Ultrasound Obstet Gynecol 2022
Published online in Wiley Online Library (wileyonlinelibrary.com). **DOI:** 10.1002/uog.23745.

Peripartum echocardiographic changes in women with hypertensive disorders of pregnancy

V. GIORGIONE[1,2], J. O'DRISCOLL[3,4], C. M. COUTINHO[2,5], C. DI FABRIZIO[1], R. SHARMA[3], A. KHALIL[1,2] and B. THILAGANATHAN[1,2]

[1]*Vascular Biology Research Center, Molecular and Clinical Sciences Research Institute, St George's University of London, London, UK;* [2]*Fetal Medicine Unit, St George's University Hospitals NHS Foundation Trust, University of London, London, UK;* [3]*Department of Cardiology, St George's University Hospitals NHS Foundation Trust, London, UK;* [4]*School of Psychology and Life Sciences, Canterbury Christ Church University, Canterbury, UK;* [5]*Department of Gynecology and Obstetrics, Ribeirão Preto Medical School, University of São Paulo, Ribeirão Preto, São Paulo, Brazil*

KEYWORDS: echocardiography; hypertensive disorders of pregnancy; left ventricular remodeling; pre-eclampsia; pregnancy

CONTRIBUTION

What are the novel findings of this work?
This study assessed whether the hemodynamic changes following delivery can modify the abnormal left-ventricular geometry and function observed in women with hypertensive disorders of pregnancy (HDP). We found no significant difference in cardiac morphology or function on transthoracic echocardiography in women with HDP before *vs* after delivery.

What are the clinical implications of this work?
Cardiac parameters of women with HDP do not improve in the postpartum period despite hemodynamic changes associated with delivery. Cardiac changes in HDP are likely to be the consequence of chronic pregnancy cardiovascular load changes and/or pre-existing cardiac dysfunction. Echocardiographic evaluation in the peripartum period could be used to detect cardiac impairment in women with HDP and identify those who require closer surveillance postpartum. This could be the first step in a screening program for HDP, which are recognized risk factors for cardiovascular disease.

ABSTRACT

Objective *Hypertensive disorders of pregnancy (HDP) are associated with significant myocardial dysfunction on echocardiography. The impact of hemodynamic changes related to volume redistribution following delivery on myocardial function in women with HDP has not been evaluated systematically. The aim of this study was to compare echocardiographic findings immediately before and after delivery in women with HDP.*

Methods *This was a prospective longitudinal study including 30 women with a diagnosis of HDP who underwent two consecutive transthoracic echocardiographic (TTE) examinations, before delivery and in the early postpartum period. Paired comparisons of the findings from the two assessments were performed.*

Results *Left-ventricular (LV) concentric remodeling or hypertrophy was detected in 21 (70%) patients. There was no significant difference in cardiac morphology indices such as LV mass index (78.9 ± 16.3 g/m^2* vs *77.9 ± 15.4 g/m^2; P = 0.611) or relative wall thickness (0.45 ± 0.1* vs *0.44 ± 0.1; P = 0.453) before* vs *after delivery. LV diastolic function did not demonstrate any peripartum variation, with similar left-atrial volume (52.4 ± 15.3 mL* vs *51.0 ± 15.6 mL; P = 0.433), lateral E′ (0.12 ± 0.03 m/s* vs *0.12 ± 0.03 m/s; P = 0.307) and E/E′ ratio (7.9 ± 2.2* vs *7.9 ± 1.7; P = 0.934) before* vs *after delivery. Systolic function indices, such as LV ejection fraction (57.5 ± 3.4%* vs *56.4 ± 2.1%; P = 0.295) and global longitudinal strain (−15.3 ± 2.6%* vs *−15.1 ± 3.1%; P = 0.582), also remained unchanged between before* vs *after delivery.*

Conclusions *Maternal hemodynamic changes associated with delivery did not influence significantly peripartum TTE indices in women with HDP. Suboptimal maternal echocardiographic findings in HDP are likely to be the consequence of chronic pregnancy cardiovascular*

Correspondence to: Prof. B. Thilaganathan, Fetal Medicine Unit, Department of Obstetrics and Gynaecology, St George's University Hospitals NHS Foundation Trust, Blackshaw Road, London SW17 0QT, UK (e-mail: basky@pobox.com)

Accepted: 19 July 2021

load changes or pre-existing maternal cardiovascular impairment. Severity and persistence of myocardial dysfunction in the postpartum period may be related to the long-term maternal cardiovascular disease legacy of HDP.

INTRODUCTION

Hypertensive disorders of pregnancy (HDP), such as pre-eclampsia (PE) and gestational hypertension, are associated with substantial changes in maternal cardiac geometry and function during pregnancy and are recognized as significant risk factors for cardiovascular disease[1,2]. In particular, women affected by PE exhibit left-ventricular (LV) diastolic dysfunction and remodeling/hypertrophy more frequently than those with a normotensive pregnancy[3]. The process of birth is accompanied by dramatic hemodynamic changes in the circulating volume[4,5]. In an uncomplicated pregnancy, increased maternal stroke volume (SV) immediately after delivery is thought to occur due to increased cardiac preload from autotransfusion of uteroplacental blood and reduction in the mechanical compression of the vena cava[4]. Assessment of hemodynamic variations using peripheral waveform devices has suggested similar improvement in hemodynamic parameters 2–3 days postpartum in HDP pregnancy[6], and it has been proposed that maternal cardiovascular parameters return to prepregnancy values within 2 weeks postpartum[5].

Several studies have demonstrated that maternal cardiac dysfunction evident before the clinical onset of PE, is present several years after pregnancy and can predispose to the development of maternal cardiovascular morbidity in the long term[7–9]. Peripartum echocardiographic assessment of LV diastolic function and geometry may be useful in women affected by HDP to identify markers of subsequent cardiovascular disease and associated adverse outcome[10,11]. Ghossein-Doha *et al.*[12] demonstrated that increased LV mass index (LVMI) at 9 months postpartum was associated with the development of persistent chronic hypertension in formerly pre-eclamptic patients. Similarly, other echocardiographic studies that investigated pregnancy complicated by HDP have been conducted mostly a few years after delivery, and not in the immediate peripartum period[8,9,12].

It remains unclear whether maternal myocardial dysfunction in HDP is improved by the process of birth and whether this may have an influence on its ability to predict long-term maternal cardiovascular morbidity. The hypothesis is that giving birth could modify maternal cardiac abnormalities that are usually observed in women affected by HDP. The primary aim of the study was to compare echocardiographic findings in women with HDP immediately before delivery and in the early postpartum period.

METHODS

Study population

This was an observational longitudinal cohort study of 30 women with a pregnancy complicated by HDP, recruited in the maternity department of St George's University Hospitals NHS Foundation Trust, London, UK, between February 2019 and August 2019. The study was approved by the local ethics committee (19/LO/0794) and all participants provided written informed consent. Sample size was not calculated because this was a pilot study of an ongoing larger adequately powered study. Medical history and obstetric data were collected from hospital records and HDP were diagnosed according to the criteria set by International Society for the Study of Hypertension in Pregnancy (ISSHP)[13]. Fetal growth restriction was defined as per the Delphi consensus agreement[14], and maternal height, weight and brachial blood pressure were obtained prior to hemodynamic assessment. Body mass index (kg/m^2) was calculated by dividing body weight by the squared height. Body surface area (BSA; m^2) was calculated using the following equation: $0.007184 \times \text{height (cm)}^{0.725} \times \text{weight (kg)}^{0.425}$. Systolic (SBP) and diastolic (DBP) blood pressure measurements were obtained using an upper arm automatic blood pressure monitor (Microlife®, Microlife AG Swiss Corporation, Widnau, Switzerland), with the woman in a resting state using an appropriately sized cuff[15]. Mean arterial pressure (MAP) was calculated using the following formula: $(2 \times \text{DBP} + \text{SBP})/3$.

Echocardiography

All subjects underwent transthoracic echocardiography (TTE) at rest in the left lateral decubitus position using a commercially available ultrasound system (GE Vivid™ E95; GE Healthcare, Horten, Norway). Two-dimensional (2D) and Doppler TTE was performed following the guidelines of the American Society of Echocardiography[16,17]. For each acquisition, three cardiac cycles of non-compressed data were stored in a cineloop format and analyzed offline by one investigator (V.G.) on a dedicated workstation (EchoPAC version 203; GE Healthcare). The investigator was blinded to the time of TTE. Using the 2D parasternal long-axis view, LV end-diastolic (LVEDd) and end-systolic diameters and thickness of the interventricular septum (IVST) and the posterior wall (PWT) were measured in mm. LV mass (LVM; g) was calculated using the following formula: $0.8 \times (1.04 \times (\text{LVEDd} + \text{PWT} + \text{IVST})^3 - \text{LVEDd}^3) + 0.6$. LVM was indexed for BSA to obtain LVMI. Relative wall thickness (RWT) was calculated as follows: $\text{RWT} = 2 \times \text{PWT/LVEDd}$. Normal cardiac geometry, concentric remodeling, concentric hypertrophy and eccentric remodeling were defined according to guidelines[17]. The following diastolic indices were measured: (i) peak E-wave velocity (m/s), peak A-wave velocity (m/s), their ratio (E/A) and deceleration time (ms) measured by pulsed-wave Doppler; (ii) lateral and septal E′ velocity (m/s) obtained by pulsed-wave tissue Doppler imaging at

the lateral and septal mitral annulus; (iii) E/E′, where E′ is the average of septal E′ and lateral E′; (iv) left-atrial maximum volume (LAV; mL); (v) tricuspid regurgitation systolic jet velocity (m/s); and (vi) pulmonary vein (PV) systolic-wave (m/s), PV diastolic-wave (m/s), PV A-wave duration (ms) and PV systolic/diastolic ratio. British Society of Echocardiography guidelines were applied to evaluate LV diastolic function[18]. LV chamber radial systolic function was derived by measuring ejection fraction using Simpson's biplane method in apical four- and two-chamber views[17]. Moreover, cardiac mechanical function was assessed using 2D speckle-tracking strain imaging in two-, three- and four-chamber views, with a frame rate of 60–90 frames/s[19]. Global longitudinal strain (GLS) quantification was performed using commercially available software (EchoPAC version 203; GE Healthcare). SV was calculated by measuring the LV outflow tract diameter 3–10 mm from the aortic valve plane in midsystole with inner edge to inner edge methodology and the pulsed-Doppler velocity time integral in the five-chamber view[20]. Cardiac output (CO) was obtained as the product of SV and heart rate, which was derived using electrocardiographic monitoring. Systemic vascular resistance (SVR) was calculated using the following formula: MAP × 80/CO. Inter- and intraobserver reproducibility for echocardiographic measurements was assessed by offline analysis in six randomly selected subjects by two independent operators (V.G. and J.O'.D.).

Statistical analysis

Variables were assessed for normality using the Shapiro–Wilk test and by visualizing data using histograms. Continuous data were expressed as mean ± SD or as median (interquartile range (IQR)), according to data distribution. Echocardiographic data obtained before and after delivery were compared using paired *t*-test or Wilcoxon signed-rank test. Statistical significance was deemed *a priori* as $P < 0.05$. The analysis was performed using the statistical software package SPSS v27.0 (IBM Corp., Armonk, NY, USA).

RESULTS

Population characteristics

Twenty patients with PE and 10 with gestational hypertension were included in the study (Table 1). The median (IQR) TTE–birth interval was 4.5 (2–8) days before and 3.5 (2–6) days after birth. There was no significant difference in heart rate, blood pressure, SVR, SV and CO before delivery *vs* immediately postpartum (Table 2). Maternal weight was significantly lower after birth than at prenatal assessment (mean weight loss, 3.4 ± 2.5 kg; $P < 0.001$). Intraobserver and interobserver variability of echocardiographic measurements obtained by TTE was excellent for the majority of parameters (Table S1).

LV geometry and diastolic and systolic function

Delivery did not affect LVM, LVMI, RWT, biplane LV end-diastolic and end-systolic volume (Table 2).

Table 1 Demographic and obstetric characteristics of 30 women with hypertensive disorders of pregnancy

Characteristic	*Value*
Maternal age (years)	33.5 ± 6.7
Pregestational BMI (kg/m^2)	26.8 ± 5.3
Ethnicity	
Caucasian	17 (56.7)
Afro-Caribbean	8 (26.7)
Asian	3 (10.0)
Mixed	2 (6.7)
Nulliparous	18 (60.0)
Chronic hypertension	5 (16.7)
Pregestational diabetes	1 (3.3)
MAP at first antenatal visit (mmHg)	94.1 ± 6.4
Diagnosis	
Gestational hypertension	10 (33.3)
Pre-eclampsia	20 (66.7)
Fetal growth restriction	7 (23.3)
GA at birth (weeks)	35.9 ± 4.0
Preterm birth	
< 37 weeks	15 (50.0)
< 34 weeks	9 (30.0)
Mode of delivery	
Vaginal	10 (33.3)
Cesarean	20 (66.7)
Total blood loss at birth (mL)	395 (300–600)

Data are given as mean ± SD, *n* (%) or median (interquartile range). BMI, body mass index; GA, gestational age; MAP, mean arterial pressure.

Table 2 Clinical and hemodynamic characteristics and left-ventricular geometry before and after delivery in 30 women with hypertensive disorders of pregnancy

Characteristic	*Before delivery*	*After delivery*	P
TTE–birth interval (days)	4.5 (2–8)	3.5 (2–6)	0.310
Weight (kg)	82.2 ± 16.4	78.8 ± 16.6	< 0.001
SBP (mmHg)	135 (128–144)	134 (129–143)	0.742
DBP (mmHg)	88 (84–95)	88 (84–90)	0.244
Antihypertensive treatment	23 (76.7)	24 (80.0)	0.754
Stroke volume (mL)	64.0 ± 10.6	66.9 ± 11.6	0.253
Heart rate (bpm)	79.9 ± 10.1	80.0 ± 8.7	0.899
Cardiac output (L/min)	5.1 ± 1.1	5.4 ± 1.2	0.362
SVR (dynes × s/cm^5)	1571.4 (1372.0–1809.8)	1514.5 (1255.4–1800.0)	0.139
Cardiac geometry			
LVIDd (cm)	4.40 ± 0.61	4.43 ± 0.46	0.661
LVIDs (cm)	2.64 ± 0.25	2.61 ± 0.46	0.786
LVM (g)	144.91 ± 32.98	144.72 ± 33.41	0.958
LVMI (g/m^2)	78.91 ± 16.29	77.88 ± 15.40	0.611
RWT	0.45 ± 0.09	0.44 ± 0.07	0.453
Abnormal geometry	21 (70.0)	21 (70.0)	—
Concentric remodeling	18	17	
Concentric hypertrophy	3	4	
Biplane EDV (mL)	117.40 ± 27.07	120.82 ± 26.34	0.427
Biplane ESV (mL)	50.17 ± 12.83	52.88 ± 12.94	0.194

Data are reported as median (interquartile range), mean ± SD, *n* (%) or *n*. DBP, diastolic blood pressure; EDV, end-diastolic volume; ESV, end-systolic volume; LVIDd, left-ventricular internal diameter at end diastole; LVIDs, left-ventricular internal diameter at end systole; LVM, left-ventricular mass; LVMI, left-ventricular mass index; RWT, relative wall thickness; SVR, systemic vascular resistance; SBP, systolic blood pressure; TTE, transthoracic echocardiography.

Twenty-one (70%) women demonstrated abnormal geometry (concentric remodeling or concentric hypertrophy) both before and after delivery (Table 2). Among them, cardiac morphology of only one patient was classified as concentric remodeling before delivery and as concentric hypertrophy after delivery. Among the nine patients with normal geometry, four were affected by gestational hypertension and five by PE. Seventeen (56.7%) women had abnormal diastolic function (Grade I or II) both before and immediately after delivery (Table 3). There was no significant change in LAV, lateral E′, E/E′ and E/A ratio, but there was a significant increase in septal E′ after *vs* prior to delivery (0.10 ± 0.02 m/s *vs* 0.09 ± 0.02 m/s; $P = 0.035$). However, biplane ejection fraction, mean GLS and twist and untwist parameters were unchanged when comparing values before and those after birth (Table 3, Figure 1).

Table 3 Left-ventricular (LV) diastolic and systolic function assessed by maternal echocardiography before and after delivery in 30 women with hypertensive disorders of pregnancy

Parameter	*Before delivery*	*After delivery*	P
Diastolic function			
LAV (mL)	52.40 ± 15.28	50.97 ± 15.56	0.433
MV E/A	1.27 ± 0.38	1.22 ± 0.27	0.326
MV deceleration time (ms)	161.67 ± 52.43	157.53 ± 37.54	0.575
PV S/D	1.26 ± 0.26	1.22 ± 0.25	0.499
Lateral E′ (m/s)	0.12 ± 0.03	0.12 ± 0.03	0.307
Septal E′ (m/s)	0.09 ± 0.02	0.10 ± 0.02	0.035
E/E′	7.88 ± 2.19	7.91 ± 1.74	0.934
TR Vmax (m/s)	2.10 ± 0.46	2.16 ± 0.34	0.487
Diastolic dysfunction	17 (56.7)	17 (56.7)	—
Grade I	3	5	
Grade II	14	12	
Systolic function			
Biplane EF (%)	57.52 ± 3.42	56.40 ± 2.12	0.295
Mean GLS (%)	−15.31 ± 2.64	−15.13 ± 3.10	0.582
Apical rotation (°)	9.82 ± 5.62	9.87 ± 5.51	0.998
Basal rotation (°)	−6.80 ± 5.67	−8.02 ± 4.06	0.325
Twist (°)	17.05 ± 6.41	17.25 ± 7.45	0.979
Twist rate (°/s)	113.82 ± 31.75	122.16 ± 53.94	0.724
Untwist rate (°/s)	−124.98 ± 46.03	−134.53 ± 41.96	0.298

Data are reported as mean ± SD, *n* (%) or *n*. EF, ejection fraction; GLS, global longitudinal strain; LAV, left-atrial volume; MV, mitral valve; PV, pulmonary vein; S/D, systolic/diastolic ratio; TR Vmax, tricuspid regurgitation peak velocity.

DISCUSSION

Despite considerable changes in maternal cardiovascular volume and resistance load at the time of birth, no substantial improvement in cardiac geometry or LV function indices was found when comparing TTE findings before *vs* soon after delivery in women with HDP. These results suggest that maternal echocardiographic findings in HDP are likely to be the consequence of chronic pregnancy cardiovascular load changes and, as such, require longer to resolve in the postpartum period. An alternative explanation is that maternal cardiac findings may not be a simple adaptive change to loading conditions in pregnancy, but may point to a pre-existing cardiac dysfunction with implications for long-term maternal cardiovascular health.

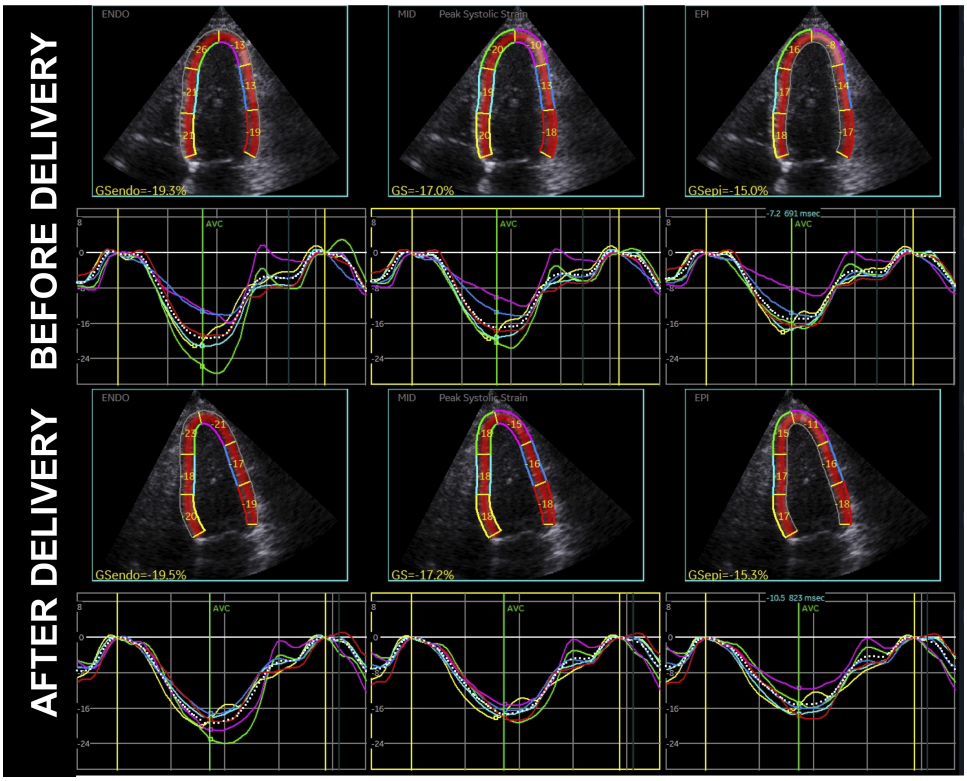

Figure 1 Layer-specific longitudinal strain analysis using two-dimensional speckle-tracking echocardiography for evaluating left-ventricular systolic function in a woman affected by pre-eclampsia, before delivery (upper rows) and in the immediate postpartum period (lower rows).

Interpretation of study findings and comparison with published literature

Previous studies using unvalidated peripheral waveform devices in the peripartum period have shown that the high-output pregnancy circulation noted in the immediate postpartum period resolves to prepregnancy levels within 2 weeks[21,22]. This increased volume load (preload) might be explained by the transfer of blood from the uterus into the systemic circulation and also due to improved venous return caused by decreased vena cava compression. Blood volume redistribution after delivery in women with HDP may be influenced by the characteristic antenatal findings of lower cardiac index, higher SVR and maladaptation to hemodynamic changes[23,24]. Our findings demonstrate that peripartum hemodynamic fluctuations result in only minimal changes in LV diastolic function and no alteration in LV geometry or systolic function.

Longitudinal studies investigating uncomplicated pregnancies reported that the greatest changes in cardiac morphology and biomarkers (N-terminal proB-type natriuretic peptide and high-sensitivity troponin I) occur within a week after delivery and not during pregnancy[25]. This is consistent with the finding that a significant proportion of women with an apparently normal pregnancy had diastolic dysfunction and abnormal cardiac remodeling at term as signs of cardiovascular maladaptation to the volume-overloaded state[26]. Ambrozic *et al.*[27] compared echocardiographic findings between 30 women with severe PE and 30 healthy controls who underwent TTE 1 day before and 1 and 4 days after delivery. The findings of their study should be considered carefully, as the comparison of cardiac geometry before delivery between these two groups was not in agreement with previous literature[3]. They showed that only normal pregnancies were able to respond to volume load in the immediate postpartum period by significantly increasing SV and transmitral E velocity compared to PE cases[27]. This difference in response could be explained by the fact that the maternal heart in HDP is not capable of increasing SV with increased preload because of impaired LV function[2,28].

Clinical and research implications

Several epidemiological studies have established that women affected by HDP are more likely to develop cardiovascular disease later in life compared to women with uncomplicated pregnancy[29]. Notably, their cardiovascular risk increases soon after delivery, as demonstrated by a recent meta-analysis, which showed that the risk of developing chronic hypertension in women with a history of HDP was 6-fold higher than that in controls within the first 2 years following pregnancy[30]. Thus, the peripartum period represents a unique opportunity to assess the cardiovascular risk of women with HDP and initiate a program of cardiovascular disease prevention and management. In order to accomplish such a goal, identifying cardiac functional and structural abnormalities in the peripartum period in women with HDP may be vital, considering their prognostic role in the general population to predict adverse outcome[10,11]. For example, an increased LVMI, as well as other established risk factors, in chronically hypertensive patients can be considered a prognostic factor for ischemic heart disease and heart failure[10].

A single-center feasibility randomized controlled trial evaluated the effect of enalapril on postnatal cardiovascular function in women affected by HDP, who were recruited and studied using TTE in the immediate postpartum period. Women treated with enalapril had an improved diastolic function and LV remodeling at 6 months postpartum compared with those who received placebo[31]. These cardiac improvements after targeted treatment have the potential to reduce long-term cardiovascular disease risk of women with a history of HDP. The findings of this study demonstrate that women affected by HDP can be screened using TTE for cardiac dysfunction, either in pregnancy or in the immediate postpartum period. Although further research on the potential use of TTE in the stratification of cardiovascular risk in women affected by HDP is needed, our findings will help to design a cardiovascular screening strategy that can identify women at an increased risk of developing cardiovascular disease. In addition, future prospective peripartum studies on HDP cases with a longer postpartum follow-up period may help elucidate further the hypothesis of pre-existence of cardiovascular disease in women with HDP and its link to long-term maternal cardiovascular health.

Strengths and limitations

This was a prospective study conducted in a single tertiary center, in which all women were managed according to the local protocol and underwent TTE. The imaging data were analyzed by the same operator (V.G.), who was blinded to the time of TTE. Moreover, the prospective study design with a sufficient number of subjects, paired comparison and an application of novel echocardiographic modalities, such as tissue Doppler imaging and speckle-tracking echocardiography, could be regarded as strengths of this study. A control group was not necessary because of the paired observations (before and after delivery) for each patient affected by HDP. The main limitation of the current study is related to the fact that multiple comparisons might have increased the risk of Type-I error for some of the TTE indices. Moreover, data on total blood volume assessed by direct invasive or indirect methods were not available.

Conclusions

This study has demonstrated that cardiac morphology and function of women affected by HDP do not improve in the postpartum period despite physiological cardiovascular changes associated with delivery. These findings suggest that maternal echocardiographic findings in HDP are likely to be the consequence of chronic pregnancy cardiovascular load changes and/or may point to pre-existing cardiac dysfunction, with implications

for long-term maternal cardiovascular health. Maternal echocardiographic findings either immediately before delivery or in the early postpartum period may be used to tailor antihypertensive therapy or to assess long-term maternal cardiovascular health.

ACKNOWLEDGMENTS

V.G. and C.D.F. have received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 765274 (iPLACENTA project). C.M.C.'s postdoctoral fellowship at St George's University Hospitals NHS Foundation Trust, London, UK was supported by funds from Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP), process number 2019/01280-3.

REFERENCES

1. Parikh NI, Gonzalez JM, Anderson CAM, Judd SE, Rexrode KM, Hlatky MA, Gunderson EP, Stuart JJ, Vaidya D; American Heart Association Council on Epidemiology and Prevention; Council on Arteriosclerosis, Thrombosis and Vascular Biology; Council on Cardiovascular and Stroke Nursing; and the Stroke Council. Adverse Pregnancy Outcomes and Cardiovascular Disease Risk: Unique Opportunities for Cardiovascular Disease Prevention in Women: A Scientific Statement From the American Heart Association. *Circulation* 2021; **143**: e902–916.
2. Castleman JS, Ganapathy R, Taki F, Lip GY, Steeds RP, Kotecha D. Echocardiographic Structure and Function in Hypertensive Disorders of Pregnancy: A Systematic Review. *Circ Cardiovasc Imaging* 2016; **9**: e004888.
3. De Haas S, Ghossein-Doha C, Geerts L, van Kuijk SMJ, van Drongelen J, Spaanderman MEA. Cardiac remodeling in normotensive pregnancy and in pregnancy complicated by hypertension: systematic review and meta-analysis. *Ultrasound Obstet Gynecol* 2017; **50**: 683–696.
4. Ueland K, Hansen JM. Maternal cardiovascular dynamics. 3. Labor and delivery under local and caudal analgesia. *Am J Obstet Gynecol* 1969; **103**: 8–18.
5. Robson SC, Hunter S, Moore M, Dunlop W. Haemodynamic changes during the puerperium: a Doppler and M-mode echocardiographic study. *Br J Obstet Gynaecol* 1987; **94**: 1028–1039.
6. Lavie A, Ram M, Lev S, Blecher Y, Amikam U, Shulman Y, Avnon T, Weiner E, Many A. Maternal cardiovascular hemodynamics in normotensive versus preeclamptic pregnancies: a prospective longitudinal study using a noninvasive cardiac system (NICaS). *BMC Pregnancy Childbirth* 2018; **18**: 229.
7. Garcia-Gonzalez C, Georgiopoulos G, Azim SA, Macaya F, Kametas N, Nihoyannopoulos P, Nicolaides KH, Charakida M. Maternal Cardiac Assessment at 35 to 37 Weeks Improves Prediction of Development of Preeclampsia. *Hypertension* 2020; **76**: 514–522.
8. Melchiorre K, Sutherland GR, Liberati M, Thilaganathan B. Preeclampsia is associated with persistent postpartum cardiovascular impairment. *Hypertension* 2011; **58**: 709–715.
9. Reddy M, Wright L, Rolnik DL, Li W, Mol BW, La Gerche A, da SilvaCosta F, Wallace EM, Palmer K. Evaluation of Cardiac Function in Women With a History of Preeclampsia: A Systematic Review and Meta-Analysis. *J Am Heart Assoc* 2019; **8**: e013545.
10. Modin D, Biering-Sorensen SR, Mogelvang R, Landler N, Jensen JS, Biering-Sorensen T. Prognostic Value of Echocardiography in Hypertensive Versus Nonhypertensive Participants From the General Population. *Hypertension* 2018; **71**: 742–751.
11. Halley CM, Houghtaling PL, Khalil MK, Thomas JD, Jaber WA. Mortality rate in patients with diastolic dysfunction and normal systolic function. *Arch Intern Med* 2011; **171**: 1082–1087.
12. Ghossein-Doha C, Peeters L, van Heijster S, van Kuijk S, Spaan J, Delhaas T, Spaanderman M. Hypertension after preeclampsia is preceded by changes in cardiac structure and function. *Hypertension* 2013; **62**: 382–390.
13. Brown MA, Magee LA, Kenny LC, Karumanchi SA, McCarthy FP, Saito S, Hall DR, Warren CE, Adoyi G, Ishaku S, International Society for the Study of Hypertension in P. Hypertensive Disorders of Pregnancy: ISSHP Classification, Diagnosis, and Management Recommendations for International Practice. *Hypertension* 2018; **72**: 24–43.
14. Gordijn SJ, Beune IM, Thilaganathan B, Papageorghiou A, Baschat AA, Baker PN, Silver RM, Wynia K, Ganzevoort W. Consensus definition of fetal growth restriction: a Delphi procedure. *Ultrasound Obstet Gynecol* 2016; **48**: 333–339.
15. Whelton PK, Carey RM, Aronow WS, Casey DE, Jr., Collins KJ, Dennison Himmelfarb C, DePalma SM, Gidding S, Jamerson KA, Jones DW, MacLaughlin EJ, Muntner P, Ovbiagele B, Smith SC, Jr., Spencer CC, Stafford RS, Taler SJ, Thomas RJ, Williams KA, Sr., Williamson JD, Wright JT, Jr. Systematic Review for the 2017 ACC/AHA/AAPA/ABC/ACPM/AGS/APhA/ASH/ASPC/NMA/PCNA Guideline for the Prevention, Detection, Evaluation, and Management of High Blood Pressure in Adults: A Report of the American College of Cardiology/American Heart Association Task Force on Clinical Practice Guidelines. *J Am Coll Cardiol* 2018; **71**: e127–248.
16. Mitchell C, Rahko PS, Blauwet LA, Canaday B, Finstuen JA, Foster MC, Horton K, Ogunyankin KO, Palma RA, Velazquez EJ. Guidelines for Performing a Comprehensive Transthoracic Echocardiographic Examination in Adults: Recommendations from the American Society of Echocardiography. *J Am Soc Echocardiography* 2019; **32**: 1–64.
17. Lang RM, Badano LP, Mor-Avi V, Afilalo J, Armstrong A, Ernande L, Flachskampf FA, Foster E, Goldstein SA, Kuznetsova T, Lancellotti P, Muraru D, Picard MH, Rietzschel ER, Rudski L, Spencer KT, Tsang W, Voigt JU. Recommendations for cardiac chamber quantification by echocardiography in adults: an update from the American Society of Echocardiography and the European Association of Cardiovascular Imaging. *Eur Heart J Cardiovasc Imaging* 2015; **16**: 233–270.
18. Mathew T, Steeds R, Jones R, Kanagala P, Lloyd G, Knight D, O'Gallagher K, Oxborough D, Rana B, Ring L, Sandoval J, Wharton G, Wheeler R. A Guideline Protocol for the Echocardiographic assessment of Diastolic Dysfunction: British Society of Echocardiography. 2013. https://www.bsecho.org/common/Uploaded%20files/Education/Protocols%20and%20guidelines/Diastolic%20dysfunction.pdf.
19. Amzulescu MS, De Craene M, Langet H, Pasquet A, Vancraeynest D, Pouleur AC, Vanoverschelde JL, Gerber BL. Myocardial strain imaging: review of general principles, validation, and sources of discrepancies. *Eur Heart J Cardiovasc Imaging* 2019; **20**: 605–619.
20. Bijl RC, Valensise H, Novelli GP, Vasapollo B, Wilkinson I, Thilaganathan B, Stohr EJ, Lees C, van der Marel CD, Cornette JMJ; International Working Group on Maternal Hemodynamics. Methods and considerations concerning cardiac output measurement in pregnant women: recommendations of the International Working Group on Maternal Hemodynamics. *Ultrasound Obstet Gynecol* 2019; **54**: 35–50.
21. Ram M, Lavie A, Lev S, Blecher Y, Amikam U, Shulman Y, Avnon T, Weiner E, Many A. Cardiac hemodynamics before, during and after elective cesarean section under spinal anesthesia in low-risk women. *J Perinatol* 2017; **37**: 793–799.
22. Hunter S, Robson SC. Adaptation of the maternal heart in pregnancy. *Br Heart J* 1992; **68**: 540–543.
23. Dyer RA, Piercy JL, Reed AR, Lombard CJ, Schoeman LK, James MF. Hemodynamic changes associated with spinal anesthesia for cesarean delivery in severe preeclampsia. *Anesthesiology* 2008; **108**: 802–811.
24. Kalafat E, Perry H, Bowe S, Thilaganathan B, Khalil A. Prognostic Value of Maternal Cardiovascular Hemodynamics in Women With Gestational Hypertension and Chronic Hypertension in Pregnancy. *Hypertension* 2020; **76**: 506–513.
25. Umazume T, Yamada T, Yamada S, Ishikawa S, Furuta I, Iwano H, Murai D, Hayashi T, Okada K, Morikawa M, Yamada T, Ono K, Tsutsui H, Minakami H. Morphofunctional cardiac changes in pregnant women: associations with biomarkers. *Open Heart* 2018; **5**: e000850.
26. Melchiorre K, Sharma R, Khalil A, Thilaganathan B. Maternal Cardiovascular Function in Normal Pregnancy: Evidence of Maladaptation to Chronic Volume Overload. *Hypertension* 2016; **67**: 754–762.
27. Ambrozic J, Lucovnik M, Prokselj K, Toplisek J, Cvijic M. Dynamic changes in cardiac function before and early postdelivery in women with severe preeclampsia. *J Hypertens* 2020; **38**: 1367–1374.
28. Schotola H, Sossalla ST, Renner A, Gummert J, Danner BC, Schott P, Toischer K. The contractile adaption to preload depends on the amount of afterload. *ESC Heart Fail* 2017; **4**: 468–478.
29. Melchiorre K, Thilaganathan B, Giorgione V, Ridder A, Memmo A, Khalil A. Hypertensive Disorders of Pregnancy and Future Cardiovascular Health. *Front Cardiovasc Med* 2020; **7**: 59.
30. Giorgione V, Ridder A, Kalafat E, Khalil A, Thilaganathan B. Incidence of postpartum hypertension within 2 years of a pregnancy complicated by pre-eclampsia: a systematic review and meta-analysis. *BJOG* 2021; **128**: 495–503.
31. Ormesher L, Higson S, Luckie M, Roberts SA, Glossop H, Trafford A, Cottrell E, Johnstone ED, Myers JE. Postnatal Enalapril to Improve Cardiovascular Function Following Preterm Preeclampsia (PICk-UP): A Randomized Double-Blind Placebo-Controlled Feasibility Trial. *Hypertension* 2020; **76**: 1828–1837.

SUPPORTING INFORMATION ON THE INTERNET

The following supporting information may be found in the online version of this article:

Table S1 Inter- and intraobserver reproducibility of echocardiographic measurements in women with hypertensive disorders of pregnancy