DOI: 10.1002/pul2.12025

RESEARCH LETTER

Pulmonary Circulation Open Access | PVRI Pulmonary Vascular Research Institute | WILEY

Development of a PET/MRI exercise stress test for determining cardiac glucose dependence in pulmonary arterial hypertension

Gregory P. Barton[1,2,3] | **Philip A. Corrado**[1] | **Christopher J. Francois**[4] | **James R. Runo**[5] | **Naomi C. Chesler**[5,6,7] | **Alan B. McMillan**[1,4,5] | **Oliver Wieben**[1,4] | **Kara N. Goss**[2,3,6]

[1]Department of Medical Physics, School of Medicine and Public Health, University of Wisconsin, Madison, Wisconsin, USA

[2]Department of Pediatrics, School of Medicine and Public Health, University of Wisconsin, Madison, Wisconsin, USA

[3]Department of Internal Medicine, University of Texas Southwestern Medical Center, Dallas, Texas, USA

[4]Department of Radiology, School of Medicine and Public Health, University of Wisconsin, Madison, Wisconsin, USA

[5]Department of Medicine, School of Medicine and Public Health, University of Wisconsin, Madison, Wisconsin, USA

[6]Department of Biomedical Engineering, School of Medicine and Public Health, University of Wisconsin, Madison, Wisconsin, USA

[7]Department of Biomedical Engineering, University of California-Irvine, Irvine, California, USA

Correspondence

Kara N. Goss, Department of Medicine and Pediatrics, Pulmonary and Critical Care Medicine, UT Southwestern Medical Center, 5323 Harry Hines Blvd., K5.104 (MC 8558), Dallas, TX 75390-8558, USA.

Email: Kara.Goss@UTSouthwestern.edu

Keywords

18-fluorodeoxyglucose, cardiac magnetic resonance, exercise, positron-emission tomography, pulmonary arterial hypertension

Funding information

National Institute of Allergy and Infectious Diseases, Grant/Award Number: T32AI007635; American Heart Association, Grant/Award Number: 18CDA34110440; National Center for Advancing Translational Sciences, Grant/Award Number: NIH UL1TR000427; National Heart, Lung, and Blood Institute, Grant/Award Numbers: F31HL144020, R01HL147590, R01HL154624; United Therapeutics Corporation, Grant/Award Number: Jenesis Innovative Clinical Research Award

To the Editor,

Pulmonary arterial hypertension (PAH) is a silent progressive disease of the pulmonary vasculature that often presents late in the disease course. Elevated pulmonary artery pressure (PAP) and pulmonary vascular resistance (PVR) cause right ventricular (RV) pressure overload, metabolic shifts, and myocardial remodeling resulting in impaired RV contractility, dysfunction, and subsequent RV failure.[1,2] Notably, RV function is known to be a better prognostic factor than PAP or PVR in PAH.[3] The treatment for PAH focuses on reducing RV afterload with vasodilator therapy, yet despite the reduction in PVR, the resting RV dysfunction may progress in patients with PAH.[3] Thus, the reason for right heart failure cannot be completely attributed to the changes in pulmonary blood flow dynamics but may also involve intrinsic metabolic shifts in the RV.

RV metabolic shifts and myocardial remodeling result in impaired RV contractility and occur early in the progression to RV failure,[1,2] as cardiac metabolism shifts from predominantly fatty acid metabolism to increasing utilization of glucose.[4] However, tools to evaluate the RV metabolic state are limited, and may not be sufficient to detect early disease. Exercise testing can be added to

imaging protocols and may aid in the earlier identification of disease states. When combined with imaging modalities such as positron-emission tomography/magnetic resonance imaging (PET/MRI), this has the potential to offer greater diagnostic capacity, providing robust information on RV structure and function, and permitting the determination of RV metabolic shifts in the setting of PAH.

Whether exercise can unmask RV glucose dependency early in PAH disease progression remains unclear. This has not been tested previously in part because classic PET/MRI protocols involve a single bolus of radiotracer with imaging 1 h later, and thus do not capture real-time metabolic changes in response to stressors such as exercise. Therefore, the purpose of this proof-of-concept study was to develop a rest-stress single scanning PET/MRI protocol that could identify the effect of exercise on cardiac metabolic substrate flexibility in patients with PAH. Further, we hypothesized that the RV in PAH patients would demonstrate a preferential increase in glucose utilization relative to the LV during exercise.

METHODS

Participants

Two newly diagnosed PAH patients with scleroderma (Subject 1: female; Subject 2: male) were recruited before initiation of vasodilator therapy from the University of Wisconsin-Madison Pulmonary Hypertension Clinic and provided written informed consent to participate. This study was approved by the University of Wisconsin Institutional Review Board (2019-0286).

PET/MRI protocol

Subjects underwent a serial rest-stress test in a 3.0 T PET-MRI scanner (GE Signa PET/MR Discovery 750 W; GE Healthcare). Participants completed baseline balanced steady-state free precession (bSSFP) cardiac MRI sequences, acquired consistent with standard clinical cardiac imaging for the determination of end-diastolic volume (EDV), end-systolic volume (ESV), stroke volume (SV), cardiac output (CO), and ejection fraction (EF), respectively. Flow through the main pulmonary artery (MPA) and aorta (Ao) was assessed with cardiac gated, cine two-dimensional (2D) phase-contrast (PC) sequences during rest and exercise. MPA flow was used to assess the change in SV and CO from rest to exercise as this reflects the output of the RV. In-scanner exercise prescription was based on the 6-min walk distance (6MWD) performance, and patients performed 10 min of supine exercise (mean power output: 33 ± 4 W) using a commercial MR-compatible recumbent stepper (Cardio Stepper Module; Ergospect GmbH).

PET imaging consisted of 15 min of resting PET data acquisition followed by the onset of in-bore exercise in which subjects performed stepping exercise for 10 min, followed by a 10-min recovery period (Figure 1a). To determine cardiac glucose uptake, 18-fluorodeoxyglucose (18F-FDG) was administered in two separate boluses of 5 mCi each before rest and exercise imaging, with dynamic 18F-FDG PET data acquired continuously. PET images were manually segmented (ITK-SNAP analysis software).[5] Plasma time–activity curves were determined from the PET LV blood pool and Patlak analysis was used to determine RV and left ventricular (LV) glucose uptake rates (K_i),[6,7] to determine the ratio of RV/LV K_i as previously described [8] (Figure 1b).

All data are expressed as mean and standard deviation unless otherwise stated. Given this is a proof-of-concept study involving two subjects, there were no statistical analyses performed.

RESULTS

Clinical and baseline cardiac functional characteristics

Two PAH patients with scleroderma completed the clinically standard diagnostic assessment, revealing mPAP: 33.5 ± 7.8 mmHg, PVR: 5.7 ± 1.84 Woods units; CI: 2.14 ± 0.47 L/min/m^2; 6MWD: 401 ± 8 m; Brain natriuretic peptide (BNP): 102 ± 81 pg/ml; NYHA functional class: II.

Resting cardiac structure and function measures were as follows: LV (EDV: 134 ± 48 ml, ESV: 61 ± 36 ml, SV: 73 ± 12 ml, CO: 4.36 ± 1.60 L/min, EF: $56\% \pm 11\%$, mass: 68 ± 41 g), and RV (EDV: 154 ± 34 ml, ESV: 90 ± 33 ml, SV: 65 ± 2 ml, EF: $43\% \pm 9\%$, mass: 19 ± 7 g).

PET/MRI exercise stress measures

The exercise challenge resulted in expected increases as derived from 2D-PC MPA flow in heart rate (HR) (59 ± 12 vs. 81 ± 7 bpm), SV (72 ± 16 vs. 104 ± 3 ml), and CO (4.28 ± 1.81 vs. 8.43 ± 0.96 L/min), respectively. Notably, there was a substantial increase in the rate of glucose uptake (53%) in the RV for each patient rest to exercise (Subject 1: 0.0181 vs. 0.0246 min^{-1}; Subject 2: 0.00179 vs. 0.00305 min^{-1}), respectively. In the LV, there was a much more modest increase in glucose uptake (6%) from rest to exercise (Subject 1: 0.0426 vs. 0.0433 min^{-1};

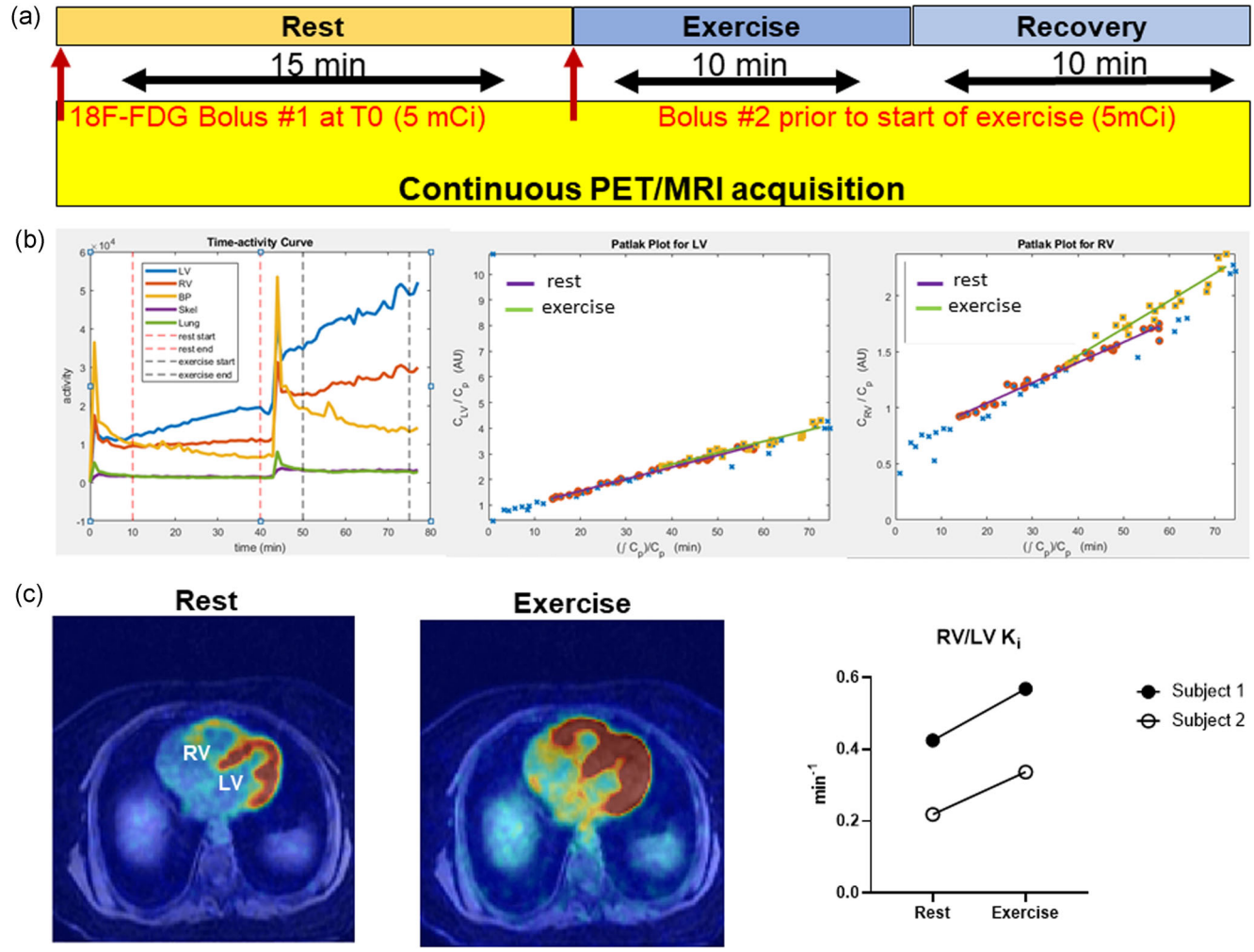

FIGURE 1 (a) Continuous 18-fluorodeoxyglucose (18F-FDG) positron-emission tomography (PET) acquisition using a two-bolus approach permits quantification of the dynamic glucose uptake response in the right (RV) and left ventricle (LV) during a serial rest-stress protocol. (b) Time-activity curves during the dual bolus injection of FDG for the blood pool, RV, LV, lung, and paraspinal muscles, respectively (left). The LV K_i (middle) and RV K_i (right) at rest and exercise were calculated using Patlak analysis. (c) Representative images from a PAH patient (Subject 1) demonstrating 18F-FDG uptake in the right (RV) and left ventricle (LV) during rest and exercise, respectively. From these representative images, LV K_i was similar during rest and exercise (0.0426 vs. 0.0433 min^{-1}), respectively. However, there was a substantial increase in RV K_i during exercise (0.0181 vs. 0.0246 min^{-1}). Both subjects exhibited a preferential increase in RV/LV K_i during exercise which was coupled with two-fold increases in cardiac output

Subject 2: 0.0082 vs. 0.0091 min^{-1}), respectively. Overall, this resulted in a preferential increase in RV/LV K_i (Subject 1: 0.425 vs. 0.568 min^{-1}; Subject 2: 0.219 vs. 0.337 min^{-1}) (Figure 1c).

DISCUSSION

The purpose of this study was to determine the feasibility of a PET/MRI exercise stress test to determine the cardiac glucose metabolic flexibility in PAH patients. We hypothesized that the RV in PAH patients would demonstrate a preferential increase in glucose utilization during exercise relative to the LV. The main findings of this study were that the RV exhibited a 53% increase in K_i while the LV exhibited a 6% increase in K_i, and the RV/LV K_i showed an overall increase of 43% from rest to exercise. These changes in RV glucose uptake were observed in parallel with a 43%, 50%, 122% increase in HR, SV, and CO, respectively. Presumably, the nonfailing LV primarily increased fatty acid utilization during exercise (not measured here), while the dysfunctional RV had significantly greater glucose dependence.

The myocardium is a metabolic omnivore[9] and in healthy myocardium, substrate metabolism is superbly coupled to contractile function and enables the myocardium to adapt to stress on a beat-to-beat basis. Loss of metabolic flexibility is a hallmark of various cardiac

diseases.[4] During the process of heart failure, cardiac metabolism shifts from predominantly fatty acid metabolism to increasing utilization of glucose metabolism.[10] Attenuated metabolic flexibility, with potential changes to adenosine triphosphate production in the myocardium, highlights perturbations in substrate metabolism which are now considered as causes rather than consequences of cardiac disease.[11] Previous work in PAH patients demonstrated altered metabolism with increased RV dependency for glucose which was inversely associated with contractile function and directly related to PVR.[12] Furthermore, the RV metabolic milieu has been shown to be sensitive to therapeutic treatments in PAH patients demonstrated by a reduction in RV glucose utilization which was dose-dependent after 6 months of carvedilol therapy,[3] which suggests the ability to augment metabolic flexibility. Although these previous works demonstrate both RV glucose dependency in PAH and that the metabolic environment is sensitive to alteration following chronic therapeutic administration, to date there has not been the development of a test to assess metabolic substrate flexibility in the acute setting in a manner relevant to everyday activities. Similar to these previous studies exhibiting increased glucose utilization in the RV, the data in this pilot study show that the use of a physiological stressor permitted the unmasking of a preferential use of glucose in the RV.

In this pilot study, we tested the feasibility of performing a PET/MRI stress test in two PAH patients as a way to determine acute metabolic adaptations in the RV using a relevant workload that is akin to the 6MWD. We found that the RV exhibits a greater glucose dependency relative to the LV in PAH. Previous studies probing RV glucose uptake have utilized the standard clinical protocol which is a single bolus of 18F-FDG followed by a static scan 1 h after bolus injection to measure standard uptake values. The novelty of this study is the utilization of dynamic PET acquisition and the use of two mini boluses of 18F-FDG, which serves two purposes. In concert with dynamic PET acquisition, the use of two bolus injections (i.e., at rest and just before exercise) permits the quantification of real-time RV and LV glucose uptake using kinetic modeling[6,7] during a serial rest-stress protocol. Future work utilizing this PET/MRI technique in PAH patients should assess whether greater RV glucose dependency at baseline or during therapy is an independent predictor of adverse outcomes. Further, the technique may be useful to assess for metabolic effects of current vasodilators or novel therapies, as there are currently no specific RV targeted therapies for PAH.

ACKNOWLEDGMENTS

This study was supported by United Therapeutics through the Jenesis Innovative Clinical Research Award (Kara N. Goss). Kara N. Goss was also supported by the University of Wisconsin Clinical and Translational Science Award (CTSA) program, through the NIH National Center for Advancing Translational Sciences (NCATS), grant NIH UL1TR000427 (Primary investigator Marc Drezner; 4KL2TR000428-10), Parker B. Francis Fellowship Award, American Heart Association Career Development Award (Kara N. Goss, #18CDA34110440). Gregory P. Barton was supported by the National Institute of Allergy and Immunological Diseases under award number T32AI007635. Philip A. Corrado was supported by the National Heart, Lung, and Blood Institute of the NIH under Award Number F31HL144020. Naomi C. Chesler was supported by the National Heart, Lung, and Blood Institute of the NIH under Award Numbers R01HL154624 and R01HL147590. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health.

CONFLICTS OF INTERESTS

The authors declare that there are no conflict of interests.

ETHICS STATEMENT

The work is the original work of the authors, has not been previously published, and was performed in manner consistent with the Committee on Publication Ethics (COPE) guidelines.

AUTHOR CONTRIBUTIONS

Conceptualization: Kara N. Goss. *Methodology*: Kara N. Goss, Gregory P. Barton, Christopher J. Francois, James R. Runo, Naomi C. Chesler, Alan B. McMillan, and Oliver Wieben. *Validation*: Kara N. Goss, Alan B McMillan, and Gregory P. Barton. *Analysis*: Gregory P. Barton, Philip A. Corrado, and Kara N. Goss. *Writing—original draft preparation*: Gregory P Barton. *Writing—review and editing*: Philip A. Corrado, Christopher J. Francois, Naomi C. Chesler, Alan B. McMillan, James R. Runo, Oliver Wieben, Kara N. Goss. *Funding acquisition*: Kara N. Goss. *Guarantor*: Kara N. Goss. All authors have read and agreed to the published version of the manuscript.

ORCID

Gregory P. Barton https://orcid.org/0000-0001-7471-5488
Kara N. Goss http://orcid.org/0000-0003-2015-9169

REFERENCES

1. van de Veerdonk MC, Kind T, Marcus JT, Mauritz GJ, Heymans MW, Bogaard HJ, Boonstra A, Marques KM, Westerhof N, Vonk-Noordegraaf A. Progressive right

ventricular dysfunction in patients with pulmonary arterial hypertension responding to therapy. J Am Coll Cardiol. 2011; 58:2511–19. https://doi.org/10.1016/j.jacc.2011.06.068
2. Vonk-Noordegraaf A, Haddad F, Chin KM, Forfia PR, Kawut SM, Lumens J, Naeije R, Newman J, Oudiz RJ, Provencher S, Torbicki A, Voelkel NF, Hassoun PM. Right heart adaptation to pulmonary arterial hypertension: physiology and pathobiology. J Am Coll Cardiol. 2013;62:D22–33. https://doi.org/10.1016/j.jacc.2013.10.027
3. Farha S, Saygin D, Park MM, Cheong HI, Asosingh K, Comhair SA, Stephens OR, Roach EC, Sharp J, Highland KB, DiFilippo FP, Neumann DR, Tang W, Erzurum SC. Pulmonary arterial hypertension treatment with carvedilol for heart failure: a randomized controlled trial. JCI Insight. 2017;2(16): e95240. https://doi.org/10.1172/jci.insight.95240
4. Karwi QG, Uddin GM, Ho KL, Lopaschuk GD. Loss of metabolic flexibility in the failing heart. Front Cardiovasc Med. 2018;5:68. https://doi.org/10.3389/fcvm.2018.00068
5. Yushkevich PA, Piven J, Hazlett HC, Smith RG, Ho S, Gee JC, Gerig G. User-guided 3D active contour segmentation of anatomical structures: significantly improved efficiency and reliability. Neuroimage. 2006;31:1116–28. https://doi.org/10.1016/j.neuroimage.2006.01.015
6. Barton GP, Vildberg L, Goss K, Aggarwal N, Eldridge M, McMillan AB. Simultaneous determination of dynamic cardiac metabolism and function using PET/MRI. J Nucl Cardiol. 2019;26:1946–57. https://doi.org/10.1007/s12350-018-1287-7
7. Corrado PA, Barton GP, Razalan-Krause FC, François CJ, Chesler NC, Wieben O, Eldridge M, McMillan AB, Goss KN. Dynamic FDG PET imaging to probe for cardiac metabolic remodeling in adults born premature. J Clin Med. 2021; 10:1301.
8. Ohira H, deKemp R, Pena E, Davies RA, Stewart DJ, Chandy G, Contreras-Dominguez V, Dennie C, Mc Ardle B, Mc Klein R, Renaud JM, DaSilva JN, Pugliese C, Dunne R, Beanlands R, Mielniczuk LM. Shifts in myocardial fatty acid and glucose metabolism in pulmonary arterial hypertension: a potential mechanism for a maladaptive right ventricular response. Eur Heart J Cardiovasc Imaging. 2016;17:1424–31. https://doi.org/10.1093/ehjci/jev136
9. Stanley WC, Recchia FA, Lopaschuk GD. Myocardial substrate metabolism in the normal and failing heart. Physiol Rev. 2005;85:1093–129. https://doi.org/10.1152/physrev.00006.2004
10. Doenst T, Pytel G, Schrepper A, Amorim P, Färber G, Shingu Y, Mohr FW, Schwarzer M. Decreased rates of substrate oxidation ex vivo predict the onset of heart failure and contractile dysfunction in rats with pressure overload. Cardiovasc Res. 2010;86: 461–70. https://doi.org/10.1093/cvr/cvp414
11. Neubauer S. The failing heart—an engine out of fuel. N Engl J Med. 2007;356:1140–51. https://doi.org/10.1056/NEJMra063052
12. Yang T, Wang L, Xiong CM, He JG, Zhang Y, Gu Q, Zhao ZH, Ni XH, Fang W, Liu ZH. The ratio of (18)F-FDG activity uptake between the right and left ventricle in patients with pulmonary hypertension correlates with the right ventricular function. Clin Nucl Med. 2014;39:426–30. https://doi.org/10.1097/rlu.0000000000000422

How to cite this article: Barton GP, Corrado PA, Francois CJ, Runo JR, Chesler NC, McMillan AB, Wieben O, Goss KN. Development of a PET/MRI exercise stress test for determining cardiac glucose dependence in pulmonary arterial hypertension. Pulm Circ. 2022;12:e12025. https://doi.org/10.1002/pul2.12025