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Non-invasive estimation of pulmonary outflow tract obstruction: A comparative study of cardiovascular phase contrast magnetic resonance and Doppler echocardiography versus cardiac catheterization

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ABSTRACT

Aim: To compare estimated pressure gradients from routine follow-up cardiovascular phase-contrast magnetic resonance (PC-MR) with those from Doppler echocardiography and invasive catheterization in patients with congenital heart disease (CHD) and pulmonary outflow tract obstruction.
Methods: In 75 patients with pulmonary outflow tract obstruction maximal and mean PC-MR gradients were compared to maximal and mean Doppler gradients. Additionally, in a subgroup of 31 patients maximal and mean PC-MR and Doppler pressure gradients were compared to catheter peak-to-peak pressure gradients (PPG).
Results: Maximal and mean PC-MR gradients underestimated pulmonary outflow tract obstruction as compared to Doppler (max gradient: bias = +8.4 mm Hg (+47.6%), $r = 0.89$, $p < 0.001$; mean gradient: +4.3 mm Hg (+49.0%), $r = 0.88$, $p < 0.001$). However, in comparison to catheter PPG, maximal PC-MR gradients (bias = +1.8 mm Hg (+8.8%), $r = 0.90$, $p = 0.14$) and mean Doppler gradients (bias = −2.3 mm Hg (−11.2%), $r = 0.87$, $p = 0.17$) revealed best agreement. Mean PC-MR gradients underestimated (bias = −7.7 mm Hg (−55.6%), $r = 0.90$, $p < 0.001$) while maximal Doppler gradients systematically overestimated catheter PPG (bias = +13.9 mm Hg (+56.5%), $r = 0.88$, $p < 0.001$).
Conclusions: Estimated maximal PC-MR pressure gradients from routine CHD follow-up agree well with invasively assessed peak-to-peak pressure gradients. Estimated maximal Doppler pressure gradients tend to overestimate, while Doppler mean gradients agree better with catheter PPG. Therefore, our data provide reasonable arguments to either apply maximal PC-MR gradients or mean Doppler gradients to non-invasively evaluate the severity of pulmonary outflow tract obstruction in the follow-up of CHD.

1. Introduction

In many patients with congenital heart disease (CHD), the assessment of the severity of pulmonary outflow tract obstruction is crucial. Historically, the catheter peak-to-peak pressure gradient (PPG) has been used as the diagnostic gold standard to evaluate the degree of pulmonary outflow tract obstruction and was employed to decide when to intervene. In todays clinical routine transthoracic echocardiography is generally decisive. The estimated maximal instantaneous Doppler gradient is the non-invasive diagnostic method of choice to define when an intervention is indicated [1,2]. Cardiovascular magnetic resonance (CMR) imaging has become a non-invasive imaging standard in the follow-up of repaired CHD [3,4]. CMR examinations in CHD typically include phase-contrast flow quantification (PC-MR) of large intrathoracic vessels e.g. to determine the degree of pulmonary regurgitation [5,6]. Patients with repaired CHD often develop combined pulmonary regurgitation and pulmonary outflow tract obstruction. While the measurement of pulmonary flow is potentially an unrivalled strength of conventional PC-MR, limitations to accurately assess peak flow velocities are present [7,8]. However, peak flow velocities are provided in

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every case of pulmonary PC-MR flow quantification, but it remains unclear how to deal with the existing data at the present time. Recent studies have shown that estimated maximal instantaneous Doppler gradients overstate catheter PPG [9,10]. Since it is known that PC-MR underestimates peak flow velocities when compared to Doppler echocardiography [11], we hypothesised that estimated maximal pressure gradients from PC-MR agree closer with catheter PPG. Therefore, the purpose of the present study was to compare estimated pressure gradients from routine follow-up cardiovascular PC-MR with those from Doppler echocardiography and invasive catheterization in CHD with pulmonary outflow tract obstruction.

2. Methods

2.1. Study subjects

Patients with CHD who underwent transthoracic Doppler echocardiography and cardiovascular PC-MR of the pulmonary outflow tract were identified by search of the local radiological-cardiovascular database. Patients with pulmonary outflow tract obstruction were included for analysis if they had Doppler (estimated maximal Doppler gradient of 6 mm Hg or higher) and cardiovascular PC-MR examination within 4 month. Additionally, a subgroup analysis of patients was performed who underwent Doppler, PC-MR as well as cardiac catheterization within 4 month. For patients with multiple Doppler examinations during these periods, the study with the lowest time delay to either PC-MR or catheterization was chosen. All examinations were clinically indicated and the results were compared retrospectively. Written informed consent could not be obtained from participants for their clinical records to be used in the study. Accordingly, data were analysed anonymously to protect their identities. The study was approved by the Institutional Review Board at the University of Göttingen Medical Centre and complies with the Declaration of Helsinki.

2.2. Doppler echocardiography

Pulmonary outflow tract maximal and mean pressure gradients were estimated using continuous wave (CW) Doppler. Echocardiography examinations were performed on iE33 ultrasound systems (Philips Healthcare, Leiden, The Netherlands) using Philips S5-1 ultrasound probes (Nyquist limit 61, gain 50%). CW Doppler measurements (frequency 1.8 MHz, angle 0 to 20°) of the pulmonary outflow tract were performed in multiple standardized views [12]. Digital offline analysis (2D Cardiac Performance Analysis, TomTec Imaging System, Munich, Germany) of the digitally recorded Doppler-data was performed to determine peak flow velocities. The heartbeat with the highest velocity detected in any imaging window was included in the analysis. A region of interest (ROI) was drawn around the systolic Doppler signal to determine the peak and the mean flow velocity (= time averaged peak flow velocity across the systolic signal) (Fig. 1). Maximal and mean Doppler gradients were estimated using the Bernoulli equation [13] $\Delta P = 4(V)^2$, where ΔP is the maximal or mean pressure gradient and V the peak or mean flow velocity.

2.3. Phase-contrast magnetic resonance

MR flow quantification was performed on 1.5 T (Symphony Syngo B17, Siemens Healthcare, Erlangen, Germany) using a retrospective ECG gated cine phase-contrast sequence in breath-holding technique with the following imaging parameters: spatial resolution $1.7 \times 1.7 \times 5.5$ mm^3, TE/TR 3.2/75.4, flip angle 30°, encoding velocity 130–450 cm s^{-1}, 20 phases. If patients were not able to follow respiratory instructions, a free breathing retrospective ECG gated cine phase-contrast technique was used alternatively with the following imaging parameters: spatial resolution $1.3 \times 1.3 \times 5.0$ mm^3, TE/TR 3.0/27.0, flip angle 30°, encoding velocity 130–430 cm s^{-1}, 30 phases. Pulmonary

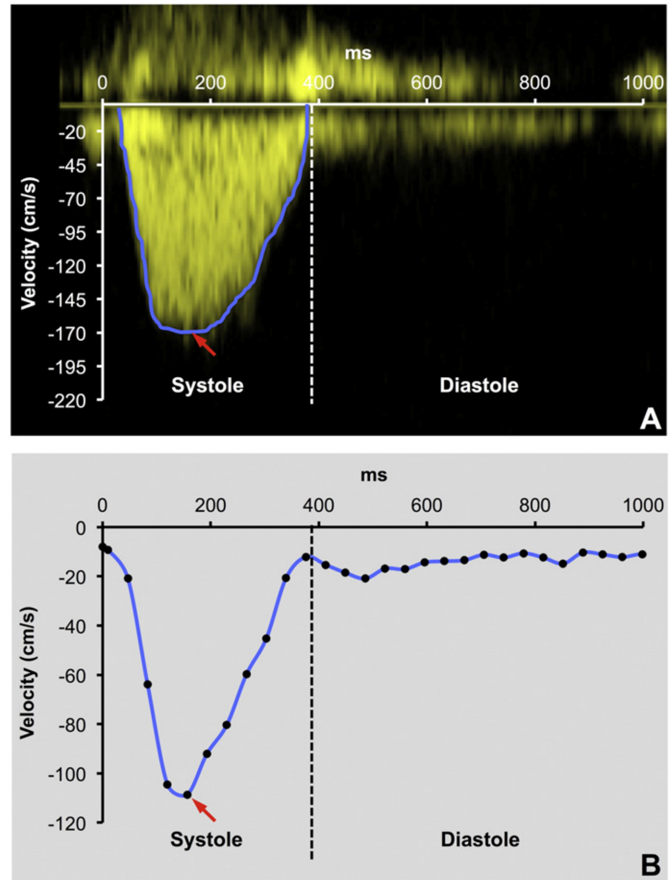

Fig. 1. Peak velocity versus time curves. Peak velocity versus time curves for (A) Doppler echocardiography and (B) phase-contrast magnetic resonance (PC-MR) acquisitions were used to identify the peak flow velocity (red arrow) and to calculate the mean flow velocity (time averaged peak flow velocity).

outflow tract blood flow was measured through plane in an imaging plane as recommended for pulmonary flow quantification in the follow-up of CHD [14,15]. Magnitude and phase-contrast maps were analysed using commercially available software (QFlow, Medis, Leiden, The Netherlands). ROIs were drawn on each of the 30 frames (free-breathing technique) or 20 frames (breath-hold technique) around the circumference of the main pulmonary artery to determine the pixel encoding of the peak flow velocity in each frame (Fig. 2). The peak flow velocity from each frame was exported to a spreadsheet to generate peak flow velocity versus time curves (Fig. 1). The peak flow velocity versus time curve was used to identify the overall peak flow velocity (= peak of all systolic frames) and to calculate the mean flow velocity (= time averaged peak flow velocity of all systolic frames). Maximal and mean PC-MR pressure gradient were estimated according to the Bernoulli equation as described above for Doppler measurements.

2.4. Cardiac catheterization

Non-invasively estimated pressure gradients were compared to the catheter peak-to-peak systolic pressure gradient (PPG). All patients underwent catheterization under conscious sedation. Invasive pressure measurements were performed with fluid-filled catheters. PPG were measured using the non-simultaneous pullback technique. The PPG was defined as the difference between the peak ventricular and peak pulmonary arterial pressure.