INTRODUCTION

COVID-19 is the clinical syndrome resulting from infection with the novel coronavirus named severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), which was first identified in December 2019. SARS-CoV-2 has since spread across the world [1, 2]. Declared a pandemic by the World Health Organization, there are over 14.5 million confirmed cases of COVID-19 worldwide and more than 600000 associated deaths, as of July 19, 2020 [3].

As the COVID-19 pandemic spreads worldwide, increasing resource burdens come to healthcare systems, and escalated measures are necessary to protect patients and healthcare workers from infection. At the same time, care for patients with cardiovascular disease without active COVID-19 needs to continue during these circumstances. In the era of the COVID-19 pandemic, approaches to diagnostic testing, including cardiovascular CT (CCT) and cardiovascular magnetic resonance (CMR), must be adapted to include safer practices for urgent and semi-urgent studies and appropriate delay of elective exams. In addition, patients with confirmed active COVID-19 and underlying cardiovascular disease or those who present with ischemic or inflammatory cardiac injury, such that CCT and CMR are indicated, will arise. CCT and CMR may offer effective and efficient diagnostic imaging choices that provide critical information for clinical decision-making.

PURPOSE

The aim of this review is to provide general guidance and specific recommendations on the practice of CCT and CMR in the era of the COVID-19 pandemic. Recognizing that practice patterns and policies vary depending on institution and locale, these
recommendations are not meant to be restrictive but rather to serve as a general framework.

BASIC CONCEPTS FOR HEALTHCARE PROFESSIONALS WITH REGARD TO COVID-19

- Social distancing—keeping at least five or six feet (1.5 m to 1.8 m) between individuals in waiting rooms and work spaces as much as feasible.
- Encourage sick employees to stay home. Personnel who develop respiratory symptoms (e.g., cough, shortness of breath) or unexplained fever should be instructed not to report to work.
- Ensure that your sick-leave policies are flexible and consistent with public health guidance and that employees are aware of these policies. Make contingency plans for increased absenteeism in the radiology team. If possible, work schedules of imaging professionals should be reorganized into teams that are working completely separately. Teams of radiographers and radiologists should be changed simultaneously if possible.
- Screen patients and visitors for symptoms of acute respiratory illness (e.g., fever, cough, difficulty breathing) or gastrointestinal symptoms and coronavirus exposure in the last 2 weeks before allowing them to enter one's healthcare facility [4]. Testing for potential infections of staff members is also crucial to avoid potential catastrophic impacts on the hospital staff and patients.

Reverse transcription polymerase chain reaction (RT-PCR) testing of a nasopharyngeal mucosal swab is currently the reference standard for proving an active SARS-CoV-2 infection, and can be used in mild or even asymptomatic patients. RT-PCR has a very high specificity making a positive test pragmatically diagnostic, but it has the limitation of a potential 30–40% false negative results (due to other factors). Antibody tests or serological tests that detect the immune response to an existing infection are not yet reliable enough nor widely available to be included in new protocols.

- Ensure technologist and imaging specialists employ best hand hygiene practices. If soap and water are not readily available, hand sanitizers that contain at least 60% ethanol are also effective.
- Consider standard droplet precautions for patients and healthcare personnel as per institutional infection control protocols.
- Increase scheduling intervals or appointment times to allow adequate time to clean equipment as needed.
- Leverage telemedicine technologies and isolated workstations to allow for reading and interpretation that permit social distancing to limit staff exposure, when possible.
- Assign a team member to monitor and incorporate regular updates to staff from the national Centers for Disease Control and Prevention and appropriate regional jurisdictions [5,6].

ACCESS TO THE IMAGING FACILITY

If possible, suspected or confirmed COVID-19 patients should be imaged using dedicated COVID-19 imaging equipment in the radiology department to prevent cross-contamination between infected and non-infected patient populations. If this is not possible due to a limited number of available primary scanners, other scanner types (e.g., single photon emission-CT scanners or the cone-beam function of angiography suites) could be used as COVID-19 patient scanners for general purposes. Finally, if a dedicated CT-scanner for infected patients is not available, at least dedicated COVID-19 time slots on the available equipment must be defined, preferably at the end of the day. These time slots can also be made available for the investigation of (potential) COVID-19 patients who require high-quality cardiovascular CT-imaging, which may not be available on the dedicated COVID-scanner.

Access routes to these scanners must be provided to transport service technicians and clinicians, and must also be clearly indicated to non-radiology staff. These routes, as well as the corresponding waiting areas, must be separated from normal patient pathways [6].

EQUIPMENT DISINFECTION

Cleaning the imaging facility after every suspected or positive COVID-19 patient before scanning a negative patient is mandatory and must be performed according to local guidelines.

Table 1. Vendor’s recommendations for disinfection of scanners and scanner facilities (in alphabetical order)

| Vendor       | Website                                                                 |
|--------------|-------------------------------------------------------------------------|
| Canon        | https://eu.medical.canon/covid-19/                                      |
| General Electric | https://cleaning.gehealthcare.com/                                      |
| Philips      | https://www.usa.philips.com/healthcare/medical-specialties/covid-19/precision-diagnostics-addressing-covid#education_and_resources |
| Siemens     | https://www.siemens-healthineers.com/en-be/clinical-specialties/critical-care/disinfection-recommendations |
|             | https://www.siemens-healthineers.com/en-ph/services/proper-disinfection |

Adapted from Beitzke et al. Int J Cardiovasc Imaging 2020 May 26 [Epub] [6].
Conversely, cleaning between scanning of two (or even more) established positive COVID-19 patients is not necessary unless (bacterial) superinfection is known. A solution of 62–71% ethanol, 0.5% hydrogen peroxide, or 0.1% sodium hypochlorite within 1 min of possible contamination has also been suggest-
ed [7]. Table 1 shows several manufacturers that have introduced equipment-specific guidelines. If possible, the scanners should be ventilated under low pressure (a similar concept as that used in septic surgical areas) to ensure that potential contaminated aerosols are cleared via climate controls and do not contami-

Table 2. Categories and use of PPE for cardiac imaging procedures in COVID-19 positive patients

| Use of PPE | Healthcare professionals | Patient |
|------------|--------------------------|---------|
| COVID-19 confirmed or suspected (unknown) | Patient contact | No direct patient contact |
| CCT/CMR | Full set of PPE including FFP2 mask, gloves, gown, goggles and/or face shield | FFP2, (gown) | Mouth and nose protection |
| Emergency with the need for intubation | Evacuate room with the exception of the emergency team | Do not enter scanner room | N/A |
| COVID-19 negative in house | Patient contact | No direct patient contact | Patient |
| CCT/CMR | FFP2 mask, gloves, gown | FFP2 or mouth and nose protection | Mouth and nose protection |

Adapted from Beitzke et al. Int J Cardiovasc Imaging 2020 May 26 [Epub] [6]. PPE: personal protection equipment, CCT: cardiovascular CT, CMR: cardiovascular magnetic resonance

Table 3. Timing considerations for common indications for CCT in COVID-19 era

| Elective indications (may be rescheduled >8 weeks) | Semi-urgent indications (consider scanning within 4–8 weeks) | Urgent indications (consider scanning within hours to <2–4 weeks) |
|---------------------------------------------------|----------------------------------------------------------|----------------------------------------------------------|
| CAD | Asymptomatic coronary artery calcium imaging | Acute chest pain when sufficient clinical suspicion for CAD | |
| | Stable chest pain without high suspicion for CAD | Stable chest pain at high risk for events, or when there is concern for possible high-risk coronary anatomy | |
| SHD | Stable structural heart patients (e.g., TAVR, TMVR, LAA closure in conjunction with the Heart Team)* | Patient requiring urgent structural intervention (e.g., TAVR, TMVR, LAA closure) | |
| A-fib | Pulmonary vein assessment for A-fib ablation planning* | Evaluation of left atrial appendage in chronic atrial arrhythmia prior to restoration of sinus rhythm | Evaluation of left atrial appendage in acute atrial arrhythmia prior to restoration of sinus rhythm† |
| Heart failure | Stable cardiomyopathy patients | Acute inpatient cardiomyopathy in low to intermediate pretest probability of CAD, only if CCT would change management | Evaluation of LVAD dysfunction |
| Valvular | Evaluation for aortic stenosis severity | Sub-acute to chronic prosthetic valve dysfunction | Acute symptomatic prosthetic heart valve dysfunction, endocarditis, paravalvular extension of endocarditis, or possible valve abscess |
| Mass/congenital | Cardiac masses, which are suspected to be benign or unlikely to plan for biopsy or surgery | New cardiac masses which are suspected to be malignant, if necessary to plan biopsy or surgery Rule-out left ventricular thrombus following equivocal echocardiography when alternative diagnostic tests (e.g., MRI) are not feasible | |

Adapted from Choi et al. J Cardiovasc Comput Tomogr 2020;14:101-104 [5]. *especially in institutions that will delay such elective cases, †when cardioversion is deemed necessary, CAD: coronary artery disease, SHD: structural heart disease, A-fib: atrial fibrillation, LAA: left atrial appendage, TAVR: transcatheter aortic valve replacement/implantation, TMVR: transcatheter mitral valve replacement/implantation, LVAD: left ventricular assist device, CCT: cardiovascular CT
nate scanner control rooms or corridors [6].

**USE OF PERSONAL PROTECTION EQUIPMENT**

Personal protective equipment (PPE) for maintaining a safe patient service onsite is of the highest importance. To avoid PPE shortages, local healthcare authorities and professional organizations should be encouraged to help and assist in supplying PPE. Various types of masks ranging from simple surgical masks for general staff to highly protective masks (N95, FFP2, and so on) for professionals who work in direct contact with COVID-19 patients are needed. Gowns, eyeglasses, and eye shields are also needed for personal protection. Table 2 shows adequate PPE in specific conditions for professionals and patients in the cardiac imaging facility [6].

**IMAGING STRATEGIES FOR CORONARY AND/OR CCT**

**General considerations**

The delivery of CCT services should be performed in a manner which will be safe to technologists and imagers, as well as patients. In addition, deferring CCT exams which can be safely postponed in order to minimize risk of exposure to patients and staff should be considered. Table 3 shows the suggestions for CCT timing based on various indications suggested by Society of Cardiovascular Computed Tomography [5].

Substituting noninvasive diagnostic imaging in place of semi-invasive or invasive diagnostic imaging and consolidating multiple diagnostic tests into one exam

Substituting noninvasive diagnostic imaging in place of semi-invasive or invasive diagnostic imaging reduces PPE use and has comparable diagnostic accuracy [8]. In general, noninvasive diagnostic imaging is associated with less interactions between the patient and the healthcare professionals, which decreases the risk of transmitting COVID-19. Consolidating imaging also reduces PPE use and healthcare professionals’ exposure because it may reduce the number of visits a suspected or positive COVID-19 patient will need. Consolidation is accomplished by an-

| Table 4. Alternative imaging in specific clinical scenarios* |
|------------------------------------------------------------|
| **Indication**                                             | **Usual care**                                     | **Suggested protocol**                           |
| Elevated troponin and equivocal diagnosis of NSTEMI         | Invasive coronary angiography                       | Coronary CT†                                     |
| Acute chest pain, negative initial troponin, intermediate risk | Invasive coronary angiography, or 24 h serial troponin + EKG | Coronary CT†                                     |
| Exclusion of LAA thrombus prior to urgent cardioversion    | TEE                                                | Cardiac CT with delayed phase                   |
| Emergent TAVR or SAVR planning                              | TEE                                                | Cardiac CT+CT angiography§                       |
| Prosthetic or native heart valve dysfunction or suspected endocarditis | TEE                                                | Cardiac CT                                       |

Adapted from North American Society of Cardiovascular Imaging [9]. *coronary and cardiac CT provide the additional benefit of partial imaging of the lung parenchyma. If typical or atypical pulmonary findings are encountered, consultation with a radiologist with thoracic expertise is encouraged, and appropriate documentation and timely communication of these findings is essential, especially in cases not known or suspected to have the disease [10]. TEE: transesophageal echocardiography

| Table 5. General recommendations for noninvasive alternatives to semi-invasive or invasive imaging* |
|---------------------------------------------------------------|
| **Indication**                                            | **Usual care**                             |
| Diagnostic invasive coronary angiography                    | Coronary CT                               |
| TEE                                                         | Cardiac CT, with or without delayed phase |

Adapted from North American Society of Cardiovascular Imaging [9]. *coronary and cardiac CT provide the additional benefit of partial imaging of the lung parenchyma. If typical or atypical pulmonary findings are encountered, consultation with a radiologist with thoracic expertise is encouraged, and appropriate documentation and timely communication of these findings is essential, especially in cases not known or suspected to have the disease [10]. TEE: transesophageal echocardiography

| Table 6. List of protocols that can be used for consolidating imaging |
|---------------------------------------------------------------|
| **Original**                                           | **Consolidated**                           |
| Coronary CT, cardiac CT, CTA, CTPA, CT chest unenhanced    | CT chest with contrast, TRO, CTPA         |
| CT chest with contrast                                    | Cannot be consolidated with another exam  |

The information obtained by imaging with a protocol listed in the "original" column is likely to be provided by a protocol listed under the "consolidated" column. Adapted from North American Society of Cardiovascular Imaging [9]. CTA: CT angiography, CTPA: CT pulmonary angiography, TRO: triple rule-out

Adapted from North American Society of Cardiovascular Imaging [9]. *coronary and cardiac CT provide the additional benefit of partial imaging of the lung parenchyma. If typical or atypical pulmonary findings are thoracic expertise is encouraged, and appropriate documentation and timely communication of these findings are essential, especially in cases not known or suspected to have the disease [10]. *coronary CT means ECG–gated CT of the heart and proximal aorta with contrast injection optimized for coronary artery being enhanced. Consider ECG-gated coronary calcium score CT before this study; *coronary CT means ECG-gated cardiac CT with contrast injection optimized for imaging of cardiac chambers and/or valve morphology with or without 90 s delay; *coronary CT with contrast injection optimized for systemic arterial enhancement (i.e., aortic). LAA: left atrial appendage, TAVR: transcatheter aortic valve replacement/implantation, NSTEMI: non ST-elevation myocardial infarction, EKG: elektrokardiogramm, ECG: electrocardiogram, TEE: transesophageal echocardiography, SAVR: surgical aortic valve replacement
Participating the future imaging needs of a patient and meeting that need by performing a lower number of more comprehensive studies. This may provide the information likely to be sought later during hospitalization, but with less imaging facility utilization. According to the level of evidence, the Tables referenced below present recommendations for use of noninvasive diagnostic imaging.

1. Noninvasive diagnostic imaging alternatives supported by strong evidence that can be performed in place of semi-invasive or invasive imaging for specific clinical indications in all patients, particularly COVID-19-positive or COVID-19 suspected patients (Table 4).

2. Noninvasive diagnostic imaging alternatives supported by expert opinion in place of semi-invasive or invasive imaging for indications other than listed in 1a and only in COVID-19-positive or COVID-19 suspected patients (Table 5).

Table 7. Suggested timeline for CMR exams by expert consensus based on common clinical indications (not intended to be exhaustive and individual clinical circumstances need to be considered)

| Elective (wait 2–4 months) | Semi-urgent (1 week–2 months) | Urgent (<1 week) |
|----------------------------|-------------------------------|-----------------|
| Cardiomyopathy             | Suspected hypertrophic cardiomyopathy or follow-up for late gadolinium enhancement | Suspected infiltrative cardiomyopathy, depending on impact on treatment Follow-up of iron overload pending chelation therapy | Acute myocarditis with implications for immediate management (within 1–3 days) |
|                            | Family history of sudden death, arrhythmogenic cardiomyopathy, or other screening in clinically stable and asymptomatic patients | Family history of sudden death, arrhythmogenic cardiomyopathy, or other screening in symptomatic patients | |
|                            | Suspected dilated cardiomyopathy to assess left ventricular function and etiology | | |
| Ischemic heart disease     | Stress perfusion in stable ischemic heart disease Viability for non-urgent revascularization | Stress perfusion in newly symptomatic patients Viability for revascularization in patients with recent symptoms | Ischemia and viability to guide urgent revascularization |
| Masses                     | Suspected benign mass, unlikely to prompt urgent surgery or biopsy | Question of thrombus with non-diagnostic echo and no contraindication to empiric anticoagulation | Suspected malignancy, likely to prompt imminent surgery, biopsy, or chemotherapy Suspected intracardiac mass or thrombus with contraindication to anticoagulation or in patients with suspected embolic events |
| Congenital heart disease   | Follow-up of right ventricular function and pulmonary regurgitation in a clinically stable patient | Pre-interventional planning in a symptomatic patient | Information that can only be derived from CMR if needed for decision-making in an acutely ill patient |
| Arrhythmia                 | Ablation planning for atrial fibrillation in clinically stable patients | Ablation planning for ventricular arrhythmias in clinically stable patients | Planning for urgent ablation in unstable patients |
| Valvular disease           | Follow-up exams in aortic valve stenosis, or quantification of aortic, mitral, tricuspid or pulmonic regurgitation in clinically stable patients | TAVR planning pending procedural urgency | TAVR, aortic, mitral, tricuspid, or pulmonic regurgitation quantification, urgent surgery or percutaneous therapy planned |
| Pericardial disease        | Follow-up for pericarditis in asymptomatic and stable patients | Acute pericarditis evaluation leading to potential change in management in symptomatic patients | Pericardial constriction requiring potential urgent surgery |
| Pulmonary hypertension     | Evaluate right ventricular function for escalation of therapy in clinically stable patients | Evaluate right ventricular function for escalation of therapy in symptomatic patients | |
| Aortic disease             | Follow up dissection and/or aneurysms or repair/coarctation in stable patients | Monitoring of near intervention threshold aneurysms/coarctation | Suspected acute dissection (immediately) |

Adapted from Han et al. J Cardiovasc Magn Reson 2020;22:26 [13]. CMR: cardiovascular magnetic resonance, TAVR: transcatheter aortic valve replacement/implantation
3. Alternative imaging that can be performed in an attempt to consolidate imaging, supported by expert opinion, in COVID-19-positive or COVID-19 suspected patients (Table 6) [9].

IMAGING STRATEGIES FOR CMR

General considerations

CMR can detect COVID-19 associated myocarditis. As a hypercoagulable state is also reported to be associated with this disease, a potential differential diagnosis to myocarditis could be myocardial infarction with non-obstructive coronary arteries (MINOCA). Stress-induced cardiomyopathy (Tako-Tsubo syndrome) in combination with COVID-19 is also reported [11]. Independent of the COVID-19 pandemic, differentiating MINOCA from myocarditis and other causes of acute myocardial injury is possible using CMR and therefore impacts patient management for secondary prevention [12]. Additionally, CMR has the potential to incidentally detect extracardiac findings (e.g., lung involvement, pleural effusion) which may be clinically relevant. However, direct diagnostic and prognostic implications of CMR imaging during the COVID-19 pandemic situation are actually not known. Therefore, the usefulness of CMR might be limited to the diagnosis and differentiation between myocarditis, Tako-Tsubo syndrome, and MINOCA.

The delivery of CMR services should be performed in a manner which will be safe to technologists and imaging specialists, as well as patients. In addition, deferring CMR exams which can be safely postponed in order to minimize risk of exposure to patients and staff should be considered. Table 7 shows the suggestions for CMR timing based on various indications suggested by Society of Cardiovascular Magnetic Resonance (SCMR) [6,13].

Scanning protocols of CMR

CMR is more time-consuming than CT and therefore has a potential higher risk for patients and staff (e.g., viral transmission). To reduce the risk, a fast and focused CMR protocol for a comprehensive assessment of cardiac involvement in COVID-19 patients is highly recommended. This protocol incorporates cine sequences for functional assessment, edema imaging for detection of acute myocardial injury, T1 mapping, as well as late gadolinium enhancement (LGE) imaging for differentiation between ischemic and non-ischemic causes of myocardial injury. This protocol should be accompanied by fast, one breath-hold sequences for assessment of thoracic complications. All efforts to reduce acquisition time (e.g., use of accelerated imaging as compressed sensing or reduction in time delay for LGE imaging) should be used. A proposed imaging protocol is summarized in Table 8.

SCMR also updates comprehensive illustration and summarized materials for CMR exam in the COVID-19 pandemic era [6,13].

OTHER RESOURCES

Several societies of cardiovascular medicine and imaging provides guidelines and statements of practice in the COVID-19 era for general and regional use [14-21].

CONCLUSION

Cardiac imaging services should help to avoid or at least cut down the number of invasive or time-consuming procedures like cardiac catheterization or transesophageal echocardiography whenever possible. Therefore CCT might be favored for ruling out coronary heart disease and left atrial (appendage) thrombus and should be offered to COVID-19 positive patients when needed. CMR may provide insights into myocardial involvement in COVID-19 patients and differentiate types of myocardial damage. Due to the associated hypercoagulable state that rules out pulmonary embolism by CT, this must also be offered to clinicians. Fast imaging protocols for CMR should be considered for COVID-19 patients with cardiac presentations.

Further, based on local capacities and possibilities to ensure safe imaging, non-infected patients should undergo cardiac imaging when indicated to prevent under-treatment of cardiac conditions.

Cardiac imaging programs set up during the pandemic have
to be tailored and focused on the safety of patients and healthcare professionals.

Conflicts of Interest
The authors have no potential conflicts of interest to disclose.

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