



Coronary Flow Reserve in Pregnant Rats with Increased Left Ventricular Afterload

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Abstract

Background: Coronary flow reserve (CFR) is used as a measure of coronary endothelial function. We investigated the effect of increased afterload on CFR of pregnant and non-pregnant rats.

Methods: Afterload increase in Wister rats (both pregnant and non-pregnant) was achieved by the infusion of angiotensin II (Ang II) for ~10 days or by subjecting them to transverse aortic constriction (TAC) for ~14 days. Control groups were infused with 0.9% NaCl or had sham surgery, respectively. In pregnant rats, the experiments were performed close to term gestation. Doppler velocity waveforms of the left main coronary artery were recorded using a high resolution ultrasound imaging system (Vevo 770, VisualSonics, Canada) at baseline while the animals were anesthetized with 1.5% inhaled isoflurane, and during maximal coronary dilatation obtained by the inhalation of 3.5% of isoflurane. CFR was calculated as the ratio between the peak coronary flow velocities (CFR_{peak}) and the velocity-time integrals (CFR_{VTI}) recorded at hyperemia and at baseline.

Results: CFR could be calculated in 60 of 75 (80%) animals. There were no differences in CFR between intervention and control groups irrespective of whether afterload was increased by Ang II or TAC. In the TAC-study CFR_{peak} (1.54 ± 0.07 vs 1.85 ± 0.17 ; $p = 0.03$) was decreased in pregnant compared to non-pregnant shams. When sham animals from both studies were pooled together both CFR_{peak} (1.42 ± 0.07 vs 1.86 ± 0.16 ; $p = 0.005$) as well as CFR_{VTI} (1.45 ± 0.07 vs 1.78 ± 0.12 ; $p = 0.03$) were significantly lower in pregnant rats compared to non-pregnant.

Conclusions: CFR can be measured non-invasively in rats using Doppler echocardiography and high concentrations of inhaled isoflurane as a coronary vasodilator. In pregnant rats, CFR is reduced close to term. CFR is not affected by increased left ventricular afterload caused by chronic Ang II infusion or TAC.

Citation: Songstad NT, Serrano MC, Sitras V, Johansen D, Ytrehus K, et al. (2014) Coronary Flow Reserve in Pregnant Rats with Increased Left Ventricular Afterload. PLoS ONE 9(7): e102147. doi:10.1371/journal.pone.0102147

Editor: Rajesh Gopalrao Katare, University of Otago, New Zealand

Received: February 1, 2014; **Accepted:** June 15, 2014; **Published:** July 9, 2014

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Funding: This work was supported by research grants from the Northern Norway Regional Health Authority, grant numbers 1411, 1668 and 2038 (<http://www.helse-nord.no/about-helse-nord/category5770.html>). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Competing Interests: The authors have declared that no competing interests exist.

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Introduction

Coronary flow reserve (CFR), i.e. the ratio of maximum to baseline coronary blood flow [1], is used as a measure of coronary endothelial function. Human studies have shown a link between impaired coronary microvascular function and adverse cardiovascular events [2,3]. In order to measure CFR, application of an agent with potent endothelium independent vasodilating properties is needed. Adenosine administered intravenously is usually preferred due to its rapid action and short half time [1,4], and has been used in both human [5,6] and animal studies [7,8]. Inhaled isoflurane, which is used as an anaesthetic in small animal research, is a potent coronary vasodilator. Hartley et al. have shown that the increase in coronary blood flow after administering

high concentrations of inhaled isoflurane can be used to estimate CFR in mice [9,10].

Normal pregnancy is characterised by increased cardiac preload and decreased afterload [11,12]. However, in hypertensive disorders of pregnancy, and in some women with congenital heart defects, the heart may be exposed to pathologically increased afterload [13]. Increased afterload reduces CFR in humans with aortic stenosis [14], and in dogs [15] and mice [10] with cardiac hypertrophy following aortic banding. Endothelium-dependent vasodilatation can be examined non-invasively in humans measuring flow mediated dilatation (FMD) of the brachial artery [16,17], and several studies have evaluated FMD in pregnancy [18–24]. However, it is debated whether endothelial function in the peripheral vessels correlates with endothelial function in the coronary vascular bed [1,17,25,26]. Furthermore, we are not

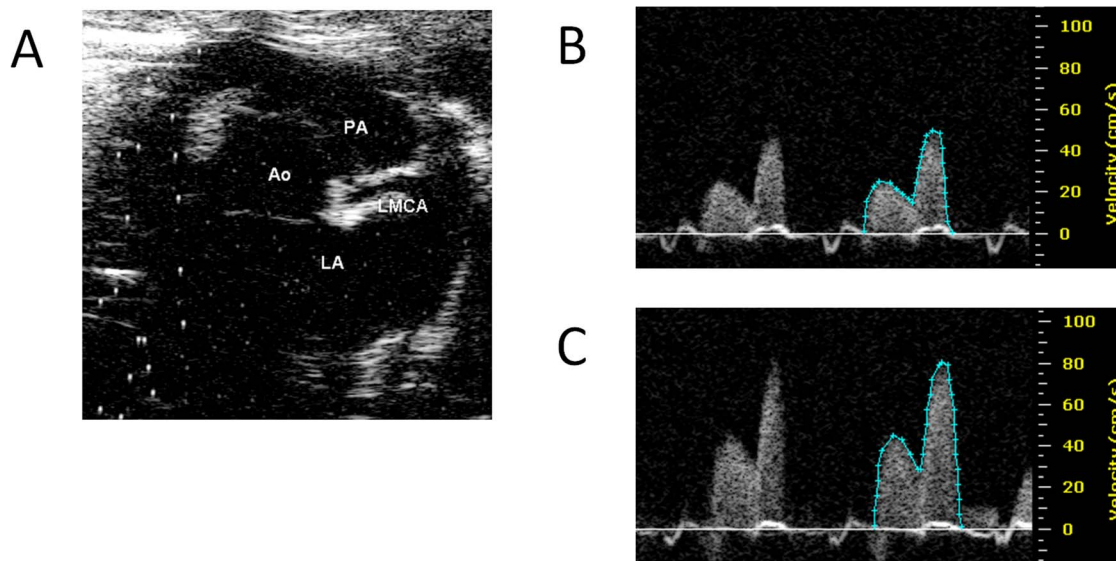


Figure 1. Measurement of coronary flow using Doppler echocardiography in rats. Parasternal short axis view of the heart (A) showing the Aorta (Ao), pulmonary artery (PA), left atrium (LA) and left main coronary artery (LMCA). Doppler velocity waveforms from the LMCA were traced and peak velocity and velocity time integrals were calculated during inhalation of 1.5% (B) and 3.5% (C) of isoflurane with oxygen. doi:10.1371/journal.pone.0102147.g001

aware of any published studies evaluating endothelial function in the coronary circulation during pregnancy, and to our knowledge the effect of increased afterload on CFR during pregnancy has not been reported.

The aims of this study were to (1) evaluate a non-invasive method of assessing CFR in rats using different concentrations of inhaled isoflurane for coronary vasodilation, (2) to investigate the differences in CFR between pregnant and non-pregnant rats and (3) to study how CFR is affected by increased afterload in pregnant and non-pregnant rats.

Materials and Methods

Ethics Statement

Animal experiments conformed to the Directive 2010/63/EU of the European Parliament on the protection of animals used for scientific purposes [27] and all procedures were approved by the Norwegian Committee on Ethics in Animal Experimentation (project ID 907 and 2177).

CFR was measured in young, female Wistar rats (Charles River, Sulzfeld, Germany) included in two experimental studies of increased cardiac afterload in pregnancy [28,29]. In the first study (Ang II-study) mini osmotic pumps (Alzet Model 2002, Cupertino, CA, USA) releasing 150 ng/kg/min of angiotensin (Ang) II (Calbiochem, Darmstadt, Germany) or 0.9% sodium chloride was implanted subcutaneously in the neck of pregnant and non-pregnant rats for ~10 days [28]. In the second study (TAC-study) transverse aorta constriction (TAC) or sham surgery was performed ~14 days before the experiments in pregnant (on gestational day 5–8) and non-pregnant rats [29]. Both interventions led to increased afterload and cardiac hypertrophy with increased mean pressure in ascending aorta (AngII-study: 110 ± 5 mmHg vs 84 ± 5 mmHg, $p = 0.001$. TAC-study: 127 ± 3 mmHg vs 96 ± 5 mmHg, $p < 0.001$) and heart weight (AngII-study: 896 ± 30 mg vs 768 ± 15 mg, $p = 0.001$. TAC-study: 845 ± 29 mg vs 671 ± 14 mg, $p < 0.001$) as well as increased expression of B-type natriuretic peptide [28,29]. In both studies the pregnant rats were examined close to term gestation

(term = ~21 days). Ten male rats were used to practice and evaluate the experimental procedure, dose of inhaled isoflurane and timing of CFR measurement using Doppler echocardiography. In four non-pregnant rats we compared the effect of 140 μ g/kg/min continuous adenosine [8] infusion through the external jugular vein to 3.5% isoflurane inhalation.

Echocardiography was performed using a high resolution ultrasound imaging system equipped with a RMV-710B transducer with a frequency of 25 MHz and a fixed focal length of 15 mm mounted on an integrated rail system (Vevo 770, Visualsonics, Toronto, Canada) as described earlier [28,29]. Anesthesia was induced with isoflurane 4% in 100% oxygen in an induction chamber. The rats were placed supine on a warm electric pad and inhaled isoflurane 1.5% in 100% oxygen was provided via a mask covering the rat's snout (Vevo Compact Anesthesia System, VisualSonics, Toronto, Canada) in spontaneously breathing rats (Ang II-study) or via an endotracheal tube in ventilated rats (TAC-study). The Doppler signals from the left main coronary artery (LMCA) was obtained from the parasternal short-axis view (Fig. 1A) by visualizing the aortic root and then moving the Doppler gate slightly anterior and to the left of the aorta. Doppler velocity waveforms with the highest peak flow velocity were recorded (Fig. 1B). Doppler signals could be detected even when the LMCA was not clearly visualized in B-mode echocardiography. After performing baseline measurements, the isoflurane concentration was increased to 3.5% and another recording of the LMCA Doppler signals was obtained after 2 minutes with the ultrasound probe fixed in the same position (Fig. 1C).

Echocardiography was performed without the knowledge of intervention, but the operator could not be blinded for pregnancy status. All ultrasound measurements were performed off-line without the knowledge of the animals' pregnancy status and intervention. Three consecutive cycles with good quality signals were measured and the average value was used for the statistics. Velocity-time integral (VTI) was outlined manually using the software provided with the ultrasound equipment (VisualSonics Vevo 770 v.3.0.0, Fig. 1BC), and peak velocity and VTI were

calculated by the software. Angle correction was not used. CFR was calculated as the ratio between coronary flow velocities recorded at hyperemia (3.5% isoflurane) and at baseline (1.5% isoflurane). CFR_{peak} was calculated as peak velocity at hyperemia/peak velocity at baseline and CFR_{VTI} was calculated as VTI at hyperemia/VTI at baseline. Only echocardiographic examinations performed by a single operator were included in each study (Ang II-study: M.C.S., TAC-study: N.T.S.). After ultrasound, blood pressure (BP) was measured invasively via a 2F microtip pressure-volume catheter (SPR-838; Millar Instruments Inc, Houston, TX, USA) in the ascending aorta [28,29].

Statistics

Data are reported as mean \pm standard error of the mean (SEM). One way analysis of variance (ANOVA) was used to compare groups and the Holm–Sidak method was used as post-hoc test. Independent-Samples T-test was used to compare two groups. Correlation between parametric variables was checked using Pearson Correlation coefficient. A p-value of <0.05 was considered statistically significant. PASW Statistics 18.0.3 (SPSS Inc., Chigaco, IL, USA) software was used for statistical analyses.

Results

In the Ang II-study we were able to obtain reliable Doppler flow velocity waveforms from the LMCA in 28 (85%) of 33 animals that had an echocardiography by the most experienced operator (M.C.S.); 13 pregnant sham, 11 pregnant Ang II, 2 non-pregnant sham, and 2 non-pregnant Ang II. Due to low numbers of non-pregnant animals, only data from pregnant animals are presented in Fig. 2. In the TAC-study echocardiography was performed by one operator (N.T.S.) in all animals. LMCA flow velocity was recorded in 36 of the 42 animals included. Four animals were excluded due to poor signal quality or inability to repeat measurements after increase of isoflurane concentration. Thus CFR measurements from 32 (76%) animals were eligible for analysis; 10 pregnant sham, 7 pregnant TAC, 7 non-pregnant sham, and 8 non-pregnant TAC.

Ten male rats were used to evaluate the effect of inhaled isoflurane on coronary flow. Coronary flow velocities increased and stabilized one to two minutes after the concentration of inhaled isoflurane was increased from 1.5% to 3.5%, and returned to baseline values three to five minutes after the isoflurane concentration was reduced to 1.5%. Increase in inhaled isoflurane concentration above 3.5% in four rats did not lead to further increase in coronary flow velocities, and there was no difference in calculated CFR_{peak} or CFR_{VTI} at 3.5% compared to 4.5% (two rats) or 5.0% (two rats) concentration of inhaled isoflurane (CFR_{peak} : 1.78 ± 0.13 vs 1.63 ± 0.11 , $p = 0.4$. CFR_{VTI} : 1.96 ± 0.29 vs 2.05 ± 0.27 , $p = 0.3$). In most animals measurement of coronary flow was not feasible when the inhaled isoflurane concentration was below 1.5% as the animals would start moving and the coronary flow signals were lost. In two rats blood flow velocities were similar at 1.0% and 1.5% isoflurane.

Adenosine infusion led to a significant increase in coronary flow velocity only in one of four rats. In this rat the calculated CFR_{peak} was similar following adenosine infusion and isoflurane inhalation (1.82 and 1.89 respectively). In three rats not responding to adenosine the calculated CFR_{peak} following isoflurane inhalation was 1.11, 1.67 and 1.72.

Calculated CFR_{peak} and CFR_{VTI} values are presented in Fig. 2. There were no differences in CFR_{peak} or CFR_{VTI} between pregnant sham and pregnant AngII-infused rats. In the TAC-study CFR_{peak} (1.54 ± 0.07 vs 1.85 ± 0.17 , $p = 0.03$) but not

CFR_{VTI} (1.57 ± 0.08 vs 1.72 ± 0.06 , $p = 0.3$) was decreased in pregnant compared to non-pregnant sham. TAC did not significantly affect CFR_{peak} or CFR_{VTI} in pregnant or non-pregnant animals. When pregnant ($n = 23$) and non-pregnant ($n = 9$) sham animals from both studies were pooled together and compared, both CFR_{peak} (1.42 ± 0.07 vs 1.86 ± 0.16 , $p = 0.005$, Fig. 3) and CFR_{VTI} (1.45 ± 0.07 vs 1.78 ± 0.12 ; $p = 0.03$) were significantly decreased in pregnant animals. There was no correlation between CFR_{peak} and systolic or diastolic BP, heart weight or left ventricular contractility measured as left ventricular fractional shortening by m-mode echocardiography.

Discussion

We measured CFR non-invasively in pregnant and non-pregnant rats using high concentrations of inhaled isoflurane as a vasodilating agent. We were able to calculate CFR using Doppler flow velocity waveforms of LMCA in most animals. CFR was reduced in pregnant rats compared to non-pregnant. Furthermore, we investigated whether increased afterload has an effect on CFR in pregnant and non-pregnant rats and found that neither chronic Ang II infusion nor aorta constriction affected CFR.

In the TAC-study CFR_{peak} was reduced in pregnant compared to non-pregnant sham operated rats. The same trend was observed in sham treated rats in the AngII-study (Fig. 2A), however only two non-pregnant rats were examined and difference was not statistically significant. Combining data on sham animals from two studies, we found that both CFR_{peak} and CFR_{VTI} were significantly lower in pregnant compared to non-pregnant rats. There are no published studies on CFR in pregnancy. FMD reflects the endothelial function in the peripheral resistance vessels but may not correlate with that of the coronary vascular bed [17,25,26,30]. Studies in pregnant women have shown that FMD decreases towards term [19,20,23] which is in line with our findings.

To our knowledge, the effects of pregnancy on CFR have not been studied before, and it is not known if reduced CFR increases the risk of adverse cardiovascular events in pregnancy. A recent study showed that the utero-placental blood flow is impaired in pregnant women with congenital heart diseases [31]. The course and outcome of pregnancy may be affected by maternal heart disease [32]. Death from heart disease is the leading cause of indirect maternal death in the UK [33]. Hirata et al. have shown an increase in CFR associated with increasing levels of 17β -estrogen in the follicular phase of the menstrual cycle in young, healthy women and after administration of conjugated estrogen in postmenopausal women [34]. Profound hormonal changes that occur during pregnancy could be responsible for reduced CFR that we observed in rats close to term. There is a need for non-invasive tests to assess risk and predict outcome in pregnant women at risk. Thus, studies of CFR in healthy human pregnancies and in pregnant women with hypertension or heart diseases using non-invasive methods and safe vasodilating agents (e.g. dipyridamole, a FDA category B drug) are warranted.

In contrast to previous findings in dogs [15] and mice [10] with increased afterload, in our study CFR was not reduced by Ang II infusion or TAC in rats. In addition to species differences, there could be several other reasons for this discrepancy. Hittinger et al. found that CFR was preserved in dogs with compensated heart hypertrophy, but was exhausted when the dogs developed decompensated pressure overload left ventricular hypertrophy [15]. In our studies the animals did not have decompensated heart failure when CFR was measured [28,29]. The coronary circula-

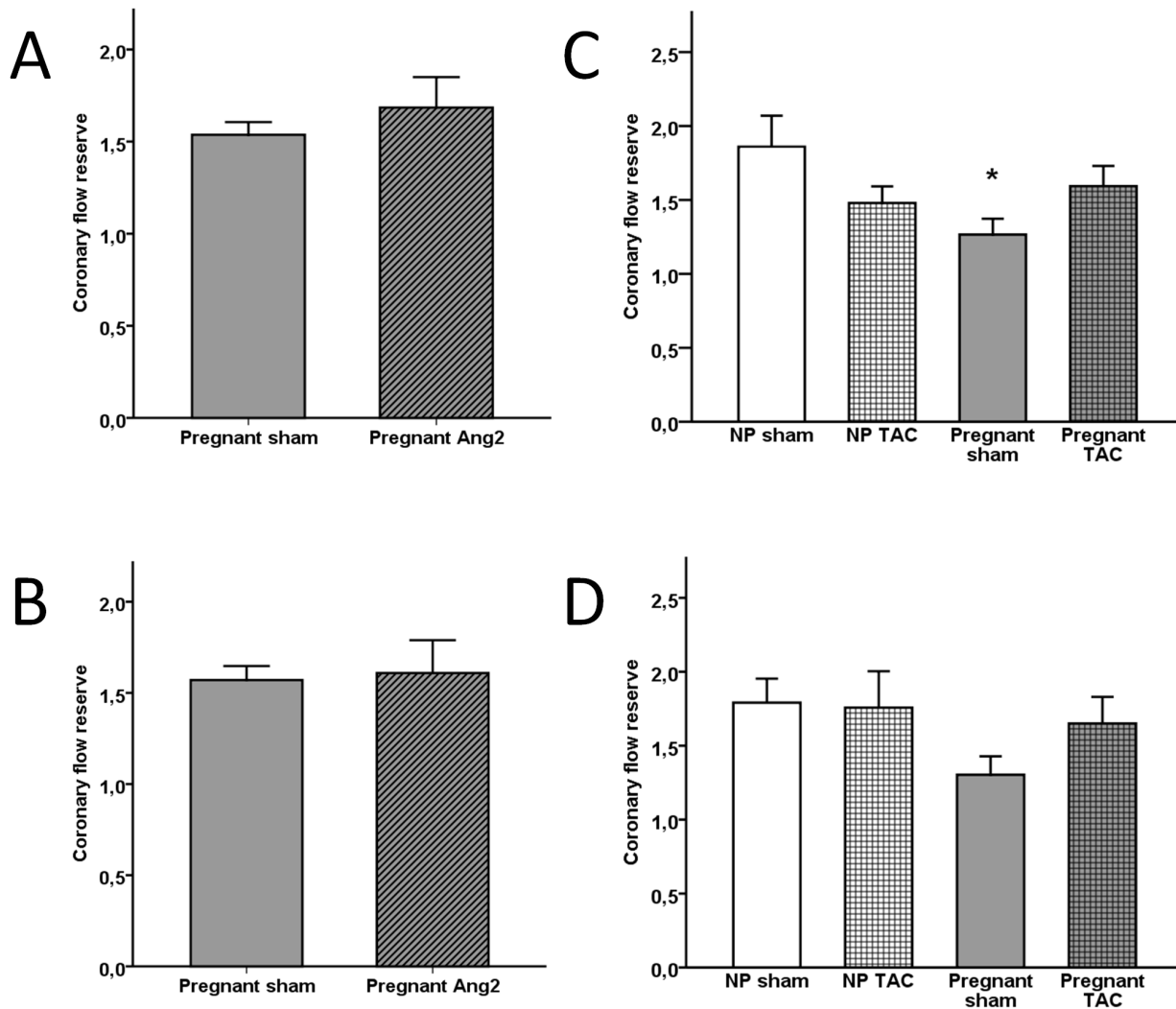


Figure 2. Coronary flow reserve in pregnant and non-pregnant rats. Mean \pm SEM for coronary flow reserve calculated from peak velocities (A, C) and velocity time integrals (B, D). Comparisons between groups were made using independent samples T-test (A, B) and one-way ANOVA and Holm-Sidak post hoc test (C, D). SEM, standard error of the mean, NP, non-pregnant, Ang2, Angiotensin II, TAC, transverse aorta constriction, $p < 0.05$ compared to non-pregnant sham (*). doi:10.1371/journal.pone.0102147.g002

tion is subjected to autoregulation and coronary blood flow is constant over a wide range of pressures, referred to as the 'zero pressure flow phenomenon' [1,35]. When the vascular bed of the heart is maximally vasodilated (e.g. by adenosine or isoflurane) the coronary autoregulation is revoked and coronary blood flow exhibits a linear relationship with the myocardial perfusion pressure [1,36]. Therefore, a change in blood pressure will affect CFR. As coronary flow is predominantly diastolic in the rat LMCA (Fig. 1BC), an increase in diastolic BP may increase calculated CFR. In our study, systolic rather than diastolic BP was increased following TAC and the pregnant sham animals had a significantly lower diastolic BP than all other groups [29]. Therefore, the reduced CFR in late pregnancy may be a result of reduced diastolic BP rather than impaired coronary endothelial function. Examining CFR and BP at mid-term could have added valuable information, but we refrained from anaesthetising the animals twice during pregnancy to avoid adverse effects on mother and fetuses.

In contrary to TAC, chronic Ang II infusion led to significantly increased diastolic as well as systolic pressure [28]. Furthermore,

Ang II infusion led to significant fibrosis of the heart tissue, whereas TAC did not [28,29]. Thus the Ang II infused rats probably were closer to heart failure. According to the 'zero pressure flow phenomenon' an increased diastolic BP in Ang II infused rats will increase calculated CFR and may mask an actual impairment of the coronary vessels ability to dilate [1,35]. Hoffmann et al. defined CFR as the maximal increase in coronary blood flow above its basal level for a given perfusion pressure when coronary circulation is maximally dilated [37], and ideally speaking, perfusion pressure needs to be taken into account while comparing coronary flows in different animals. Thus, even though the CFR was not significantly affected by Ang II infusion, we cannot conclude that coronary microvascular dilatation is not impaired by Ang II.

The gold standard method for measuring CFR is by using adenosine infusion. We used inhaled isoflurane which is commonly used as a safe anesthetic in rats. This method is non-invasive and does not require insertion of an intravenous cannula and is more practical. We found that this method of measuring CFR in rats using different concentrations of inhaled isoflurane and echocar-

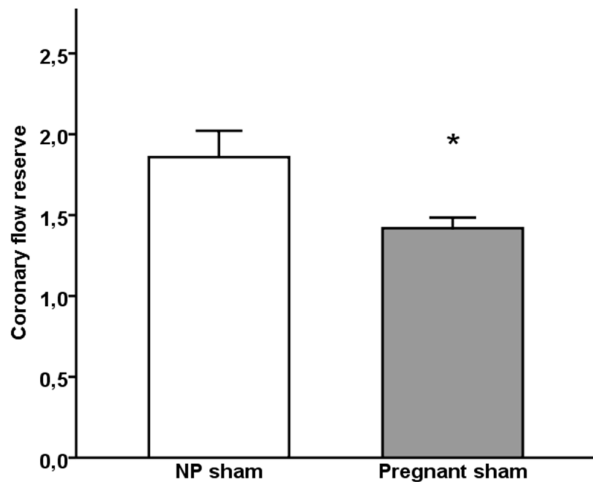


Figure 3. Coronary flow reserve in sham rats. Mean \pm SEM for coronary flow reserve calculated from peak velocities in non-pregnant (NP) and pregnant sham animals from both studies. Independent-Samples T-test was used to compare groups. SEM, standard error of the mean, NP, non-pregnant, $p < 0.05$ compared to non-pregnant sham (*). doi:10.1371/journal.pone.0102147.g003

diography is feasible in a laboratory setting. The operator of the Ang II-study was more experienced in small-animal echocardiography than the operator of the TAC-study and had a higher success rate in obtaining reliable CFR measurements. However, the difference between operators was not significant ($p = 0.4$). The most frequent cause of not obtaining CFR measurements was inability to detect LMCA flow velocity signals consistently. Using an ultrasound system equipped with color Doppler could facilitate the identification of coronary artery, and increase the success rate.

3.5% of isoflurane was chosen as high-concentration as this was set as the maximum maintenance dose used in rats in our laboratory. High concentrations of inhaled isoflurane may lead to

reduced cardiac output, reduced BP, circulatory collapse and cardiac arrest. In four male rats an increase in isoflurane concentration above 3.5% did not lead to further increase in coronary flow velocity indicating that the coronary vessels were maximally dilated at 3.5%.

Due to the small caliber of coronary artery and limited image resolution, its diameter is difficult to measure and coronary volume blood flow cannot be calculated non-invasively. However, coronary flow reserve estimated using Doppler flow velocity waveforms correlates well with invasively measured CFR [38]. Previous studies mostly report CFR_{peak} rather than CFR_{VTI} . We have presented both the CFR_{peak} and CFR_{VTI} in our results.

An increase in peak velocity during the diastole is expected following coronary vasodilatation. However, an increase in systolic component was also observed during hyperemia (Fig. 1BC). Therefore measuring VTI of the flow velocity waveform during the whole cardiac cycle might be a better estimate of coronary flow than just the peak velocity.

Conclusions

It is feasible to measure CFR in rats non-invasively using Doppler echocardiography and high concentration of inhaled isoflurane as the vasodilating agent. CFR was not affected by increased left ventricular cardiac afterload caused by chronic Ang II infusion or TAC both in pregnant and non-pregnant rats. CFR is reduced in late pregnancy (close to term) in rats. Whether this reduction is a result of impaired coronary endothelial function or is merely a reflection of reduced diastolic BP in late pregnancy remains to be elucidated.

Author Contributions

Conceived and designed the experiments: NTS VS DJ KY GA. Performed the experiments: NTS MCS VS DJ. Analyzed the data: NTS MCS GA. Contributed reagents/materials/analysis tools: KY GA. Wrote the paper: NTS GA.

References

- Hirata K, Amudha K, Elina R, Hozumi T, Yoshikawa J, et al. (2004) Measurement of coronary vasomotor function: getting to the heart of the matter in cardiovascular research. *Clin Sci* 107: 449–460.
- Al Suwaidi J, Hamasaki S, Higano ST, Nishimura RA, Holmes DR Jr, et al. (2000) Long-term follow-up of patients with mild coronary artery disease and endothelial dysfunction. *Circulation* 101: 948–954.
- Schächinger V, Britten MB, Zeiher AM (2000) Prognostic impact of coronary vasodilator dysfunction on adverse long-term outcome of coronary heart disease. *Circulation* 101: 1899–1906.
- Gan LM, Wikstrom J, Fritsche-Danielson R (2013) Coronary Flow Reserve from Mouse to Man—from Mechanistic Understanding to Future Interventions. *J Cardiovasc Transl Res* 6: 715–728.
- Hozumi T, Yoshida K, Ogata Y, Akasaka T, Asami Y, et al. (1998) Noninvasive Assessment of Significant Left Anterior Descending Coronary Artery Stenosis by Coronary Flow Velocity Reserve With Transthoracic Color Doppler Echocardiography. *Circulation* 97: 1557–1562.
- Lethen H, Tries HP, Brechtken J, Kersting S, Lambertz H (2003) Comparison of transthoracic Doppler echocardiography to intracoronary Doppler guidewire measurements for assessment of coronary flow reserve in the left anterior descending artery for detection of restenosis after coronary angioplasty. *Am J Cardiol* 91: 412–417.
- Wold LE, Ying Z, Hutchinson KR, Velten M, Gorr MW, et al. (2012) Cardiovascular Remodeling in Response to Long-Term Exposure to Fine Particulate Matter Air Pollution/Clinical Perspective. *Circulation: Heart Failure* 5: 452–461.
- Hagg U, Gronros J, Wikstrom J, Jonsdotir IH, Bergstrom G, et al. (2005) Voluntary physical exercise and coronary flow velocity reserve: a transthoracic colour Doppler echocardiography study in spontaneously hypertensive rats. *Clin Sci (Lond)* 109: 325–334.
- Hartley CJ, Reddy AK, Madala S, Michael LH, Entman ML, et al. (2007) Effects of Isoflurane on Coronary Blood Flow Velocity in Young, Old and ApoE^{-/-} Mice Measured by Doppler Ultrasound. *Ultrasound in Medicine & Biology* 33: 512–521.
- Hartley CJ, Reddy AK, Madala S, Michael LH, Entman ML, et al. (2008) Doppler Estimation of Reduced Coronary Flow Reserve in Mice with Pressure Overload Cardiac Hypertrophy. *Ultrasound in Medicine & Biology* 34: 892–901.
- Valensise H, Novelli GP, Vasapollo B, Borzi M, Arduini D, et al. (2000) Maternal cardiac systolic and diastolic function: relationship with uteroplacental resistances. A Doppler and echocardiographic longitudinal study. *Ultrasound in Obstetrics and Gynecology* 15: 487–497.
- Blanco PG, Tórtora M, Rodríguez R, Arias DO, Gobello C (2011) Ultrasonographic assessment of maternal cardiac function and peripheral circulation during normal gestation in dogs. *The Veterinary Journal* 190: 154–159.
- Lang RM, Pridjian G, Feldman T, Neumann A, Lindheimer M, et al. (1991) Left ventricular mechanics in preeclampsia. *Am Heart J* 121: 1768–1775.
- Marcus ML, Doty DB, Hiratzka LF, Wright CB, Eastham CL (1982) Decreased Coronary Reserve. *New England Journal of Medicine* 307: 1362–1366.
- Hittinger L, Shannon RP, Bishop SP, Gelpi RJ, Vatner SF (1989) Subendomyocardial exhaustion of blood flow reserve and increased fibrosis in conscious dogs with heart failure. *Circ Res* 65: 971–980.
- Celermajer DS, Sorensen KE, Gooch VM, Miller, Sullivan ID, et al. (1992) Non-invasive detection of endothelial dysfunction in children and adults at risk of atherosclerosis. *The Lancet* 340: 1111–1115.
- Acharya G, Kiserud T, Lunde P (2009) Ultrasound assessment of maternal endothelial function: a tool for epidemiology. *Norsk epidemiologi* 19.
- Dorup I, Skajaa K, Sorensen KE (1999) Normal pregnancy is associated with enhanced endothelium-dependent flow-mediated vasodilation. *American Journal of Physiology-Heart and Circulatory Physiology* 276: H821–H825.
- Savvidou M, Kametas N, Donald A, Nicolaides K (2000) Non-invasive assessment of endothelial function in normal pregnancy. *Ultrasound in obstetrics & gynecology* 15: 502–507.

20. Kinzler WL, Smulian JC, Ananth CV, Vintzileos AM (2004) Noninvasive ultrasound assessment of maternal vascular reactivity during pregnancy: a longitudinal study. *Obstetrics & Gynecology* 104: 362.
21. Sierra-Laguado J, Garcia R, Lopez-Jaramillo P (2006) Flow-mediated dilatation of the brachial artery in pregnancy. *International journal of gynecology & obstetrics* 93: 60–61.
22. Saarelainen H, Laitinen T, Raitakari OT, Juonala M, Heiskanen N, et al. (2006) Pregnancy-related hyperlipidemia and endothelial function in healthy women. *Circulation journal: official journal of the Japanese Circulation Society* 70: 768.
23. Quinton AE, Cook C-M, Peek MJ (2007) A Longitudinal Study Using Ultrasound to Assess Flow-Mediated Dilatation in Normal Human Pregnancy. *Hypertension in Pregnancy* 26: 273–281.
24. Seeliger C, Brueckmann A, Schleussner E (2012) [Maternal endothelial function in the course of pregnancy and postpartum - ultrasound-based longitudinal assessment using flow-mediated dilatation (FMD)]. *Ultraschall Med* 33: E126–131.
25. Bottcher M, Madsen MM, Refsgaard J, Buus NH, Dørup I, et al. (2001) Peripheral flow response to transient arterial forearm occlusion does not reflect myocardial perfusion reserve. *Circulation* 103: 1109–1114.
26. Khan F, Patterson D, Belch J, Hirata K, Lang C (2008) Relationship between peripheral and coronary function using laser Doppler imaging and transthoracic echocardiography. *Clinical Science* 115: 295–300.
27. European Parliament, Council of the European Union (2010) Directive 2010/63/EU of the European Parliament and of the Council of 22 September 2010 on the protection of animals used for scientific purposes. *Official J Eur Union*.
28. Aljabri MB, Songstad NT, Lund T, Serrano MC, Andreasen TV, et al. (2011) Pregnancy protects against antiangiogenic and fibrogenic effects of angiotensin II in rat hearts. *Acta Physiol (Oxf)* 201: 445–456.
29. Songstad NT, Johansen D, How O-J, Kaarensen PI, Ytrehus K, et al. (2014) Effect of Transverse Aortic Constriction on Cardiac Structure, Function and Gene Expression in Pregnant Rats. *PLoS ONE* 9: e89559.
30. Hirata K, Kadirvelu A, Kinjo M, Sciacca R, Sugioka K, et al. (2007) Altered coronary vasomotor function in young patients with systemic lupus erythematosus. *Arthritis & Rheumatism* 56: 1904–1909.
31. Pieper PG, Balci A, Aarnoudse JG, Kampman MAM, Sollie KM, et al. (2013) Uteroplacental Blood Flow, Cardiac Function, and Pregnancy Outcome in Women With Congenital Heart Disease. *Circulation* 128: 2478–2487.
32. Roos-Hesselink JW, Ruys TPE, Stein JI, Thilén U, Webb GD, et al. (2013) Outcome of pregnancy in patients with structural or ischaemic heart disease: results of a registry of the European Society of Cardiology. *European Heart Journal* 34: 657–665.
33. Enquiries CfMaC (2011) Saving Mothers' Lives: Reviewing maternal deaths to make motherhood safer: 2006–2008. *BJOG: An International Journal of Obstetrics & Gynaecology* 118: 1–203.
34. Hirata K, Shimada K, Watanabe H, Muro T, Yoshiyama M, et al. (2001) Modulation of coronary flow velocity reserve by gender, menstrual cycle and hormone replacement therapy. *Journal of the American College of Cardiology* 38: 1879–1884.
35. Hoffman JI, Spaan JA (1990) Pressure-flow relations in coronary circulation. *Physiol Rev* 70: 331–390.
36. Baumgart D, Haude M, Liu F, Ge J, Goerge G, et al. (1998) Current concepts of coronary flow reserve for clinical decision making during cardiac catheterization. *Am Heart J* 136: 136–149.
37. Hoffman JI (1984) Maximal coronary flow and the concept of coronary vascular reserve. *Circulation* 70: 153–159.
38. Wilson RF, Laughlin DE, Ackell PH, Chilian WM, Holida MD, et al. (1985) Transluminal, subselective measurement of coronary artery blood flow velocity and vasodilator reserve in man. *Circulation* 72: 82–92.