**arrow**). (**C**) The lower Ppa (**arrow**) was present with the Prv because the pulmonary artery catheter was damped from a distal position. (**D**) Normal Ppa and central venous pressure (CVP). The maximal systolic gradient between the Ppa and the Prv is 13 mm Hg instead of 20 mm Hg. (See Video 10, view video online.) ETCO2, end-tidal carbon dioxide; HR, heart rate; Pfa, femoral arterial pressure; Pra, radial arterial pressure; rSO2, regional oxygen saturation; SpO2, oxygen saturation using pulse oximetry.

they can further investigate the cause and ultimately treat it according to the etiology. Hemodynamic instability during prone positioning can result from RVOTO as the RVOT is compressed between the spine and sternum.[249,250] Returning the patient to a supine position should relieve the obstruction.

Limitations

There are several limitations to this systematic review. First, most retrieved studies were either case reports or case series with a very small number of patients and are regarded as the lowest-quality form of scientific evidence. Second, because there were so few retrospective studies on RVOTO, the number of articles retrieved on RVOTO in the non-selected adult cardiac and non-cardiac surgery populations was very low. For this reason, estimates of prevalence are limited by the heterogeneity of studies. Third, only one database (PubMed) was searched, and almost half of the articles included in the study were obtained from bibliographies or by using reverse citation, calling into question the appropriateness of the search strategy. However, we still consider it unlikely that high-quality studies on the prevalence and etiology of RVOTO were missed. Finally, the arbitrary definition and stratification of RVOTO as moderate (RV−PA systolic pressure gradient of 6-25 mm Hg) or severe (>25 mm Hg) will require further validation and outcome studies as there is no clear consensus regarding its definition. A currently registered prospective study (NCT04092855) will determine the exact prevalence of RVOTO in cardiac surgical patients.

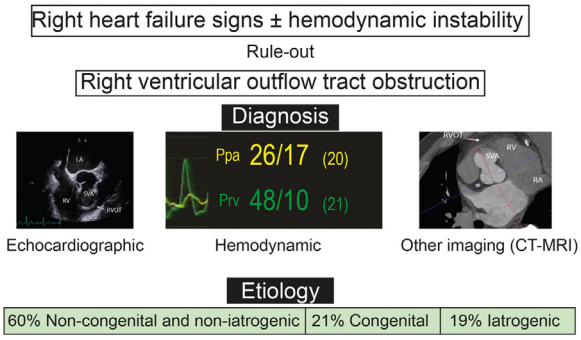

Figure 9. Approach to right ventricular outflow tract obstruction. CT, computed tomography; LA, left atrium; MRI, magnetic resonance imaging; Ppa, pulmonary artery pressure; Prv, right ventricular pressure; RA, right atrium; RV, right ventricle; RVOT, right ventricular outflow tract; SVA, sinus of Valsalva aneurysm.

Conclusion

Cases of RVOTO have been reported mostly in the cardiac surgical population, yet this complication can occur in any patient with predisposing factors (Fig. 9). This review included 291 patients from 233 studies on reported cases of RVOTO. The most common etiology was non-congenital and non-iatrogenic. Most cases of RVOTO were found to be due to causes that were extrinsic and mechanical in nature. A meta-analysis on 5 cohorts suggests that the prevalence of this phenomenon in the adult cardiac surgery population is 4.0%; however, these studies present moderate heterogeneity. Further studies documenting the prevalence of RVOTO using standardized criteria and its association with other clinical factors will help us better understand this uncommon and possibly underreported diagnosis.

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Supplementary Material

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