

ORIGINAL RESEARCH

CONGENITAL HEART DISEASE

COVID-19-Related Thrombotic and Bleeding Events in Adults With Congenital Heart Disease



Flavia Fusco, MD,^a Richard A. Krasuski, MD,^b Soraya Sadeghi, BS,^c Marlon S. Rosenbaum, MD,^d Matthew J. Lewis, MD, MPH,^d Matthew R. Carazo, MD,^e Fred H. Rodriguez 3rd, MD,^e Dan G. Halpern, MD,^f Jodi L. Feinberg, NP,^f Francisca A. Galilea, MD,^g Fernando Baraona, MD,^g Ari M. Cedars, MD,^h Jong M. Ko, BS,^h Prashob Porayette, MD,ⁱ Jennifer R. Maldonado, BS,^j Alexandra A. Frogoudaki, MD, PhD,^j Amiram Nir, MD,^k Anisa Chaudhry, MD,^l Anitha S. John, MD, PhD,^m Arsha Karbassi, MD,ⁿ Javier Ganame, MD, PhD,ⁿ Arvind Hoskoppal, MD, MHS,^o Benjamin P. Frischhertz, MD,^p Benjamin Hendrickson, MD,^q Carla P. Rodriguez-Monserrate, MD,^r Christopher R. Broda, MD,^s Daniel Tobler, MD,^t David Gregg, MD,^u Efrén Martínez-Quintana, MD, PhD,^v Elizabeth Yeung, MD,^w Eric V. Krieger, MD,^x Francisco J. Ruperti-Repilado, MD,^y George Giannakoulas, MD,^z George K. Lui, MD,^{aa} Georges Ephrem, MD, MSc,^{ab} Harsimran S. Singh, MD, MSc,^{ac} Almeneisi Hasan, MD,^{ad} Heather L. Bartlett, MD,^{ae} Ian Lindsay, MD,^{af} Jasmine Grewal, MD,^{ag} Jeremy Nicolarsen, MD,^{ah} John J. Araujo, MD,^{ai} Jonathan W. Cramer, MD,^{aj} Judith Bouchardy, MD,^{ak} Khalid Al Najashi, MD,^{al} Kristi Ryan, NP,^{am} Laith Alshawabkeh, MD,^{an} Lauren Andrade, MD,^{ao} Magalie Ladouceur, MD, PhD,^{ap} Markus Schwerzmann, MD,^{aq} Matthias Greutmann, MD,^{ar} Pablo Merás, MD,^{as} Paolo Ferrero, MD,^{at} Payam Dehghani, MD,^{au} Poyee P. Tung, MD,^{av} Rocio Garcia-Orta, MD, PhD,^{aw} Rose Tompkins, MD,^{ax} Salwa M. Gendi, MD,^{ay} Scott Cohen, MD, MPH,^{az} Scott E. Klewer, MD,^{ba} Sebastien Hascoet, MD,^{bb} Shailendra Upadhyay, MD,^{bc} Stacy D. Fisher, MD,^{bd} Stephen Cook, MD,^{be} Timothy B. Cotts, MD,^{bf} Adrienne H. Kovacs, PhD,^{bg} Jamil A. Aboulhosn, MD,^c Giancarlo Scognamiglio, MD, PhD,^a Craig S. Broberg, MD, MCR,^{bg} Berardo Sarubbi, MD, PhD^a

From the ^aAdult Congenital Heart Disease Unit, Monaldi Hospital, Naples, Italy; ^bDepartment of Cardiovascular Medicine, Duke University Health System in Durham, Durham, North Carolina, USA; ^cAhmanson/UCLA Adult Congenital Heart Center, Los Angeles, California, USA; ^dDivision of Cardiology, Columbia University Medical Center, New York, New York, USA; ^eDivision of Cardiology, Emory University School of Medicine, Atlanta, Georgia, USA; ^fDivision of Cardiology, New York University Langone Health, New York, New York, USA; ^gInstituto Nacional del Tórax - Pontificia Universidad Católica de Chile, Santiago, Chile; ^hDivision of Cardiology, Johns Hopkins University School of Medicine, Baltimore, Maryland, USA; ⁱDivision of Cardiology, University of Iowa Stead Family Children's Hospital, Iowa City, Iowa, USA; ^jSecond Cardiology Department, ATTIKON University Hospital, Athens, Greece; ^kPediatric Cardiology and Adult Congenital Heart Disease Unit, Shaare Zedek Medical Center, Jerusalem, Israel; ^lPenn State Hershey Heart and Vascular Institute, State College, Pennsylvania, USA; ^mDivision of Cardiology, Children's National Hospital, Washington, District of Columbia, USA; ⁿMcMaster University, Hamilton, Ontario, Canada; ^oUPMC Adult Congenital Heart Disease Program, Pittsburgh, Pennsylvania, USA; ^pDivision of Cardiovascular Medicine, Vanderbilt University Medical Center, Nashville, Tennessee, USA; ^qLe Bonheur Heart Institute, University of Tennessee Health Science Center, Memphis, Tennessee, USA; ^rDepartment of Cardiology, Boston Children's Hospital, Boston, Massachusetts, USA; ^sDepartment of Pediatrics, Baylor College of Medicine, Houston, Texas, USA; ^tDivision of Cardiology, University Hospital of Basel, Basel, Switzerland; ^uDivision of Cardiology, Medical University of South Carolina, Charleston, South Carolina, USA; ^vCardiology Service, Universitario Insular-Materno Infantil, Las Palmas de Gran Canaria, Spain; ^wColorado's Adult and Teen Congenital Heart Program, Colorado University School of Medicine, Aurora, Colorado, USA; ^xDivision of Cardiology, University of Washington School of Medicine, Seattle, Washington, USA; ^yDivision of Cardiology, University Hospital Geneva, Geneva, Switzerland; ^zCardiology Department, AHEPA University Hospital, Thessaloniki, Greece; ^{aa}Division of Cardiovascular Medicine and Pediatric Cardiology, Stanford University School of Medicine, Stanford, California, USA; ^{ab}Krannert Cardiovascular Research Center, Indiana University School of Medicine, Indianapolis, Indiana, USA; ^{ac}Department of Medicine & Pediatrics, Weill Cornell Medicine, New York Presbyterian Hospital, New York, New York, USA; ^{ad}The Heart Institute, Cincinnati Children's Hospital Medical Center, Cincinnati, Ohio, USA; ^{ae}Department of Pediatrics and Medicine, University of Wisconsin, Madison, Wisconsin, USA; ^{af}Division of Pediatric Cardiology, University of Utah, Salt Lake City, Utah, USA; ^{ag}St. Paul's Hospital, University of British Columbia, Vancouver, British Columbia, Canada; ^{ah}Department of Pediatric and Adult Cardiology, Providence Adult and Teen Congenital Heart Program, Spokane, Washington, USA; ^{ai}Department of Pediatric and Adult Congenital Heart Disease, Somer Incare Cardiovascular Center, Rionegro, Colombia; ^{aj}Division of Cardiovascular Medicine, University of Nebraska Medical Center, Omaha, Nebraska, USA; ^{ak}Department of Cardiology and Cardiac Surgery, University Hospital Lausanne, Lausanne, Switzerland; ^{al}Pediatric Cardiology Department, Prince Sultan Cardiac Center, Riyadh, Saudi Arabia; ^{am}Adult Congenital

**ABBREVIATIONS
AND ACRONYMS****ACHD** = adult congenital heart disease**ARDS** = acute respiratory distress syndrome**DVT** = deep venous thrombosis**ECMO** = extracorporeal membrane oxygenation**ICU** = intensive care unit**MI** = myocardial infarction**PE** = pulmonary embolism**TE** = thromboembolic events**ABSTRACT**

BACKGROUND Altered coagulation is a striking feature of COVID-19. Adult patients with congenital heart disease (ACHD) are prone to thromboembolic (TE) and bleeding complications.

OBJECTIVES The purpose of this study was to investigate the prevalence and risk factors for COVID-19 TE/bleeding complications in ACHD patients.

METHODS COVID-19-positive ACHD patients were included between May 2020 and November 2021. TE events included ischemic cerebrovascular accident, systemic and pulmonary embolism, deep venous thrombosis, myocardial infarction, and intracardiac thrombosis. Major bleeding included cases with hemoglobin drop >2 g/dL, involvement of critical sites, or fatal bleeding. Severe infection was defined as need for intensive care unit, endotracheal intubation, renal replacement therapy, extracorporeal membrane oxygenation, or death. Patients with TE/bleeding were compared to those without events. Factors associated with TE/bleeding were determined using logistic regression.

RESULTS Of 1,988 patients (age 32 [IQR: 25-42] years, 47% male, 59 ACHD centers), 30 (1.5%) had significant TE/bleeding: 12 TE events, 12 major bleeds, and 6 with both TE and bleeding. Patients with TE/bleeding had higher in-hospital mortality compared to the remainder cohort (33% vs 1.7%; $P < 0.0001$) and were in more advanced physiological stage ($P = 0.032$) and NYHA functional class ($P = 0.01$), had lower baseline oxygen saturation ($P = 0.0001$), and more frequently had a history of atrial arrhythmia ($P < 0.0001$), previous hospitalization for heart failure ($P < 0.0007$), and were more likely hospitalized for COVID-19 ($P < 0.0001$). By multivariable logistic regression, prior anticoagulation (OR: 4.92; 95% CI: 2-11.76; $P = 0.0003$), cardiac injury (OR: 5.34; 95% CI: 1.98-14.76; $P = 0.0009$), and severe COVID-19 (OR: 17.39; 95% CI: 6.67-45.32; $P < 0.0001$) were independently associated with increased risk of TE/bleeding complications.

CONCLUSIONS ACHD patients with TE/bleeding during COVID-19 infection have a higher in-hospital mortality from the illness. Risk of coagulation disorders is related to severe COVID-19, cardiac injury during infection, and use of anticoagulants. (JACC Adv 2023;2:100701) © 2023 The Authors. Published by Elsevier on behalf of the American College of Cardiology Foundation. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Heart Program, OSF Healthcare Children's Hospital of Illinois, Peoria, Illinois, USA; ^{a11}Department of Cardiovascular Medicine, University of California-San Diego, La Jolla, California, USA; ^{a12}Division of Cardiology, Hospital of University of Pennsylvania, Philadelphia, Pennsylvania, USA; ^{a13}Adult Congenital Heart Disease Unit, Hôpital Européen Georges Pompidou, AP-HP, Université de Paris Cité, Paris, France; ^{a14}Center for Congenital Heart Disease, University Hospital Inselspital, Bern, Switzerland; ^{a15}Department of Cardiology, University of Zurich, Zurich, Switzerland; ^{a16}Cardiology Department, University Hospital La Paz, Madrid, Spain; ^{a17}Cardiovascular Department, ASST Papa Giovanni XXIII, University of Milano, Bergamo, Italy; ^{a18}Prairie Vascular Research Network, University of Saskatchewan, Regina, Saskatchewan, Canada; ^{a19}Division of Adult Congenital Heart Disease, University of Texas at Houston, Houston, Texas, USA; ^{a20}Cardiology Department, Hospital Universitario Virgen de las Nieves, Granada, Spain; ^{a21}The Geurin Family Congenital Heart Program, Cedars-Sinai Medical Center, Los Angeles, California, USA; ^{a22}Adult Congenital Heart Disease Program, West Virginia University, Morgantown, West Virginia, USA; ^{a23}Adult Congenital Heart Disease Program, Medical College of Wisconsin, Milwaukee, Wisconsin, USA; ^{a24}Division of Cardiology, University of Arizona, Tucson, Arizona, USA; ^{a25}Department of Pediatric Cardiology and Congenital Heart Disease, Hôpital Marie Lannelongue, Le Plessis Robinson, France; ^{a26}Division of Pediatric Cardiology, Connecticut Children's Medical Center, Hartford, Connecticut, USA; ^{a27}Department of Medicine and Pediatrics, University of Maryland School of Medicine, Baltimore, Maryland, USA; ^{a28}Adult Congenital Heart Center, Helen DeVos Children's Hospital, Grand Rapids, Michigan, USA; ^{a29}Department of Medicine and Pediatrics, University of Michigan Medical School, Ann Arbor, Michigan, USA; and the ^{a30}Knights Cardiovascular Institute, Oregon Health & Science University, Portland, Oregon, USA.

The authors attest they are in compliance with human studies committees and animal welfare regulations of the authors' institutions and Food and Drug Administration guidelines, including patient consent where appropriate. For more information, visit the [Author Center](#).

Initial experience with novel COVID-19 demonstrated an association with thrombotic and hemorrhagic complications, with an adverse impact on the disease course.¹ Adults with congenital heart disease (ACHD) are a potentially vulnerable group inherently prone to thrombosis and/or bleeding. We previously demonstrated that ACHD patients who do poorly with COVID-19 have a higher physiological stage severity,² a metric that reflects heart failure, valve dysfunction, arrhythmias, or symptoms. Given the ongoing persistence of global COVID-19, there is an opportunity to describe the impact of COVID-19-related coagulation disorders in the complex ACHD population in order to provide the best treatment. Therefore, we aimed to describe the prevalence of thromboembolic and bleeding complications associated with COVID-19 infection in ACHD patients and identify factors associated with these complications.

METHODS

STUDY DESIGN AND INCLUSION CRITERIA. The current study was conducted as part of an international, multicenter, retrospective cohort study on acute outcomes from COVID-19 infection among ACHD patients.² Collaborators from ACHD centers globally participated after approval by local ethics oversight. Informed consent was waived given the nature of the study design. Oregon Health and Science University served as the online data coordinating center, using a secure data collection tool (REDCap). Data analysis for the present substudy was performed at Monaldi Hospital, Naples, Italy.

Eligible patients met the following inclusion criteria for enrollment: known diagnosis of congenital heart disease (CHD), age 18 years or older at enrollment, and COVID-19 diagnosis. Patients with a presumptive diagnosis were also included from areas with high disease incidence, where local guidelines at the beginning of the pandemic recommended considering positive those with highly suggestive symptoms during the early phases of the pandemic due to the lack of testing availability. Patients with no diagnosis of CHD were excluded.

DATA COLLECTION. All consecutive patients meeting the inclusion criteria were recruited at local ACHD center from the beginning of COVID-19 pandemic until November 2021, when enrollment was closed. For each patient, comprehensive clinical data were retrospectively obtained from existing medical records by researchers at each center. Data included cardiac diagnoses, comorbidities, previous interventions and most recent outpatient vital signs, laboratory and echocardiographic findings. Specific

information regarding previous indications for anticoagulation or antiplatelet therapy and current medications were collected. Details of the COVID-19 infection diagnosis and disease course were also recorded. Severe viral infection was defined as need for intensive care unit (ICU) admission, endotracheal intubation for mechanical ventilation, acute respiratory distress syndrome, renal replacement therapy, need for extracorporeal membrane oxygenation, or death. No protected patient identifiers were collected, including dates. Additional details on study design and data collection have been previously published.² Data were reviewed at the data coordinating center for internal consistency. All inconsistencies and outliers were flagged, and queries were sent to local investigators for confirmation or correction. Anatomic classification and physiological stage were designated according to the 2018 American College of Cardiology/American Heart Association on ACHD.³

ENDPOINT. The study endpoints were COVID-19 coagulation disorders, defined as occurrence of a thromboembolic (TE) or bleeding event either clinically evident or subclinical events detected with appropriate tests during disease course or within 4 weeks from diagnosis, which is the recognized cutoff to define “long COVID”.⁴ TE events included ischemic cerebrovascular accident/transient ischemic attack, systemic embolism, pulmonary embolism (PE), deep venous thrombosis (DVT), myocardial infarction (MI), or intracardiac thrombosis. Ischemic cerebrovascular accidents, PE, DVT, and intracardiac thrombosis were diagnosed with appropriate imaging tests, and MI was defined according to the fourth universal definition of MI.⁵ Bleeding episodes were considered major if they fulfilled the International Society on Thrombosis and Haemostasis criteria, specifically a hemoglobin drop >1.24 mmol/L (2 g/dl), bleeding necessitating hospitalization or interventions, requirement of ≥ 2 units of packed red blood cell transfusion, bleeding in critical sites (intracranial, intraspinal, intraocular, pericardial, intra-articular, intramuscular with compartment syndrome), or fatal bleeding.

STATISTICAL ANALYSIS. Patients identified as having TE/bleeding were compared to those without either event. Statistical analysis was carried out using R version 4.0.5. Data normality was assessed by Shapiro-Wilk testing. Continuous variables were reported as mean \pm SD or median (IQR) according to data distribution. Comparisons between groups were assessed with Student *t*-test or Wilcoxon rank-sum test. Categorical variables were presented as

frequencies (percentage of total). Differences in proportions were evaluated with chi-square testing. ORs with 95% CIs were determined using binary logistic regression to examine the association between risk factor exposure and coagulation disorder. Variables with >20% missing values were excluded. All predictors with a univariate P value <0.10, as well as the clinically relevant variables, were included in a multivariable model, after which stepwise backward selection based on Bayesian Information Criteria was allowed to determine the best-fit model. To test collinearity between variables included in the same model, variance inflation factors were calculated; values close to 1 were considered as absence of collinearity. A value of $P < 0.05$ was considered statistically significant for all tests.

RESULTS

STUDY POPULATION. A total of 59 CHD centers contributed to the study. Of 2,135 submitted patients, 1,988 (median age 32 [IQR: 25-42] years, 47% male) met full inclusion criteria and were used in the analysis. Of these, 1,686 (84%) had a positive polymerase chain reaction for SARS-CoV-2. The cohort included a broad representation of the spectrum of CHD anatomic complexity and physiological stage. A breakdown by anatomic classification is shown (Supplemental Table 1). Of the total, 235 (12%) had Fontan circulation and 48 (2%) had Eisenmenger physiology. From the total cohort, 281 (14%) were on antiplatelet therapy, and 197 (10%) were prescribed anticoagulation. Indications for anticoagulation/antiplatelet therapy before COVID-19 and type of medications prescribed during infection are summarized in Supplemental Table 2.

THROMBOEMBOLISM/BLEEDING EVENTS. Overall, 30 (1.5%) patients (median age 35.5 [IQR: 24.7-50] years, 50% male) had an event meeting criteria for TE/bleeding. This included 12 patients with a TE event, 12 with major bleeding, and 6 patients who experienced both. Patients with TE/bleeding included 8 with repaired tetralogy of Fallot, 4 with a repaired ventricular septal defect, 4 Fontan patients, 3 with a systemic right ventricle, and 2 with partial anomalous venous return, as well as single patients with pulmonary atresia, Eisenmenger, Ebstein's, bicuspid aortic valve, subaortic stenosis, atrial septal defect, atrioventricular septal defect, Shone's, and heterotaxy. Nineteen (63%) had a history of atrial arrhythmia, and 13 (43%) were on anticoagulants before infection.

As expected, coagulation disorders were almost always detected in hospitalized patients. Of those

with TE/bleeding, 24 (80%) were hospitalized, and 19 (63%) were admitted in the ICU. Among all hospitalized patients, combined TE/bleeding incidence was 8.1%, and 18.6% among those were admitted to ICU. In particular, 4.7% of hospitalized patients and 10.7% of ICU patients had a TE event, and similarly, 3.7% and 9.8% had major bleeding in hospital and in ICU, respectively.

TE events included 6 patients with DVT, 5 with PE, 3 with systemic emboli, 4 with cerebral ischemia, and 1 with mechanical prosthesis thrombosis. Major bleeding complications reported were brain hemorrhages in 4, massive hemoptysis in 1, retroperitoneal bleeding in 1, vaginal bleeding in 1, and gastrointestinal bleeding requiring transfusion in 2. In addition, 9 patients experienced minor bleeding episodes. Ten out of the 30 patients (33%) died from COVID-19, and in 4 of these cases, the ultimate cause of death was either a TE or bleeding complications.

Main baseline demographic and clinical data in those with and without TE/bleeding are shown in Table 1. Patients with coagulation disorders had similar age, sex, and body mass index compared to the group without these events. Anatomic complexity was not associated with TE/bleeding, whereas advanced physiological stage was associated (NYHA functional class 3-4; $P = 0.032$). Patients with events had high NYHA functional class and lower oxygen saturation prior to infection. A higher proportion of patients with TE/bleeding had a history of atrial arrhythmia, previous hospitalization for heart failure, known coronary artery disease, and need for anticoagulation or antiplatelet therapy. There was no difference in hemoglobin, liver, or renal function between the groups.

CLINICAL COURSE OF INFECTION WITH OR WITHOUT COAGULATION DISORDERS.

Clinical events and laboratory findings during COVID-19 infection were compared between those with or without TE/bleeding (Table 2). Overall, 44 patients (2.2%) died due to COVID-19-related complications. Those with TE/bleeding were more likely to be hospitalized, more likely to be placed in intensive care, had a longer hospital stay, more frequent arrhythmias, and more often required antiviral therapy, among all other indicators of severe disease. Liver and renal function laboratory tests were worse. Cardiac injury, defined in agreement with the fourth universal definition of MI,⁵ was demonstrated by increased troponin values and was reported in only 55 patients (2.7% among all hospitalized patients), but was more common among those with TE/bleeding. Patients

TABLE 1 Baseline Demographic and Clinical Data in the Study Population and Stratified According to the Occurrence of Thromboembolism or Bleeding Events

| | All (N = 1,988) | Thromboembolism or Bleeding Events (n = 30) | No Events (n = 1,958) | P Value |
|---|--------------------|---|--------------------------|-------------------|
| Age (y) | 32 (25-42) | 35.5 (24.7-50) | 32 (25-42) | 0.36 |
| Male | 929 (47%) | 15 (50%) | 914 (47%) | 0.46 |
| Weight (Kg) | 73.5 (63-89) | 66 (50-81.8) | 73.8 (63-89) | 0.12 |
| Height (cm) | 167 (160-175) | 162 (160-169.2) | 167 (160-175) | 0.052 |
| Body mass index (kg/m ²) | 25.9 (23-30.8) | 25.0 (22.1-27.6) | 26.0 (22.9-30.8) | 0.41 |
| Smoking/vaping | 231 (12%) | 4 (20%) | 227 (12%) | 0.64 |
| Anatomic complexity | | | | |
| I | 319 (16%) | 7 (23%) | 312 (16%) | 0.83 |
| II | 1,050 (53%) | 13 (43%) | 1,037 (53%) | |
| III | 619 (31%) | 10 (33%) | 609 (32%) | |
| Physiopathological stage | | | | 0.032 |
| A | 490 (25%) | 10 (33%) | 480 (25%) | |
| B | 707 (35%) | 7 (23%) | 700 (36%) | |
| C | 658 (33%) | 10 (33%) | 648 (33%) | |
| D | 116 (6%) | 3 (10%) | 113 (6%) | |
| Unknown | 17 (0.03%) | | 17 (0.8%) | |
| Systemicrightventricle | 265 (13%) | 3 (10%) | 259 (13%) | 0.21 |
| Eisenmenger syndrome | 48 (2%) | 1 (5%) | 47 (2%) | 0.36 |
| Fontan palliation | 235 (12%) | 4 (13%) | 231 (12%) | 1.00 |
| Cyanosis | 158 (8%) | 4 (13%) | 154 (8%) | 0.75 |
| Oxygen saturation (%) | 97 (96-99) | 94 (94-96.5) | 97 (96-99) | 0.0001 |
| NYHA functional class | | | | |
| I | 1,052 (53%) | 3 (10%) | 1,049 (54%) | 0.001 |
| II | 569 (29%) | 1 (3%) | 568 (29%) | |
| III | 170 (8%) | 12 (40%) | 158 (8%) | |
| IV | 22 (1.1%) | 9 (30%) | 13 (0.7%) | |
| Unknown | 175 (9%) | 5 (16%) | 170 (9%) | |
| History of atrial arrhythmia | 461 (23%) | 19 (63%) | 442 (22.5%) | <0.0001 |
| Indication for anticoagulation | 197 (10%) | 13 (43%) | 184 (9%) | <0.0001 |
| Previous antiplatelet therapy | 281 (14%) | 13 (43%) | 268 (14%) | <0.0001 |
| History of ventricular tachycardia | 204 (10%) | 6 (20%) | 198 (10%) | 0.07 |
| PMK/ICD | 277 (13%) | 4 (13%) | 273 (14%) | 0.85 |
| Mechanical prosthetic valve | 198 (10%) | 6 (20%) | 192 (10%) | 0.06 |
| Previous endocarditis | 99 (5%) | 2 (6%) | 97 (5%) | 0.82 |
| Pulmonary arterial hypertension | 135 (7%) | 3 (10%) | 134 (7%) | 0.38 |
| Previous hospitalization for HF | 169 (8.5%) | 9 (30%) | 160 (8%) | 0.0007 |
| Diabetes | 110 (5%) | 1 (3%) | 109 (6%) | 0.47 |
| Previous coronary artery disease | 36 (1.8%) | 3 (15%) | 33 (1.6%) | <0.0001 |
| Systemic ventricle systolic function | | | | |
| Normal | 1,635 (82%) | 20 (66%) | 1,615 (83%) | 0.36 |
| Mildly reduced | 179 (9%) | 5 (17%) | 174 (9%) | |
| Moderately reduced | 77 (4%) | 3 (10%) | 74 (4%) | |
| Severely reduced | 7 (0.4%) | 2 (7%) | 5 (0.2%) | |
| Unknown | 90 (4.5%) | | 90 (4.5%) | |
| Baseline subpulmonary ventricle systolic function | | | | |
| Normal | 998 (50%) | 15 (50%) | 983 (50%) | 0.53 |
| Mildly reduced | 221 (11%) | 10 (33%) | 211 (11%) | |
| Moderately reduced | 102 (5%) | 5 (17%) | 97 (5%) | |
| Severely reduced | 19 (0.9%) | 0 | 19 (0.9%) | |
| Unknown | 648 (33%) | | 648 (33%) | |
| At least moderate valvular disease | 645 (32%) | 4 (20%) | 641 (32%) | 0.25 |

Values are median (IQR) or n (%). **Bold** indicate statistically significant values.
 HF = heart failure; ICD = implantable defibrillator cardioverter; PMK = pacemaker.

TABLE 2 COVID-19 Infection Data in the Study Population and Stratified According to the Occurrence Thromboembolism or Bleeding Events

| | All (N = 1,988) | Thromboembolism or Bleeding Events (n = 30) | No Events (n = 1,958) | P Value |
|-------------------------------------|-------------------------------|---|--------------------------|--------------------|
| Pregnancy | 58 (3%) | 1 (3%) | 57 (3%) | 1.00 |
| Hospital admission | 293 (15%) | 24 (80%) | 269 (14%) | <0.0001 |
| Length of in-hospital stay (d) | 7 (3-13) | 13 (10-18) | 6 (3-12) | 0.0008 |
| Cardiac injury | 55 (2.7%) | 11 (55%) | 44 (2.2%) | <0.0001 |
| New arrhythmia | SVT→39 (1.9%) VT→18 (0.9%) | 5 (16%) 6 (20%) | 34 (1.7%) 12 (0.6%) | <0.0001 <0.0001 |
| ICU | 102 (5%) | 19 (63%) | 83 (4.2%) | <0.0001 |
| Mechanical ventilation | 58 (2.9%) | 15 (50%) | 43 (2.1%) | <0.0001 |
| ARDS | 50 (2.5%) | 13 (43%) | 37 (1.8%) | <0.0001 |
| ECMO | 9 (0.4%) | 7 (23%) | 2 (0.1%) | <0.0001 |
| CRRT | 18 (0.9%) | 8 (26%) | 10 (0.5%) | <0.0001 |
| Death | 44 (2.2%) | 10 (30%) | 34 (1.7%) | <0.0001 |
| Severe disease | 121 (6%) | 19 (63%) | 102 (5.2%) | <0.0001 |
| COVID-19 treatment | 238 (12%) | 14 (47%) | 224 (11%) | <0.0001 |
| Antibiotic | 166 (8%) | 10 (33%) | 156 (8%) | <0.0001 |
| Anti-inflammatory drugs | 79 (4%) | 5 (16%) | 74 (4%) | 0.001 |
| Antiviral/anti-SARS-CoV-2 spike IgG | 86 (4%) | 4 (13%) | 82 (4%) | 0.012 |
| Convalescent/hyperimmune plasma | 7 (0.3%) | 2 (6%) | 5 (0.2%) | <0.0001 |
| Anticoagulation | 243 (12%) | 22 (73%) | 221 (5.2%) | <0.0001 |
| Peak creatinine (mg/dl) | 1 (0.8-1.3) | 1.6 (0.83-1.9) | 1 (0.8-1.2) | 0.033 |
| GFR (ml/min) | 49.8 (43.5-63.2) | 30.4 (22.9-39.2) | 55.7 (41.2-70.7) | 0.0006 |
| ALT (U/L) | 31 (22-47) | 33 (20-48.5) | 29 (19-50) | 1.00 |
| AST (U/L) | 29 (19-50) | 39 (26-58.5) | 30 (22-46) | 1.00 |
| Total bilirubin (mg/dl) | 0.9 (0.5-1.3) | 1.5 (1-2.2) | 0.8 (0.5-1.2) | 0.002 |
| BNP (upper level of normal) | 1.5 (0.8-6) | 2.56 (1.76-8.22) | 1.34 (0.86-5.8) | 0.011 |
| WBC (*1,000 u/L) | 7.4 (5.1-11) | 13.6 (8-18.3) | 7.2 (5.09-10.5) | 0.0001 |
| CRP (mg/L) | 14.5 (3.646) | 66 (11.3-119.5) | 13.3 (2.75-43.1) | 0.002 |
| Platelets (*1,000 u/L) | 194 (133-260) | 110 (79-216) | 200 (139-262) | 0.004 |

Values are n (%) or median (IQR). **Bold** indicate statistically significant values.
ALT = alanine transaminase; ARDS = acute respiratory distress syndrome; AST = aspartate transaminase; BNP = brain natriuretic peptide; CRP = C-reactive protein; CRRT = continuous renal replacement therapy; ECMO = extracorporeal membrane oxygenation; GFR = glomerular filtration rate; ICU = intensive care unit; IgG = immunoglobulin G; WBC = white blood cells.

with TE/bleeding had higher in-hospital mortality compared to the remainder of the cohort (33% vs 1.7%, $P < 0.0001$). Further details on history, antithrombotic treatment, and clinical course during COVID-19 for those with coagulopathic events are presented in the [Supplemental Table 3](#).

Factors related to the course of COVID-19 disease that were significant univariate predictors of TE/bleeding included hospital admission, development of new supraventricular (defined as new onset of sustained atrial fibrillation/flutter/tachycardia) and ventricular tachycardia (defined as new onset of sustained ventricular tachycardia), and all the indices of severe disease such as need for intubation or mechanical support ([Table 3](#)).

FACTORS ASSOCIATED WITH THROMBOEMBOLISM OR BLEEDING. By univariate logistic regression, factors significantly associated with TE/bleeding included advanced physiological stage, NYHA

functional class, previous atrial arrhythmia, previous antiplatelet therapy, previous indication for anticoagulant therapy, anticoagulant use during COVID-19, presence of a mechanical valve prosthesis, history of coronary artery disease, and previous hospital admission for heart failure ([Table 3](#)). Results of univariate analysis for thrombotic and bleeding events alone are shown in [Supplemental Tables 4 and 5](#).

On multivariable analysis, previous indication to anticoagulation (OR: 4.92; 95% CI: 2-11.76; $P = 0.0003$), cardiac injury (OR: 5.34; 95% CI: 1.98-14.76; $P = 0.0009$), and severe COVID-19 (OR: 17.39; 95% CI: 6.67-45.32; $P < 0.0001$) were independently associated with increased risk of bleeding and/or thrombosis ([Table 3, Central Illustration](#)). When repeating the multivariable analysis with the exclusion of 302 with presumptive COVID-19 diagnosis, the results were confirmed.

DISCUSSION

To our knowledge, this is the first study addressing the risks for and impact of COVID-19-related coagulation disorders in ACHD. In our population of 1,988 patients, TE, or bleeding occurred in 1.5% of the total cases and was associated with higher morbidity and in-hospital mortality. Risks for coagulation disorders identified herein are of interest. Disease complexity was not associated with TE/bleeding, but NYHA functional class and more advanced physiological stage were univariate predictors of the outcome. Those with events had more often been hospitalized for heart failure prior to infection, yet did not differ by echocardiographic report of ventricular function. Cyanosis was not a discriminator, but baseline oxygen saturation was lower in those with coagulopathy. Noticeably, 20% of patients with endpoint events showed both thrombotic and bleeding complications, suggesting that those events have overlapping pathogenesis. Importantly, coagulation disorders were more prevalent in patients taking anticoagulants or antiplatelet therapy prior to infection, as well as in conditions related to these therapies such as prior atrial arrhythmia, mechanical valves, and coronary artery disease. Interestingly, previous use of anticoagulant agents, cardiac injury, and severe COVID-19 were all independently associated with increased risk of bleeding and/or thrombosis. When analyzing risk factors for TE or bleeding events alone, prior indication to anticoagulation remained associated to both outcome events.

Concern for coagulopathic events was raised early on in the COVID-19 pandemic. TE complications as well as gastrointestinal bleeding were both associated with increased in-hospital mortality in COVID-19 patients.^{6,7} Altered coagulation has been plausibly related to multiple mechanisms. A pronounced inflammatory response causing a cytokine storm seemed to play a role, which, coupled with direct endothelial injury by viral invasion and blood stasis evoked Virchow’s triad triggering a systemic prothrombotic state and facilitating bleeding.⁸ A systematic review of 42 studies enrolling 8,271 COVID-19 patients during the first pandemic wave found a 5% incidence of TE events and 31% among ICU patients.⁷ In an international multicenter study involving roughly 1 million individuals with COVID-19, the 90-day cumulative incidence of venous thromboembolism was approximately 1% overall and 4.5% for hospitalized patients, with higher incidence in patients >65 years of age.⁹ Bleeding rates were reported to be 4.8% overall and 7.6% in critically ill patients.¹⁰ The findings stimulated the implementation of numerous ongoing clinical

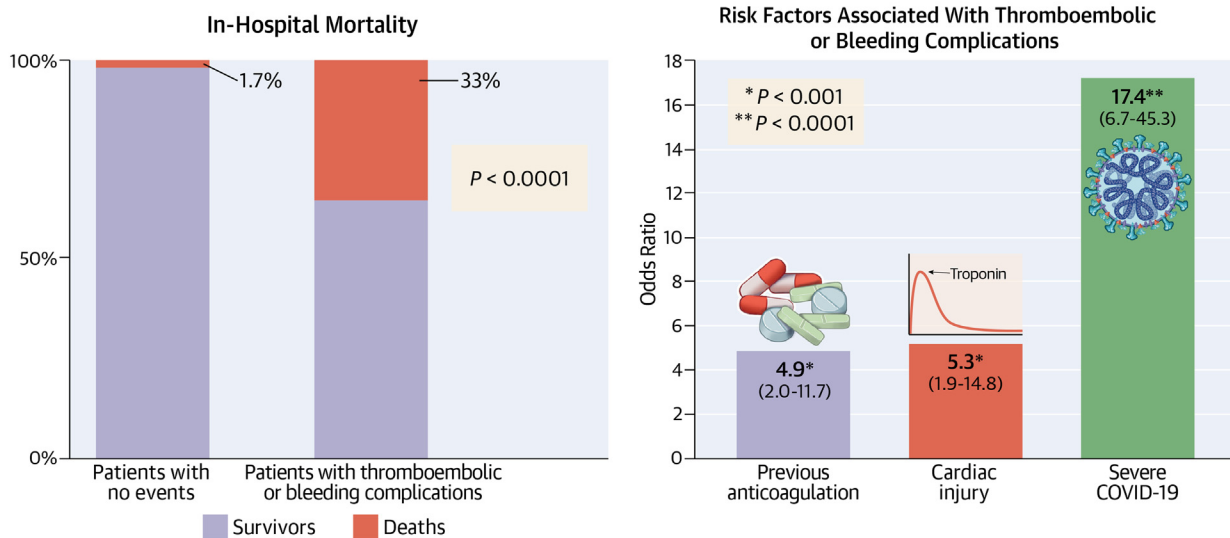
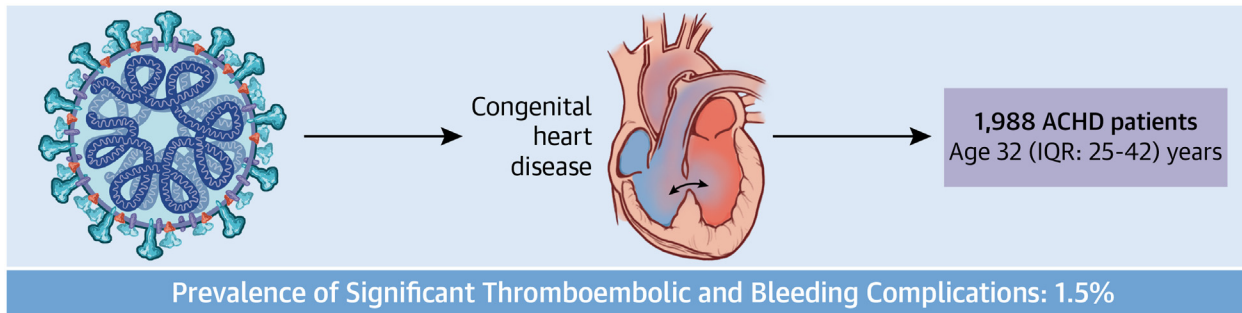
TABLE 3 Risk Factors for the Occurrence of Thromboembolism/Bleeding Events in the ACHD Population

| | OR (95% CI) | P Value |
|--|--------------------|-------------------|
| Age | 1.01 (0.99-1.04) | 0.12 |
| Male | 1.12 (0.54-2.30) | 0.74 |
| Oxygen saturation | 0.98 (0.96-1.00) | 0.26 |
| Physiological class | 2.59 (1.09-2.59) | 0.001 |
| NYHA functional class III-IV | 3.49 (1.62-7.20) | 0.009 |
| Baseline atrial fibrillation | 5.92 (2.48-12.96) | <0.0001 |
| History of ventricular tachycardia | 2.16 (0.79-5.04) | 0.094 |
| Previous indication to anticoagulation | 5.5 (2.50-11.58) | <0.0001 |
| Anticoagulation during COVID-19 | 18.25 (7.89-49.56) | <0.0001 |
| Previous antiplatelet therapy | 2.3 (1.11-4.80) | 0.025 |
| Mechanical valve | 2.77 (1.08-6.20) | 0.016 |
| Congestive heart failure admission | 4.96 (2.12-10.70) | <0.0001 |
| Coronary artery disease | 6.48 (1.49-19.50) | 0.003 |
| New supraventricular arrhythmia | 11.6 (3.7-30.0) | <0.0001 |
| New ventricular tachycardia | 37.4 (12.2-103.5) | <0.0001 |
| Hospitalization | 24.1 (10.4-65.6) | <0.0001 |
| Duration of hospitalization | 1.03 (1.00-1.06) | 0.029 |
| Cardiac injury | 31.1 (13.8-69.6) | <0.0001 |
| ICU | 36.3 (17.0-81.2) | <0.0001 |
| Mechanical ventilation | 51.86 (23.1-118.2) | <0.0001 |
| ARDS | 46.7 (20.6-106.1) | <0.0001 |
| ECMO | 165.1 (40.8-825.1) | <0.0001 |
| CRRT | 84.7 (28.6-253.2) | <0.0001 |
| Severe COVID-19 | 36.7 (17.1-83.8) | <0.0001 |
| Multivariable analysis | | |
| Previous indication to anticoagulation | 4.92 (2.00-11.76) | 0.0003 |
| Cardiac injury | 5.34 (1.98-14.76) | 0.0009 |
| Severe COVID-19 | 17.39 (6.67-45.32) | <0.0001 |

Bold indicate statistically significant values.
 ARDS = acute respiratory distress syndrome; CRRT = continuous renal replacement therapy; ECMO = extracorporeal membrane oxygenation; ICU = intensive care unit.

trials to establish the optimal thromboprophylactic management of COVID-19 patients. Waiting for additional trial data, the American Society of Hematology guideline panel suggested the routine administration of heparin in critically ill COVID-19 patients,¹¹ while the International Society on Thrombosis and Haemostasis recommended therapeutic anticoagulation even in selected hospitalized noncritical ill patients.¹² Nevertheless, despite these measures and improved treatment regimens overall, the burden of TE remained unaltered between the first and second waves of the pandemic.¹³

Many ACHD patients, such as those with Fontan palliation or cyanosis, are generally considered at risk for coagulopathic disorders. Certain conditions may present a unique interplay of multiple risk factors that impact coagulation. These include atypical flow patterns causing stasis of blood, the presence of prosthetic materials that may be prothrombotic, chronic hepatic congestion that may impact clotting factor production, a higher incidence

CENTRAL ILLUSTRATION COVID-19 Related Coagulation Disorders in ACHD Patients

Fusco F, et al. JACC Adv. 2023;2(10):100701.

Among 1,988 COVID-19 positive ACHD patients with median age of 32 (IQR: 25-42) years the incidence of coagulopathy was 1.5% and was associated with significantly higher risk of death (bottom left panel). Previous indication to anticoagulation, cardiac injury during infection and COVID-19 severity were independently associated to the risk of coagulation disorders (bottom right panel, OR and 95% CI are reported inside the bars of the bar graph). ACHD = adult patients with congenital heart disease.

of supraventricular arrhythmias,¹⁴ or cyanosis with compensatory erythrocytosis. Persistent shunts may also predispose to paradoxical systemic embolic events such as stroke.¹⁵ Furthermore, patients with univentricular physiology and Fontan palliation, or with Eisenmenger syndrome are known to have paradoxical vulnerability to both thrombotic and hemorrhagic diathesis, likely due to altered platelet function, endothelial dysfunction, and deranged coagulation factor production.¹⁶⁻¹⁸ In turn, coagulopathies themselves may have devastating detrimental effects on the global hemodynamics of ACHD patients. Therefore, COVID-19-related coagulation disorders seem particularly concerning in this vulnerable population.

Our data found the incidence of TE/bleeding events during COVID-19 among ACHD patients to be harmonious with previous reports in the general population.^{1,6,7,10,11} Yet, despite the overall low prevalence in our large cohort, the absolute burden of COVID-19 coagulation disorders may be high when considering the large number of ACHD patients worldwide, many of whom have the risk factors we identified. Alteration of coagulation is a strong marker of poor outcome in COVID-19; in our ACHD cohort, in-hospital mortality was significantly higher among those who experienced coagulation disorders compared to those with no coagulopathy. While it is impossible to know whether coagulation disorders were more prevalent simply due to being more

detectable in hospitalized patients rather than a direct cause of poor outcome, in 4/10 patients dying with coagulopathic changes, the cause of death was the TE/bleeding event, highlighting its potential devastating effects. Moreover, our data may potentially be helpful for early identification of ACHD patients at higher risk to develop TE/bleeding events during the course of infection. Although severe COVID-19 was the strongest predictor of coagulopathy in our ACHD cohort, multivariable logistic regression showed that baseline indication for anticoagulation was associated with increased risk of coagulation disorders independently from COVID-19 severity, suggesting that particular attention should be paid to the management of COVID-19-positive ACHD patients under this medication.

It could be argued that a switch in anticoagulation therapy during infection could represent a confounding factor in our analysis. Nevertheless, it should be noted that, for most patients with TE, previous oral anticoagulant therapy was upgraded to heparin infusion with possibility of a closer follow-up of coagulation parameters (ie, activated partial thromboplastin time measurement). While multiple confounders are likely to play a role in these associations, the data show patients on anticoagulation had a higher risk of events, though this is purely observational. Anticoagulation is extensively used in the ACHD population to prevent TE events, independently from risk scores commonly used in the population with acquired heart disease.¹⁹ Use of these medications is likely an indirect indicator of disease severity and preexisting vulnerability to coagulation issues.

The most consistent hemostatic abnormalities described in COVID-19 in the general population include thrombocytopenia²⁰ and increased D-dimer levels.²¹ C-Reactive protein, among others, has been found to be associated with death or thrombosis in COVID-19 patients²² and has been proposed as a useful biomarker to follow disease course.²³ Unfortunately, despite significant differences of platelets and C-reactive protein values between groups, the role of biomarkers could not be assessed in the logistic regression analysis due to the amount of missing laboratory data in our cohort, reflecting the fact that many patients with mild infections did not receive laboratory testing.

Ideally, global vaccination campaigns could lead to significant improvements in overall risk by both preventing infection and reducing severity of the subsequent disease course. Early data have shown COVID-19 vaccine safety in the ACHD population.^{24,25} However, further data are required to ascertain whether routine COVID-19 vaccination may reduce

the risk of TE/bleeding in the ACHD population. In addition, it is interesting to point out that current data suggest that only partial protection may be achieved through vaccination against newer variants,²⁶ which have also been involved in increased thrombotic risk.²⁷ Incomplete immunization may also lead to potentially persistent intermittent outbreaks.²⁸ Moreover, early administration of antiviral therapy in susceptible individuals may also have an impact on TE/bleeding events. In our population, the higher proportion of patients treated with antiviral therapy in the group with events may be influenced by the more severe infection course in these patients. Further, occult TE has been suspected even in patients with only mild disease, which is a substantial proportion of cases.^{29,30} Therefore, the cases we identified may be only the most severe, meaning that the real burden of coagulopathy in the ACHD population is likely much greater than realized.

STUDY LIMITATIONS. Our study is limited by its retrospective design, including a highly heterogeneous population. Furthermore, all patients in our study were followed by ACHD-specialized tertiary centers. Consequently, the study was susceptible to referral bias and could include more complicated ACHD patients and/or worse COVID-19 infections. Yet our cohort represents a wide sample of the ACHD spectrum. The impact of COVID-19 coagulopathy in patients who were infected but did not seek care through participating ACHD clinics could not be determined. Asymptomatic individuals represented only a fraction of cases in our cohort, whereas they are said to be much higher in the general population (up to one-third or more). Due to the retrospective nature of the study, routine laboratory or imaging tests were not performed in all patients leading to a potential underestimation of event rate. Our risk factor analysis was limited by our relatively low number of cases and missing data; therefore, potential effects of confounding were more difficult to explore. Our population was skewed towards younger ages, and the potential effects of age could not be determined. Hospitalization greatly enhances detection and reporting of events, and thus the associations we found during disease course are expected to be influenced by significant confounding. For example, endotracheal intubation could trigger significant inflammatory mediators and alter coagulation independently of viral effects. Thus, it is difficult to fully ascertain the cause-and-effect relationship between coagulation events and outcomes. In addition, our study focused on short-term effects and did not explore potential medium- and long-term

complications from COVID-19 coagulopathy. COVID-19 vaccination has been rarely implicated in the development of an immune-mediated prothrombotic case.³¹ Despite early data suggesting a moderate safety of COVID-19 vaccination in ACHD patients,^{24,25} an increased thrombotic risk from the vaccination could not be excluded in our study due to absence of data on the vaccination status in our population. Nevertheless, most cases occurred before availability of vaccines, and 21 out of 30 (70%) patients with COVID-19 coagulopathy were infected before COVID-19 vaccination, while 4 (13%) were infected early after vaccine approval and were most likely unvaccinated. For the remaining 16% of patients who had a thrombotic/bleeding complication, date of infection was not available. Moreover, the effects of different viral variants on the risk of coagulopathy could not be determined in our study. Considering current worldwide infection and vaccination numbers, a probable transition to a new phase of COVID-19 from pandemic to endemic disease, with more and less virulent variants, has been postulated.³² Thus, the clinical features of the disease will likely be constantly changing. Despite all these limits, to the best of our knowledge, this is the first study to investigate the impact of COVID-19 coagulation disorders in a large ACHD population with an international multicenter study.

CONCLUSIONS

ACHD patients are prone to COVID-19-related coagulation disorders, which are associated with higher in-hospital mortality. Our data may allow identification of an ACHD population at higher risk of events requiring strict monitoring: patients with previous indications for anticoagulation, cardiac injury, and severe COVID-19 displayed the highest risk. Anticoagulation therapies were not protective in this observational study. Our results suggest value in maintaining vigilance for coagulation disorders due to COVID-19 in ACHD patients and supporting the implementation of preventive measures in this population including aggressive vaccination efforts.

ACKNOWLEDGEMENTS The authors gratefully acknowledge several collaborators and centers who contributed to the study but were not included in the authorship list due to our administrative oversight. Their important contribution to the study should nevertheless be recognized along with other authors. These include the following individuals and programs: Mikael Dellborg, Adult Congenital Heart Unit, Sahlgrenska University Hospital, and Department of

Molecular and Clinical Medicine, Sahlgrenska Academy, University of Gothenburg, Gothenburg, Sweden; Paul Khairy, Adult Congenital Heart Disease Center, Montreal Heart Institute, Montreal, Canada; Lina Gumbiene and Lina Kapleriene, Cardiac and Vascular Diseases, Faculty of Medicine, Institute of Clinical Medicine, Vilnius University, Vilnius, Lithuania; Saurabh Rajpal, The Ohio State University and Nationwide Children's Hospital, Columbus, Ohio, USA; Massimo Chessa, MD, PhD, ACHD Unit - Centro di Cardiologia Pediatrica e del Congenito Adulto, IRCCS-Policlinico San Donato, San Donato Milanese, Milano, Italy; Danielle Massarella, Peter Munk Cardiac Centre, University Health Network, Toronto, Ontario, Canada; Shabnam Mohammadzadeh, Tehran University of Medical Sciences, Tehran, Iran; and Pooja Gupta, Children's Hospital of Michigan, Central Michigan University, Detroit, Michigan, USA.

FUNDING SUPPORT AND AUTHOR DISCLOSURES

The authors have reported that they have no relationships relevant to the contents of this paper to disclose.

ADDRESS FOR CORRESPONDENCE: Dr Berardo Sarubbi, Adult Congenital Heart Disease Unit, Monaldi Hospital, Via Leonardo Bianchi, 80131 Naples, Italy. E-mail: berardo.sarubbi@ospedalideicolli.it.

PERSPECTIVES

COMPETENCY IN MEDICAL KNOWLEDGE:

Coagulation disorders in ACHD patients are associated to raise in-hospital mortality and morbidity risk.

COMPETENCY IN PATIENT CARE: Particular attention should be paid for prevention and timely recognition of coagulation disorders in ACHD patients with risk factors. Use of anticoagulation during COVID-19 does not seem to reduce the risk, although our findings are purely observational. Our data may allow identification of ACHD patients at higher risk of developing coagulation disorders during COVID-19 infection.

TRANSLATIONAL OUTLOOK 1: Long-term effects from COVID-19 thrombosis in survivors of ACHD patients should be explored with a prospective study.

TRANSLATIONAL OUTLOOK 2: Randomized controlled trial, despite significant difficulties, may provide definite data on the role of anticoagulation during COVID-19 infection in ACHD patients.

REFERENCES

1. Bikdeli B, Madhavan MV, Jimenez D, et al. Global COVID-19 Thrombosis Collaborative Group, Endorsed by the ISTH, NATF, ESVM, and the IUA, supported by the ESC Working Group on Pulmonary Circulation and Right Ventricular Function. COVID-19 and thrombotic or thromboembolic disease: implications for prevention, antithrombotic therapy, and follow-up: JACC state-of-the-Art review. *J Am Coll Cardiol*. 2020;75(23):2950-2973.
2. Broberg CS, Kovacs AH, Sadeghi S, et al. COVID-19 in adults with congenital heart disease. *J Am Coll Cardiol*. 2021;77(13):1644-1655.
3. Stout KK, Daniels CJ, Aboulhosn JA, et al. 2018 AHA/ACC guideline for the management of adults with congenital heart disease: a report of the American College of Cardiology/American Heart Association Task Force on Clinical Practice Guidelines. *J Am Coll Cardiol*. 2019;73(12):e81-e192.
4. COVID-19 Rapid Guideline: Managing the Long-Term Effects of COVID-19. National Institute for Health and Care Excellence (NICE); 2020.
5. Thygesen K, Alpert JS, Jaffe AS, et al. Fourth universal definition of myocardial infarction (2018). *J Am Coll Cardiol*. 2018;72(18):2231-2264.
6. Trindade AJ, Izard S, Coppa K, et al. Gastrointestinal bleeding in hospitalized COVID-19 patients: a propensity score matched cohort study. *J Intern Med*. 2021;289(6):887-894.
7. Malas MB, Naazie IN, Elsayed N, Mathlouthi A, Marmor R, Clary B. Thromboembolism risk of COVID-19 is high and associated with a higher risk of mortality: a systematic review and meta-analysis. *EClinicalMedicine*. 2020;29:100639.
8. Leentjens J, van Haaps TF, Wessels PF, Schutgens REG, Middeldorp S. COVID-19-associated coagulopathy and antithrombotic agents-lessons after 1 year. *Lancet Haematol*. 2021;8(7):e524-e533.
9. Burn E, Duarte-Salles T, Fernandez-Bertolin S, et al. Venous or arterial thrombosis and deaths among COVID-19 cases: a European network cohort study. *Lancet Infect Dis*. 2022;22(8):1142-1152.
10. Al-Samkari H, Karp Leaf RS, Dzik WH, et al. COVID-19 and coagulation: bleeding and thrombotic manifestations of SARS-CoV-2 infection. *Blood*. 2020;136(4):489-500.
11. Cuker A, Tseng EK, Nieuwlaar R, et al. American Society of Hematology 2021 guidelines on the use of anticoagulation for thromboprophylaxis in patients with COVID-19. *Blood Adv*. 2021;5(3):872-888.
12. Schulman S, Sholzberg M, Spyropoulos AC, et al. ISTH guidelines for antithrombotic treatment in COVID-19. *J Thromb Haemost*. 2022;20(10):2214-2225. <https://doi.org/10.1111/jth.15808>
13. Kaptein FHJ, Stals MAM, Grootenboers M, et al. Incidence of thrombotic complications and overall survival in hospitalized patients with COVID-19 in the second and first wave. *Thromb Res*. 2021;199:143-148.
14. Bouchardy J, Therrien J, Pilote L, et al. Atrial arrhythmias in adults with congenital heart disease. *Circulation*. 2009;120(17):1679-1686.
15. Lanz J, Brophy JM, Therrien J, Kaouache M, Guo L, Marelli AJ. Stroke in adults with congenital heart disease: incidence, cumulative risk, and predictors. *Circulation*. 2015;132(25):2385-2394.
16. Heidendaal JF, Engele LJ, Bouma BJ, et al. Coagulation and anticoagulation in Fontan patients. *Can J Cardiol*. 2022;38(7):1024-1035.
17. Broberg C, Ujita M, Babu-Narayan S, et al. Massive pulmonary artery thrombosis with haemoptysis in adults with Eisenmenger's syndrome: a clinical dilemma. *Heart*. 2004;90(11):e63.
18. Caramuru LH, Lopes AA, Maeda NY, Aiello VD, Filho CC. Long-term behavior of endothelial and coagulation markers in Eisenmenger syndrome. *Clin Appl Thromb Hemost*. 2006;12(2):175-183.
19. Yang H, Bouma BJ, Dimopoulos K, et al. Non-vitamin K antagonist oral anticoagulants (NOACs) for thromboembolic prevention, are they safe in congenital heart disease? results of a worldwide study. *Int J Cardiol*. 2020;299:123-130.
20. Lippi G, Plebani M, Henry BM. Thrombocytopenia is associated with severe coronavirus disease 2019 (COVID-19) infections: a meta-analysis. *Clin Chim Acta*. 2020;506:145-148.
21. Lippi G, Favaloro EJ. D-Dimer is associated with severity of coronavirus disease 2019: a pooled analysis. *Thromb Haemost*. 2020;120(5):876-878.
22. Smilowitz NR, Kunichoff D, Garshick M, et al. C-reactive protein and clinical outcomes in patients with COVID-19. *Eur Heart J*. 2021;42(23):2270-2279.
23. Gorog DA, Storey RF, Gurbel PA, et al. Current and novel biomarkers of thrombotic risk in COVID-19: a consensus Statement from the international COVID-19 thrombosis biomarkers colloquium. *Nat Rev Cardiol*. 2022;19(7):475-495.
24. Fusco F, Scognamiglio G, Merola A, et al. COVID-19 vaccination in adults with congenital heart disease: real-world data from an Italian tertiary centre. *Int J Cardiol Congenit Heart Dis*. 2021;6:100266.
25. Fusco F, Scognamiglio G, Roma AS, et al. Mid-term follow-up after COVID-19 vaccination in adults with CHD: a prospective study. *Cardiol Young*. 2023;1-7. <https://doi.org/10.1017/S1047951123000689>
26. Andrews N, Stowe J, Kirsebom F, et al. COVID-19 vaccine effectiveness against the omicron (B.1.1.529) variant. *N Engl J Med*. 2022;386(16):1532-1546.
27. Grobbelaar LM, Kruger A, Venter C, et al. Relative hypercoagulopathy of the SARS-CoV-2 beta and delta variants when compared to the less severe omicron variants is related to TEG parameters, the extent of fibrin amyloid microclots, and the severity of clinical illness. *Semin Thromb Hemost*. 2022;48(7):858-868.
28. Kuhlmann C, Mayer CK, Claassen M, et al. Breakthrough infections with SARS-CoV-2 omicron despite mRNA vaccine booster dose. *Lancet*. 2022;399(10325):625-626.
29. Chen B, Jiang C, Han B, et al. High prevalence of occult thrombosis in cases of mild/moderate COVID-19. *Int J Infect Dis*. 2021;104:77-82.
30. Ho FK, Man KKC, Toshner M, et al. Thromboembolic risk in hospitalized and Nonhospitalized COVID-19 patients: a self-controlled case series analysis of a Nationwide cohort. *Mayo Clin Proc*. 2021;96(10):2587-2597.
31. Klok FA, Pai M, Huisman MV, Makris M. Vaccine-induced immune thrombotic thrombocytopenia. *Lancet Haematol*. 2022;9(1):e73-e80.
32. Telenti A, Arvin A, Corey L, et al. After the pandemic: perspectives on the future trajectory of COVID-19. *Nature*. 2021;596(7873):495-504.

KEY WORDS adult congenital heart disease, bleeding, COVID-19, thrombosis

APPENDIX For supplemental tables, please see the online version of this paper.