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Research Article

Usefulness of MRI to Detect Pulmonary Hypertension in A Population Pre-Selected by Echocardiography -

Clement Venner[1-3], Freddy Odille[2,3], Damien Voilliot[1-3], Ari Chaouat[4], François Chabot[4], Jacques Felblinger[2,3,5], Laurent Bonnemains[2,3,6]*

[1]*Department of Cardiology, CHU Nancy, Nancy, France*
[2]*U947, INSERM, Nancy, France*
[3]*IADI, Université de Lorraine, Nancy, France*
[4]*Department of Pneumology, CHU Nancy, Nancy, France*
[5]*CIC-IT 1433, CHU Nancy, Nancy, France*
[6]*Department of Cardiac Surgery, CHU Strasbourg, Strasbourg, France*

***Address for Correspondence:** Laurent Bonnemains, Department of Cardiac Surgery, CHU Strasbourg, 1 rue de l'hôpital, 67000 Strasbourg, France and IADI, CHU Brabois, rue du Morvan, 54511 Vandoeuvre, France, Tel: +33 3 83153241; Fax: +33 3 83154062, Email: laurent.bonnemains@inserm.fr

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ABSTRACT

Purpose: To evaluate the diagnostic power of cardiac MRI within an all-comers population of patients suspected of pulmonary hypertension after an echocardiography.

Methods: Fifty-six consecutive patients,suspected of pulmonary hypertension after an echocardiography, were assessed with right heart catheterization and cardiac MRI (including a high temporal resolution pulmonary flow curve). We extracted from the MR data the main parameters proposed by all precedent studies available in the literature. We looked for multivariate linear relations between those parameters and the mean pulmonary arterial pressure (mPAP), and eventually assessed with a logit regression the ability of those parameters to diagnosepulmonary hypertension in our population.

Results: The multivariate model retained only two parameters: the right ventricle ejection fraction and the pulmonary trunk minimum area. The prediction of mPAP (r^2=0.5) yieldedlimits of agreement of 15mmHg. However the prediction of pulmonary hypertension within the population was feasible and the method yielded a specificity of 80% for a sensitivity of 100%.

Conclusion: The performance of MRI to assess mPAPis too low to be used as a surrogate to right heart catheterization but MRI could be used as second line examination after echocardiography to avoid right heart catheterization for normal patients.

Keywords: MRI; Pulmonary hypertension; Diagnostic power

INTRODUCTION

Pulmonary Hypertension (PH) is a severe pulmonary disease characterized by an elevation of the mean Pulmonary Arterial Pressure (mPAP) and modifications of the right ventricle [1]. So far echocardiography remains the screening test for PH by assessing right ventricle's morphology and estimating pulmonary hemodynamic essentially based on tricuspid regurgitation maximal velocity [2]. This screening can also be performed by Magnetic Resonance Imaging (MRI) [3]. However, the precise estimation of mean pulmonary arterial pressure lacks accuracy and right heart catheterization remains the diagnostic gold standard [4–7]. During the past years, several formulas have been presented to compute mPAP from MRI parameters, either based on mean parameters such as mean velocity [7], pulmonary trunk area [7], septal curvature [8], and ejection fraction [9], or based on parameters extracted from high-temporal resolution pulmonary flow curves such as absolute acceleration time [10] or maximal flow acceleration [10]. However, those parameters need a particular attention to be correctly measured that may be difficult to achieve in every-day practice. Furthermore, PH is nowadays suspected earlier and younger patients could have different baseline characteristics [11]. To bridge the gap between research and clinical practice, the proposed methods must be validated in an all-comers population of patients suspected of PH with low elevation of mPAP.

In this work we wished to test the applicability of the different published MRI parameters for the assessment of mPAP as a surrogate to right heart catheterization within an all-comers population of suspected PH cases. Furthermore, we speculated that such sequences could help to distinguish patients with normal and raised mPAP through a differential variation of several parameters and serve as a diagnostic test in order to avoid unnecessary right heart catheterization in a population suspected of PH and pre-selected by echocardiography.

MATERIAL AND METHODS

Population

Between September 2012 and December 2014, we prospectively recruited 56 consecutive adult patients suspected of PHand referred to our institution All patients had an estimated systolic pulmonary pressure above 35 mmHg, assessed from the maximal velocity of the tricuspid regurgitation using the Bernoulli simplified formula and an evaluation of the right auricular pressure, as recommended [12]. They underwent right heart catheterizationand cardiac MRI during the same hospital stay, as detailed hereafter. The median delay between MRI and heart catheterization was <1d, but the max delay was 3 days.

Right Heart Catheterization

Right heart catheterization was performed using a 7.5F Swan-Ganz catheter (Edwards Lifesciences, Irvine, CA) via a transjugular approach. All exams were performed in a supine position with an adapted air flow and without anesthesia. Blood pressures were measured at the end of expiration after a zero calibration. The pulmonary artery pressure curves were recorded during at least six consecutive heart beats and mPAP were computed from the curves and recorded.

Magnetic Resonance Imaging

MRI was performed using a 1.5 Tesla scanner (SignaHDxt, General Electric Healthcare, Milwaukee, WI) connected to an 8-element cardiac phased-array surface coil for the reception of signal. Localizing sequences were initially recorded to determine the orientation of the main pulmonary trunk and of the heart short axis. The heart was centered in the B0 field to minimize phase errors and an inhomogeneity correction was used to minimize the effects of eddy currents and Maxwell gradients (shimming).

For analyses of Right Ventricle (RV) volume and function, a stack of 10 to 14 contiguous short-axis slices, covering the ventricles, was recorded using an balanced steady-state free precession sequence with Electrocardiogram (ECG) gating and during end-expiratory breath-holds. Main acquisition parameters were as follows: 8 mm slice-thickness, 3.4-4.1 ms repetition time, 1.4-1.7 ms echo time, 45° flip angle, 10 to 16 K-space lines per segment (depending on breath-holding capacity), 30 phases per cardiac cycle with view sharing, field-of-view ranging from 32 to 38 cm and a 224x224 matrix. When breath-holding capacities were overcome, parallel imaging was used. For analyses of the Pulmonary Artery (PA), phase contrastacquisitions were performed with the standard phase contrast sequence, 1 view per segment and 3 averaged excitations. Acquisitions were ECG-triggered and in free breathing. Sequence parameters were as follow: initial velocity upper limit of 150cm/s (but adapted upwards when necessary), bandwidth of 240-260 Hz/pixel, low flip angle of 15°, slice thickness of 10mm. Echo and repetition times were respectively 3.3-

3.5 and 7-8ms. Field of view ranged between 32 and 38cm according to patient's body surface. The image matrix was 256x256pixels yielding a resolution close to 1.5x1.5mm². These settings allowed a temporal resolution matching two repetition times close to 15ms. Mean sequence acquisition time was 3-3.5minutes.

MRI post processing

Acquired data were processed using commercially available softwares: FLOW 3.3 MR Flow Quantification Software (Medis – Medical Imaging System, Leiden, Netherlands) and Medis MASS Analysis Plus software package version 6.0 (MASS Analysis Plus, Leiden, The Netherlands). PA contouring was done semi-automatically with *post hoc* manual adjustment to follow the inner layer [Figure 1]. The following parameters were computed and stored: area, velocity and flow measurements. The RV volumes and ejection fraction were assessed in a conventional fashion [13]. Three points were manually positioned by a senior cardiologiston the endocardial surface of RV septal wall as recommended by [8]. The septal curvature was computed by a Matlab program (The Math Works Inc., Natick, MA) as the inverse of the radius of curvature of the circle circumscribed by the 3 points [8]. The velocity and flow curves were semi-automatically interpreted by another Matlabprogram in order to obtain the different parameters proposed by the literature [4,6–8,10]. All these parameters are presented in (Table 1).

Statistical analysis

All statistical analyses were performed using R studio-0.98.1062 based on R-3.0.1 [14]. Continuous variables were reported as mean ± standard deviation.p value <0.05 was considered statistically significant.

Prediction of mPAP by MRI

Associations between right heart catheterization-derived mPAP and MRI-derived parameters were assessed unilaterally and intensity of associations were expressed using Pearson's coefficient of correlation r. Parameters with the higher determination coefficients (r^2>0.25) were retained as potential predictors for multivariate linear regression analysis. The multivariate analysis was performed on

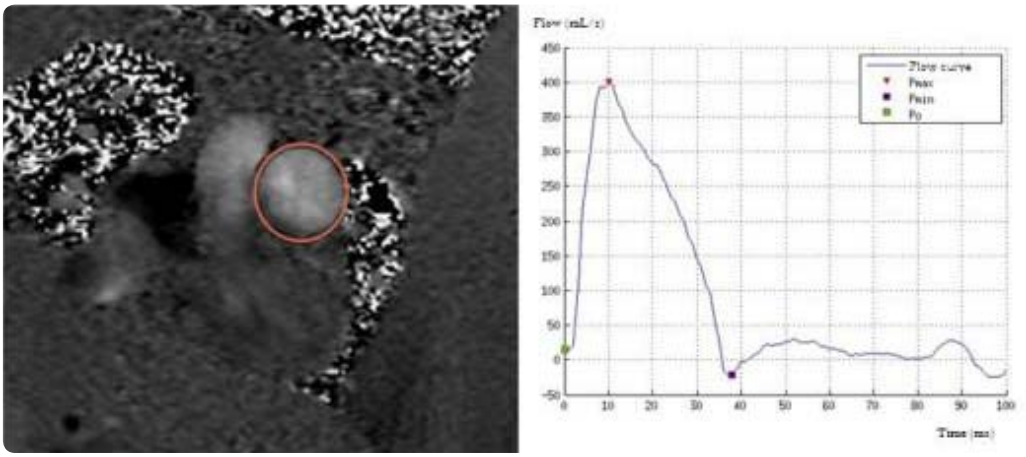

Figure 1: Example of typical phase contrast acquisition in the pulmonary trunk and the flow curve obtained after post-treatment.

Table 1: MRI parameters proposed by similar studies as surrogates to right-heart catheterization and results of the univariate linear regression in our population.

Parameter		Mean±SD	Correlated to mPAP	
Name	Definition		r^2	p
max PA area [6,7]	**Indexed maximum PA area (cm^2/m^2)**	**7.78±0.24**	**0.27**	**10^{-4}**
min PA area [6,7]	**Indexed minimum PA area (cm^2/m^2)**	**6.17±0.24**	**0.34**	**<10^{-4}**
mean PA area [7]	Mean indexed PA area (cm^2/m^2)	6.78±0.24	0.24	4.10^{-4}
PA pulsatility[6,7]	(PA Area Max – PA Area Min)/PA Area Max (%)	18±8	0.24	5.10^{-4}
Peak velocity [6,7,10]	Maximum velocity in the PA during the cycle (cm/s)	77±32		0.82
Average velocity [4,6,7]	Mean velocity in the PA (cm/s)	7.1±2.7	0.13	0.01
Acceleration time [4,7,10]	Time to peak of velocity (ms)	103±40		0.11
Cardiac output [4,6,10]	Indexed output flow in the pulmonary trunk ($l/mn/m^2$)	2.7±0.86		0.68
Volume of acceleration [4,10]	Indexed V. ejected during acceleration time (mL/m^2)	11.8±4.1	0.09	0.03
Maximum flow acceleration [10]	Maximal upward slope of the flow curve (mL/s^2)	26±11		0.51
RV ejection fraction[6]	**Ejection Fraction (%)**	**41±13**	**0.34**	**<10^{-4}**
RV end-diastole volume [6]	Indexed end-diastole volume (mL/m^2)	102±45		0.08
RV end-systole volume [6]	Indexed end-systole volume (mL/m^2)	63±38	0.13	0.01
Septumcurvature[8]	Inverse of septal curvature radius (dm^{-1})	1.5±2.1		0.68

Legend : PA=Pulmonary Artery, RV=Right Ventricle

a subset of the population arbitrarily chosen so that the size of the sample is 10 patients per tested variable. We used a stepwise backward method based on the Akaikeinformation criterion usingmPAP as the dependent variable. Regression equation was expressed as the sum of the non-adjusted regression coefficient plus each significant parameter multiplied by its β weight. The model's overall significance wasexpressed bythe p-value of the analysis. The performance of the prediction was assessed by a linear regression analysis between the predicted and the measured mPAP performed within the whole population. The results were expressed with coefficient of determination, p-value and limits of agreement computed as 1.96 times the standard deviation of the residuals.

Diagnosis of PH by MRI

Notwithstanding disease's severity and etiological subtypes, 2 groups of patients were defined according to their value of mPAP: group H (mPAP>25mmHg) and group N (mPAP≤25mmHg). In order to predict patient's group affiliation (H or N), a multivariate logistic regression was performed with a stepwise backward method based on the Akaike information criterion using the parameters previously identified as potential predictors. The probability of the diagnosis was expressed as the inverse logit transform of a linear function of each significant parameter. Results were expressed as specificity to obtain a sensitivity of 100% and represented the percentage of spared right heart catheterization. Results were illustrated by a Receiver Operating Characteristic (ROC) curve.

Reproducibility of MRI parameters

Inter-observer reproducibility was assessed,on the 25 first patients,for the parameters selected by the multivariate models. Results were represented by a Bland-Altman diagram. The observers were both experimented in cardiac MRI (CV: 2years and LB: 8years).

RESULTS

The population was constituted of 22 men (45.8%) and 34 females. The mean age was 61.1 ± 16.5 years. Two patients (3.5%) were excluded for poor quality of high resolution pulmonary flow curve.The other patients were eventually classified using the actual PH classification[15]: 27 patients (50%) were diagnosed with PH type 1 (pulmonary arterial hypertension), 8 patients (15%) with PH type 4, 4 patients (7%) with PH type 2,6 patients (11%) with PH of other type (1'-3-5) and 9patients (17%) with no PH. The mean NYHA class was 2.7. The six-minute walking distance was 405±125m. The pulsed oxygen saturation was 92±4.7. Nine patients (84%)were supplied with oxygen.

Prediction of mPAP by MRI

The results of the univariate linear regression analyses for every parameter found in our review of the literature are presented in Table 1. Only the following parameters were submitted to the multivariate analysis: Pulmonary artery indexed min and max areas, right ventricle ejection fraction.

The multivariate linear analysis was performed within a subset of 30 patients. The backward regression converged significantly ($p<10^{-4}$) and kept only the minimum pulmonary artery indexed area and the right ventricle ejection fraction. The multivariate prediction model, in our population, was:

$$mPAP^{(mmHg)} = 41.9 \pm 8.0 + 2.7 * Surface_{min}^{(cm2/m2)} - 0.49 * Ejection\ Fraction^{(\%)}$$

The capacity of the model to predict mPAP, in the whole population, is illustrated with (Figure 2) ($p<10^{-4}$). The coefficient of determination of the linear prediction is $r^2=0.50$. The limit of agreement of the two methods was 14.5mmHg and the maximum error was 32.2 mmHg.

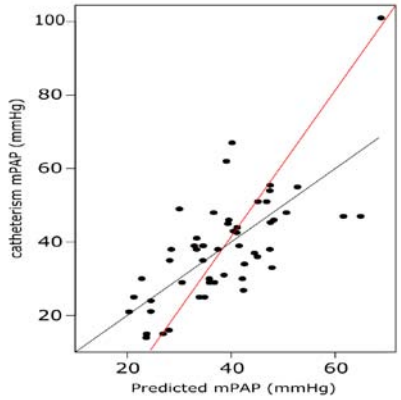

Figure 2: Regression analysis of the predicted mean pulmonary pressure compared to the measured value during a right heart catheterization. The red line is the correlation line, whereas the black line represents the identity.

Diagnosis of PH by MRI

Group N was constituted of 9 patients and group H of 45 patients. There was no difference between group N and group H concerning age, sex or morphological characteristics but, of course, PAP (mean, diastolic and systolic) and pulmonary vascular resistance were higher in group H.

The multivariate logisticanalysis was performed within a subset of 30 patients. The backward regression converged significantly ($p<10^{-4}$) and kept only the pulmonary artery maximum indexed surface and the right ventricle ejection fraction.The prediction model, in our population, was:

$$p(PH) = logit\_inv\left(\begin{array}{l} 6.74 \pm 4.4 + 5.9 * \\ Surface_{max}^{(cm2/m2)} - 19.1 * Ejection\ Fraction^{(\%)} \end{array}\right)$$

The capacity of the model to predict PH in the whole population was presented in a ROC curve (Figure 3). The area under the ROC curve was 0.93. To achieve asensitivity of 100% (no PH is undetected)

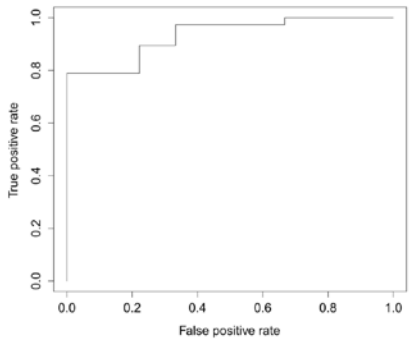

Figure 3: Diagnosis capacity of cardiac MRI to detect patient with PH.

the test yielded a specificity of 80%. Therefore 80% of the normal patients would have been correctly diagnosed by the test and the corresponding right heart catheterizationscould have been avoided. When the two parameters were assessed separately, the area under the ROC curves were retrospectively 0.85 for the pulmonary artery maximum indexed surface and 0.87 for the right ventricle ejection fraction.

Reproducibility of MRI parameters

The reproducibility of right ventricle ejection fraction, pulmonary artery indexed surface in end-diastole and end-systole have been assessed on the 25 first patients of the population. The bland and Altman analysis yielded no significant bias for the intra-observer reproducibility of the parameters and the limits of agreement were respectively: 9% for the ejection fraction, 0.4cm^2 and 0.39cm^2 for the min and max pulmonary artery surfaces (Figure 4).

DISCUSSION

Our study confirms the importance of cardiac MRI in the assessment of PH. Thanks to a multivariate logistic regression model we were able to discriminate patients with mPAP lower than the actual diagnostic threshold (≤25mmHg) versus those with higher values. These results suggest that cardiac MRI could be used as a first line surrogate test after echocardiography for a screening purpose in order to avoid unnecessary right heart catheterization and its risk of complications.

Our results are in line with previous studies. The importance of the pulmonary trunk surface has already been pointed out by Sanz et al who reported that this simple parameter could be used to separate PH patients from normal patients in a population suspectedof PH with area under the ROC curve of 0.95 [7]. The area under the curve in our population was somewhat lower (0.85) whereas the two studies had similar design. In another more recent study, the same team also emphasized the role of right ventricle ejection fraction as predictor of PH [6]. The ejection fraction was also recognized as a potential predictor of mPAP with r^2=0.29 by Swift et al [9]. Our study confirmsthat pulmonary trunk surface and right ventricle ejection fraction are good parameters to discriminate patient with/without PHin a population selected by an echocardiographic screening and suspected of PH. By combining those two parameters, we were able to obtain an area under the ROC curve of 0.93. In our study, the prediction of mPAP based on MRI datayielded a limit of confidence

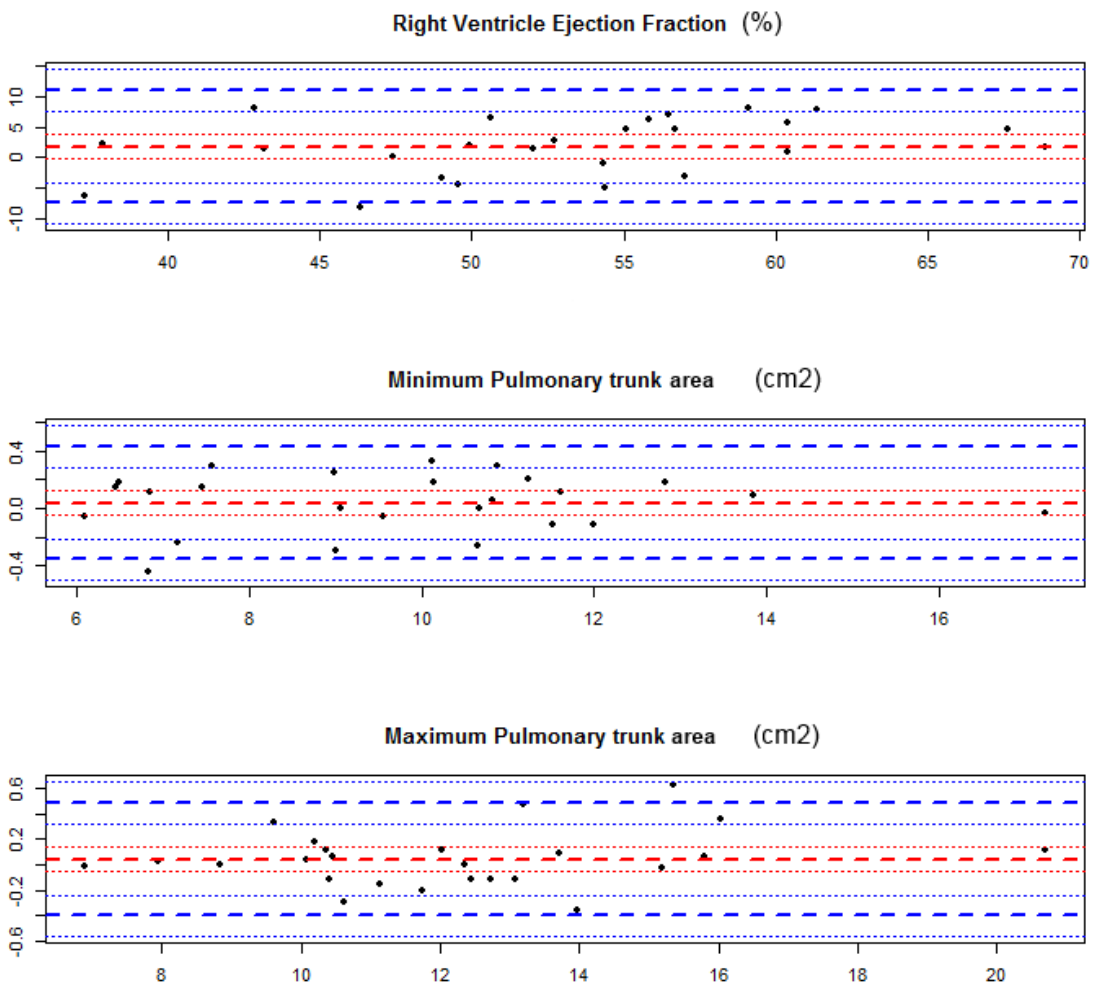

Figure 4: Reproducibility of the three parameters retained by the multivariate analysis in our population, as Bland and Altman plots.

(+2DS of the error) of15mmHg. This value has been already reportedina recent study from Zhang et al [16].

However, in contradiction with Sanz team [6,7], there was no clear linear correlation between the mean velocity in the pulmonary trunk and mPAP in our population. This is probably due to a non-linear link between these parameters. Mean velocity indeedcorresponds tothe ratio of the pulmonary stroke volume and the mean pulmonary trunk area. At the onset of the disease, the numerator is often normal and the denominator elevated. While the disease evolves, the numerator decreases and the denominator increasesas well. Therefore, the link between mean velocity and mPAPis probably not linear, as Garcia-Alvarez et al noticed [6].

Other recent studies such as Kreitner et al. [10] have proposed to use more complex parameters such as acceleration time (time to peak velocity), maximal systolic flow, volume of acceleration (area under the flow curve during acceleration time) or maximal upward slope of the pulmonary trunk flow curve. The modifications of the pulmonary flow curves during the evolution of PH have been well described in echocardiography [17] and correlations between those parameters and mPAP were expected. However, in our study, the correlations were very low. This could be explained by the low temporal resolution of MRI when compared to echocardiography. Indeed, even our so-called high temporal resolution phase contrast sequence had a nominal temporal resolution of 15ms (two TR). Moreover, these acquisitions were performed in free-breathing and lasted several minutes (time to perform three excitations per k-space line). Recently, we proved that such acquisitions spanned over a large number of heart beats had a lower temporal resolution due to the necessity to realign and to project each cardiac cycle into a mean template during the reconstruction phase [18]. This difference between the nominal temporal resolution (two TR) and the real temporal resolution after reconstruction is a possible explanation why Roeleveld et al [19] found no correlation between mPAP and acceleration time (p=0.21) or between systolic PAP and acceleration/ejection time (p=0.10). Another explanation for the low correlations between flow information and PAP could reside in the non-linear relationship between flow and pressure and in the existence of backwards compression waves due to reflexion. In other words, the shape of the pulmonary flow curve is influenced by the pulmonary resistance and by the pulmonary capacitance.

Recently, septal curvature was proposed as a good marker of mPAP in a pediatric population [8]. This was not confirmed in our adult population. This could be explained by a good ventricular synchrony in their pediatric population (mean QRS duration reported at 84ms). In adult populations of PAH, left/right ventricular dyssynchronyis common and can highly influence the septum motion.

LIMITATIONS

This study was performed on a relatively small population of 56 patients prospectively included for an assessment of a suspected PH in a unique center. The MRI assessment and the right heart catheterization was performed within 24h most of the time (85%) but not always (maximum = 3 days).

CONCLUSION

The use of cardiac MRI in the assessment of PH has been advocated many times. The prediction of mPAP by combination of MRI-derived parameters may be feasible in certain very well trained teams but seems difficult for an every-day clinical practice. Whereas the coefficient of determination of such prediction can reach r^2=0.50, the individual errors of predictions are too high to replace right heart catheterization.

However, the right ventricle ejection fraction and the pulmonary artery area are simple parameters able to discriminate patients with/without PH. MRI could be used as a second screening test after echocardiography, when the situation is ambiguous.

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REFERENCES

1. Bradlow WM, Hughes ML, Keenan NG, Bucciarelli-Ducci C, Assomull R, Gibbs JSR, et al. Measuring the heart in pulmonary arterial hypertension (PAH): implications for trial study size. J Magn Reson Imaging. 2010; 31: 117–124.

2. Hoeper MM, Bogaard HJ, Condliffe R, Frantz R, Khanna D, Kurzyna M, et al. Definitions and diagnosis of pulmonary hypertension. J. Am. Coll. Cardiol. 2013; 62: D42-D50.

3. Nogami M, Ohno Y, Koyama H, Kono A, Takenaka D, Kataoka T, et al. Utility of phase contrast MR imaging for assessment of pulmonary flow and pressure estimation in patients with pulmonary hypertension: comparison with right heart catheterization and echocardiography. J Magn Reson Imaging. 2009; 30: 973–980.

4. Abolmaali N, Seitz U, Esmaeili A, Kock M, Radeloff D, Ackermann H, et al. Evaluation of a resistance-based model for the quantification of pulmonary arterial hypertension using MR flow measurements. J Magn Reson Imaging. 2007; 26: 646–653.

5. Ley S, Mereles D, Puderbach M, Gruenig E, Schöck H, Eichinger M, et al. Value of MR phase-contrast flow measurements for functional assessment of pulmonary arterial hypertension. Eur Radiol. 2007; 17: 1892–1897.

6. García-Alvarez A, Fernández-Friera L, Mirelis JG, Sawit S, Nair A, Kallman J, et al. Non-invasive estimation of pulmonary vascular resistance with cardiac magnetic resonance. Eur. Heart J. 2011; 32: 2438–2445.

7. Sanz J, Kuschnir P, Rius T, Salguero R, Sulica R, Einstein AJ, et al. Pulmonary arterial hypertension: noninvasive detection with phase-contrast MR imaging. Radiology. 2007; 243: 70–79.

8. Pandya B, Quail MA, Steeden JA, McKee A, Odille F, Taylor AM, et al. Real-time magnetic resonance assessment of septal curvature accurately tracks acute hemodynamic changes in pediatric pulmonary hypertension. Circ Cardiovasc Imaging. 2014; 7: 706–713.

9. Swift AJ, Rajaram S, Hurdman J, Hill C, Davies C, Sproson TW, et al. Noninvasive estimation of PA pressure, flow, and resistance with CMR imaging: derivation and prospective validation study from the ASPIRE registry. JACC Cardiovasc Imaging. 2013; 6: 1036–1047.

10. Kreitner K-F, Wirth GM, Krummenauer F, Weber S, Pitton MB, Schneider J, et al. Noninvasive assessment of pulmonary hemodynamics in patients with chronic thromboembolic pulmonary hypertension by high temporal resolution phase-contrast MRI: correlation with simultaneous invasive pressure recordings. Circ Cardiovasc Imaging. 2013; 6: 722–729.

11. Ling Y, Johnson MK, Kiely DG, Condliffe R, Elliot CA, Gibbs JSR, et al. Changing demographics, epidemiology, and survival of incident pulmonary arterial hypertension: results from the pulmonary hypertension registry of the United Kingdom and Ireland. Am. J. Respir. Crit. Care Med. 2012; 186: 790–796.

12. Yock PG, Popp RL. Noninvasive estimation of right ventricular systolic pressure by Doppler ultrasound in patients with tricuspid regurgitation. Circulation. 1984; 70: 657–662.

13. Bonnemains L, Mandry D, Marie P-Y, Micard E, Chen B, Vuissoz P-A. Assessment of right ventricle volumes and function by cardiac MRI: quantification of the regional and global interobserver variability. Magn Reson Med. 2012; 67: 1740–1746.

14. R Development Core Team. R: A Language and Environment for Statistical Comput ing. Vienna: R Foundation for Statistical Computing; 2009.

15. Galiè N, Humbert M, Vachiery J-L, Gibbs S, Lang I, Torbicki A, et al. 2015 ESC/ERS Guidelines for the diagnosis and treatment of pulmonary hypertension: The Joint Task Force for the Diagnosis and Treatment of Pulmonary Hypertension of the European Society of Cardiology (ESC) and the European Respiratory Society (ERS): Endorsed by: Association for European Paediatric and Congenital Cardiology (AEPC), International Society for Heart and Lung Transplantation (ISHLT). Eur. Heart J. 2016; 37: 67–119.

16. Zhang Z, Wang M, Yang Z, Yang F, Li D, Yu T, et al. Noninvasive prediction of pulmonary artery pressure and vascular resistance by using cardiac magnetic resonance indices. Int. J. Cardiol. 2017; 227: 915–922.

17. Bossone E, Ferrara F, Grünig E. Echocardiography in pulmonary hypertension. Curr. Opin. Cardiol. 2015; 30: 574–586.

18. Bonnemains L, Odille F, Meyer C, Hossu G, Felblinger J, Vuissoz P-A. Is High Temporal Resolution Achievable for Paediatric Cardiac Acquisitions during Several Heart Beats? Illustration with Cardiac Phase Contrast Cine-MRI. PLoS ONE. 2015; 10: e0143744.

19. Roeleveld RJ, Marcus JT, Boonstra A, Postmus PE, Marques KM, Bronzwaer JGF, et al. A comparison of noninvasive MRI-based methods of estimating pulmonary artery pressure in pulmonary hypertension. J Magn Reson Imaging. 2005; 22: 67–72.