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RESEARCH

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Normative ranges of biventricular volumes and function in healthy term newborns

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Abstract

Background Cardiovascular magnetic resonance (CMR) is increasingly used in newborns with congenital heart disease. However, reporting on ventricular volumes and mass is hindered by an absence of normative data in this population.

Design/methods Healthy term (37–41 weeks gestation) newborns underwent non-sedated, free-breathing CMR within the first week of life using the 'feed and wrap' technique. End-diastolic volume (EDV), end-systolic volume (ESV) stroke volume (SV) and ejection fraction (EF) were calculated for both left ventricle (LV) and right ventricle (RV). Papillary muscles were separately contoured and included in the myocardial volume. Myocardial mass was calculated by multiplying myocardial volume by 1.05 g/ml. All data were indexed to weight and body surface area (BSA). Inter-observer variability (IOV) was performed on data from 10 randomly chosen infants.

Results Twenty healthy newborns (65% male) with a mean (SD) birth weight of 3.54 (0.46) kg and BSA of 0.23 (0.02) m2 were included. Normative LV parameters were indexed EDV 39.0 (4.1) ml/m^2, ESV 14.5 (2.5) ml/m^2 and ejection fraction (EF) 63.2 (3.4)%. Normative RV indexed EDV, ESV and EF were 47.4 (4.5) ml/m^2, 22.6 (2.9) ml/m^2 and 52.5 (3.3)% respectively. Mean LV and RV indexed mass were 26.4 (2.8) g/m^2 and 12.5 (2.0) g/m^2, respectively. There was no difference in ventricular volumes by gender. IOV was excellent with an intra-class coefficient > 0.95 except for RV mass (0.94).

Conclusion This study provides normative data on LV and RV parameters in healthy newborns, providing a novel resource for comparison with newborns with structural and functional heart disease.

Keywords Neonates, Cardiovascular magnetic resonance imaging, Normative data, Left ventricular volume, Left ventricular mass, Right ventricular volume, Right ventricular mass

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Introduction

Neonatal cardiovascular magnetic resonance (CMR) is being increasingly utilized for assessment of structural and functional cardiac conditions. CMR has the unique ability to provide a detailed assessment of cardiac anatomy, non-invasive hemodynamics, volumetric data and tissue characterization, without the use of potentially harmful ionizing radiation [1]. In addition, there is a growing body of literature reporting performance of neonatal CMR without anesthesia using the feed-and-wrap technique, suggesting its increasing applicability [2].

In neonates and infants, accurate measurement of biventricular volumes are needed for preoperative assessment and surgical planning for patients with congenital heart disease (CHD) associated with borderline left or right heart structures [3]. While transthoracic echocardiography is often used for initial estimation of ventricular size in neonates, experimental animal studies comparing echocardiography and CMR-derived ventricular volumes have shown CMR to be a more precise method of chamber quantification [4]. Further, measurement of right ventricular (RV) volumes by echocardiography is difficult given the complex tripartite morphology of the chamber with literature now supporting the use of CMR as the preferred method [5, 6]. CMR also has a role in neonates with other heart diseases including tissue characterization of intracardiac masses and pulmonary hypertension [7, 8]. Indeed, CMR is the current gold standard for measurement of biventricular volumes and mass.

The interpretation of CMR in the neonatal population is limited by the inability to compare ventricular volumes and mass to those in normal neonates. There has been a recent momentum in pediatrics to establish CMR datasets for healthy infants and children [9–12], although these studies have minimal inclusion of neonates. Recent work by our group involved performance of CMR in neonates to assess the impact of maternal obesity on cardiac size [13]. However, current literature lacks normative CMR data in a dedicated newborn population. Given this knowledge gap, our study reports normal values of biventricular volumes and mass in a healthy neonatal population using non-sedated free-breathing CMR imaging obtained in the first few days of life.

Methods

Study population

Healthy term (37–41 weeks gestation) newborns underwent non-sedated, free-breathing CMR within the first week of life using the 'feed-and-wrap' technique. Newborns were a subset of infants born to mothers with a normal body mass index (BMI) in a larger multisite study examining the impact of maternal obesity on newborn outcomes [13, 14]. Neonates born to mothers with a normal BMI [lean cohort, (20–25 kg/m^2)] in early pregnancy were included to avoid potential effects of maternal obesity. This study was approved by the Regional Ethics Committee and written informed parental consent was obtained. CMR was performed on infants while inpatients on the postnatal ward. No infant had required admission to the intensive care unit.

Imaging technique

All infants were scanned using acoustic ear protection, pulse oximetry, vector electrocardiogram (ECG) monitoring and without sedation or anesthesia, as described previously [15]. Scans were performed on 3T CMR scanner (Achieva, Philips Healthcare, Best, Netherlands) using an 8-channel pediatric body receive coil. An ECG-gated 2-dimensional balanced steady-state free precession (bSSFP) short axis 10 slice stack optimized for neonatal CMR (acquired in-plane resolution = 1 × 1 mm, slice thickness = 4 mm, TR/TE = 3.8/1.9 ms, flip angle = 35°, signal averages = 4) was placed over the heart, aligned with the mitral valve using previously acquired pilot scans. Four chamber and two chamber cines were additionally included as reference images.

Post-processing

Images were transferred to the post-processing Circle Cardiovascular Imaging (cvi42) software (version 5.10.3, Circle Cardiovascular Imaging, Calgary, Canada). End-diastolic and end-systolic phases were determined on the cine bSSFP short-axis stack. Manual contouring of biventricular endocardial borders was performed. Four chamber and two chamber cine images were used for cross-referencing particularly in basal slices for accurate determination of the atrioventricular valvar plane through the cardiac cycle. Left ventricular (LV) papillary muscles were separately contoured and included in the LV mass (LVM) calculation and excluded from the ventricular volume. RV trabeculations and papillary muscles were not contoured separately and were included in RV blood pool. A smooth endocardial border was drawn for the RV volumes. Epicardial borders for both ventricles were traced in diastole to measure the myocardial volume. The interventricular septum, including the septal band was included as part of the LVM. Myocardial volume was multiplied by the factor 1.05 g/ml to obtain the myocardial mass. (Fig. 1) Stroke volume (SV) was calculated as the difference between end-diastolic volume (EDV) and end-systolic volume (ESV). Ejection fraction (EF) was calculated as the SV divided by EDV × 100. LV and RV volumes and mass (RVM) were described as absolute values as well as indexed to weight and body surface area (BSA). RV and LV cardiac outputs were measured by multiplying respective SV by heart rate.

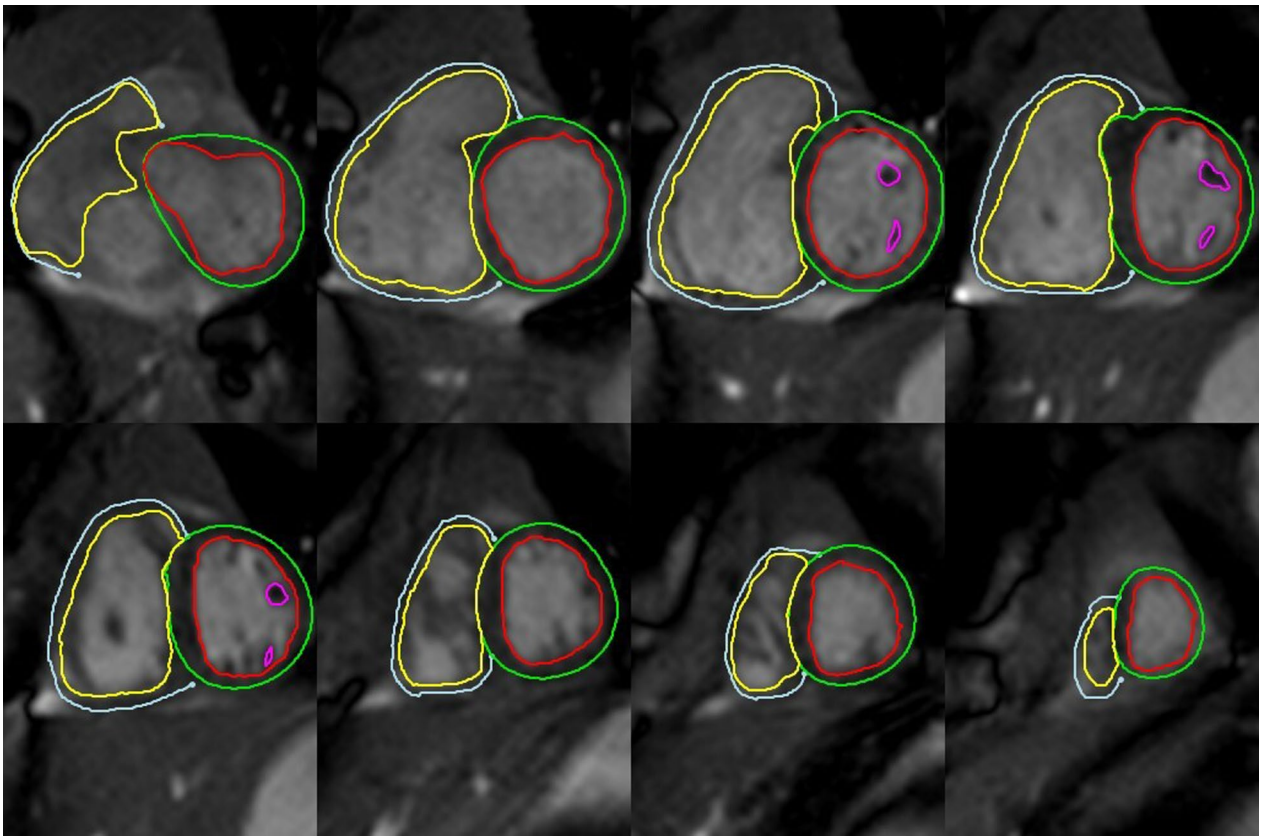

Fig. 1 Mulitslice view of short-axis stack in end-diastole with contours. Myocardial borders were defined by performing a detailed manual tracing of the epicardium and endocardium. Left ventricular (LV) papillary muscles were separately contoured and included in the LV myocardial mass (LVM)

Statistical analysis

Data are described using mean (standard deviation) for continuous variables and percentages for categorical variables. The volumetric variables were assessed for normal distribution using the Shapiro–Wilk test. The association of gestational age to ventricular volumes was assessed using Pearson correlation coefficient and a p-value of < 0.05 was considered statistically significant. The primary data analysis was performed using Excel 2019 (Microsoft Corporation, Redmond, Washington, USA). The comparative analysis was performed using Stata (version 15.1, Stata Corporation, College Station, Texas, USA).

Interobserver variability

Ten randomly selected neonates' CMR data were chosen for interobserver variability assessment. Post-processing was performed on each of these studies by a second independent observer using the same methodology as stated above. Intraclass coefficient (ICC) estimates and their 95% confidence interval (CI) were calculated using Stata (version 15.1; Stata Corporation).

Results

A total of 20 healthy newborns (65% male) were included in the study. All neonates were born at term with a mean gestational age of 39.9 (1.2) weeks. Average maternal age was 34.2 (5.3) years. Mean age at the time of the scan in hours was 31.8 (14.0) hours (range of 9–56). One newborn did not have height included in the dataset precluding measurement of BSA and indexed values. Demographic details of the cohort are shown in Table 1.

Ventricular parameters

The average LV end-diastolic volume (LVEDV) was 9.0 (1.2) ml. The mean LVEDV indexed by BSA (LVEDVI) was 39.0 (4.1) ml/m^2. The average absolute and BSA indexed LV end-systolic volume (LVESV, LVESVI) was 3.3 (0.5) ml and 14.5 (2.5) ml/m^2, respectively. LV ejection fraction (LVEF) measured 63.2 (3.4)%. The LVM was 6.0 (0.7) g with an LVM index (LVMI) of 26.4 (2.8) g/m^2.

Table 1 Demographic variables of the population (n = 20)

Variable	Mean (SD)
Maternal Age (years)	34.2 (5.3)
Maternal BMI (kg/m^2)	22.0 (1.2)
Gestational age (weeks)	39.9 (1.2)
Age at scan (hours)	31.8 (14.0)
Birth weight (g)	3545 (462)
Length (cm) *	51.9 (3.2)
BSA (m^2) *	0.23 (0.02)
Heart rate (beats/min)	100.3 (9.8)

BMI body mass index, *BSA* body surface area

* For these values, n = 19

Table 2 Left ventricular (LV) parameters

Variable (unit)	Mean (SD)	Lower/Upper limits **
Absolute values		
LVEDV (ml)	9.0 (1.2)	6.6–11.3
LVESV (ml)	3.3 (0.5)	2.2–4.3
LVEF (%)	63.2 (3.4)	56.4–69.9
LVSV (ml)	5.7 (0.8)	4.0–7.3
LVM (g)	6.0 (0.7)	4.6–7.5
LVCO (ml/min)	624 (110)	404–843
Indexed to body weight		
LVEDV/kg (ml/kg)	2.5 (0.3)	1.9–3.1
LVESV/kg (ml/kg)	0.9 (0.2)	0.5–1.3
LVSV/kg (ml/kg)	1.6 (0.1)	1.4–1.9
LVM/kg (g/kg)	1.7 (0.2)	1.3–2.1
LVCO/kg (ml/min/kg)	177 (25)	126–227
Indexed to BSA		
LVEDV/BSA (ml/m^2)*	39.0 (4.1)	30.8–47.2
LVESV/BSA (ml/m^2)*	14.5 (2.5)	9.5–19.4
LVSV/BSA (ml/m^2)*	24.5 (2.3)	20.0–29.0
LVM/BSA (g/m^2)*	26.4 (2.8)	20.7–32.0
LVCI (L/min/m2)*	2.7 (0.4)	1.9–3.5

LVCI left ventricular cardiac index, *LVCO* left ventricular cardiac output, *LVEDV* left ventricular end-diastolic volume, *LVEF* left ventricular ejection fraction, *LVESV* left ventricular end-systolic volume, *LVM* left ventricular mass, *LVSV* left ventricular stroke volume

*Variables with n = 19, rest of the variables have n = 20, **Calculated as mean ± 2 × SD

LVM, LVEDV and LVESV were also indexed to body weight as shown in Table 2.

Similarly, the mean absolute RV end-diastolic volume (RVEDV) of the cohort was 11.0 (1.7) ml. The RVEDV indexed by BSA (RVEDVI) was 47.4 (4.5) ml/m^2. The RV ejection fraction (RVEF) was 52.5 (3.3)%. The average RV end-systolic volume (RVESV) was 5.2 (0.9) ml with an RVEDV indexed to BSA (RVEDVI) of 22.6 (2.9) ml/m^2. Absolute RVM and BSA indexed mass (RVMI) were 2.9 (0.5) g and 12.5 (2.0) g/m^2, respectively. In addition, the ratio of the RVEDV to the LVEDV was 1.2 (0.2). RV parameters including values indexed to birth weight are shown in Table 3.

Table 3 Right ventricular (RV) parameters

Variable (unit)	Mean (SD)	Lower/Upper limits **
Absolute values		
RVEDV (ml)	11.0 (1.7)	7.6–14.4
RVESV (ml)	5.2 (0.9)	3.4–7.0
RVEF (%)	52.5 (3.3)	45.9–59.1
RVSV (ml)	5.8 (0.9)	4.0–7.6
RVM (g)	2.9 (0.5)	1.9–3.9
RVCO (ml/min)	638 (126)	386–890
Indexed to body weight		
RVEDV/kg (ml/kg)	3.1 (0.3)	2.5–3.7
RVESV/kg (ml/kg)	1.5 (0.2)	1.1–1.9
RVSV/kg (ml/kg)	1.6 (0.2)	1.2–2.0
RVM/kg (g/kg)	0.8 (0.1)	0.6–1.0
RVCO/kg (ml/min/kg)	181 (30)	120–241
Indexed to BSA		
RVEDV (ml/ m^2) *	47.4 (4.5)	38.5–56.4
RVESV (ml/ m^2) *	22.6 (2.9)	16.9–28.3
RVSV (ml/ m^2) *	24.9 (2.5)	19.9–29.9
RVM (g/m^2) *	12.5 (2.0)	8.5–16.5
RVCI (L/min/m2) *	2.7 (0.5)	1.8–3.7

RVCI right ventricular cardiac index, *RVCO* right ventricular cardiac output; *RVEDV* right ventricular end-diastolic volume, *RVEF* right ventricular ejection fraction; *RVESV* right ventricular end-systolic volume, *RVM* right ventricular mass, *RVSV* right ventricular stroke volume

*Variables with n = 19, rest of the variables have n = 20

**Calculated as mean ± 2 × standard deviation (SD)

Biventricular volumes and mass by sex

There were 13 male and 7 female infants. Volumetric data for LV and RV are described for males and females separately in Table 4.

Relationship to gestational age

There was a weak relationship between LVESVI and gestational age (r = -0.51, p = 0.03). There was no correlation between gestational age and any other variables of biventricular volumes or mass. (Additional file 1: Table S1).

Interobserver variability

Post-processing was repeated on ten randomly selected newborns by a second independent observer. The intraclass correlation (ICC) estimate between individual measurements and average measurement were

Table 4 Ventricular volumes and mass by sex

Variables	Males Mean (SD) N = 13	Females Mean (SD) N = 7
LVEDV (ml)	9.0 (1.0)	8.9 (1.5)
LVESV (ml)	3.4 (0.5)	3.2 (0.6)
LVEF (%)	62.6 (3.5)	64.1 (3.1)
LVSV (ml)	5.6 (0.7)	5.7 (1.0)
LVM (g)	6.0 (0.7)	6.2 (0.8)
RVEDV (ml)	10.9 (1.6)	11.3 (1.9)
RVESV (ml)	5.2 (0.8)	5.2 (1.1)
RVSV (ml)	5.6 (0.9)	6.1 (0.9)
RVEF (%)	51.6 (2.7)	54.1 (3.9)
RVM (g)	2.9 (0.5)	2.8 (0.5)
LVEDV/BSA (ml/m^2)*	38.9 (3.4)	39.2 (5.7)
LVESV/BSA (ml/m^2)*	14.6 (2.4)	14.1 (2.8)
LVSV/BSA (ml/m^2)*	24.3 (1.6)	25.0 (3.4)
LVM/BSA (g/m^2)*	25.8 (2.3)	27.6 (3.6)
RVEDV/BSA (ml/m^2)*	46.9 (4.1)	48.7 (5.4)
RVESV/BSA (ml/m^2)*	22.7 (2.6)	22.4 (3.7)
RVSV/BSA (ml/m^2)*	24.2 (2.2)	26.3 (2.8)
RVM/BSA (g/m^2)*	12.7 (2.0)	12.1 (2.1)

BSA body surface area, *LVEDV* left ventricular end-diastolic volume, *LVEF* left ventricular ejection fraction, *LVESV* left ventricular end-systolic volume, *LVM* left ventricular mass, *LVSV* left ventricular stroke volume, *RVEDV* right ventricular end-diastolic volume, *RVEF* right ventricular ejection fraction, *RVESV* right ventricular end-systolic volume, *RVM* right ventricular mass, *RVSV* right ventricular stroke volume

*For these values, n = 6 for females

Table 5 Inter-observer variability testing using intraclass coefficient (ICC) for 10 randomly selected patients with 95% confidence intervals (CI)

Variable	ICC	95% CI
LVEDV	0.98	0.65–1.00
LVESV	0.99	0.98–1.00
LVM	0.97	0.74–0.99
RVEDV	0.98	0.39–1.00
RVESV	0.98	0.24–1.00
RVM	0.94	0.76–0.98

LVEDV left ventricular end-diastolic volume, *LVEF* left ventricular ejection fraction, *LVM* left ventricular mass; *RVEDV* right ventricular end-diastolic volume, *RVEF* right ventricular ejection fraction, *RVM* right ventricular mass

calculated. LVEDV, LVESV, RVEDV, RVESV and LVM had excellent inter-observer reproducibility, while that for RVM was slightly lower (Table 5).

Discussion

Neonatal CMR has historically been challenging primarily due to the need for anesthesia and image optimization. With numerous recent studies reporting refined imaging techniques in neonates without sedation, [15–17] and with the application of CMR data in assessment of patients with CHD, the performance of CMR in this population has increased. There remains, however, a lack of normative data for neonates, although this is available for children and young adults [10]. We believe the present study to be among the first to describe normative data on biventricular chamber volumes, myocardial masses and cardiac output in a cohort of term newborns. This data will enable quantification of z-scores in newborns with structural and functional cardiac lesions.

Importance of CMR in accuracy of volumetric data

Echocardiography is usually the first line method for assessment of LV volumes and mass. Three dimensional echocardiography is superior to 2-dimensional echocardiography in this regard, although there are wide limits of agreement and it underestimates ventricular volumes when compared to CMR in adult patients [18]. LVM is best estimated by CMR [19]. In an animal model study, bSSFP imaging by CMR correlated well with ventricular mass obtained on autopsy [20]. A correlation between CMR derived LVM and directly measured LVM was also found in studies on human explanted hearts [21]. Furthermore, the RV has a complex geometric tripartite shape that limits its measurement by 2-dimensional echocardiography [5]. CMR is also highly accurate and reproducible in assessment of RV volumes and mass in animal and human studies [22, 23]. Given the superior endocardial definition, lack of radiation and excellent reproducibility associated with CMR, it is currently the gold standard for assessment of biventricular volumes and mass [6, 24].

Indications for utilization of CMR in neonatal population

Neonatal CMR is being increasingly performed for both CHD and acquired cardiac conditions [8]. Neonates with left sided obstructive lesions such as hypoplastic left heart syndrome, aortic stenosis or Shone's complex, require accurate determination of LV volumes and mass. Similarly, estimation of RV volumes is important for surgical planning and prognostication in neonates with borderline RV size such as those with unbalanced atrioventricular canal defects and pulmonary atresia. These infants can undergo a univentricular or biventricular surgical procedure. The decision to utilize the hypoplastic ventricle as an independent pumping chamber often involves a complex model that includes measured ventricular volumes. Previously, echocardiographic LV volume was one of the determinants of success of biventricular repair in infants with borderline left-sided structures [25]. However, because these patients often have altered LV geometry and septal configuration 2-dimensional assessment

is limited. More recently, CMR-derived ventricular volumes have been included as key determinants of surgical decision making in this population [3]. An indexed LVEDV cutoff of 20 ml/m^2 or more is used in some centers as favoring biventricular surgery [3, 26]. However, the lack of available CMR normative data as noted by Nathan et al. precludes comparative assessment [26]. Using our dataset, an indexed LVEDV of 20 ml/m^2 would measure as 4.6 standard deviations below the mean, indicative of moderate LV hypoplasia. In a large multicenter study of patients with pulmonary atresia and intact ventricular septum, a higher baseline RV end-diastolic area measured by 2-dimensional echocardiography was associated with biventricular repair [27]. CMR is likely to play a role in these patients in the future to provide accurate RV measurements. Indications for neonatal CMR, other than CHD include assessment of intracardiac masses, myocardial tissue characterization and pulmonary hypertension [7, 8]. By providing biventricular volumes and mass in healthy newborns, our study provides a reference for neonatal cardiac assessment.

Image acquisition and analysis

Similar to other centers, neonatal CMR was safely performed without sedation in our study using multi-signal average breathing and a feed-and-wrap technique [2]. Additionally, image-based shimming and frequency stabilization as previously described, were utilized for optimal image quality [15]. Most pediatric studies perform ventriculography using bSSFP short-axis stacks, but others utilize axial stacks [28, 29]. Further, there is heterogeneity in the methodology used for contouring volumes. Some reports identify inclusion of papillary muscles in LV volumes, while others recommend contouring the papillary muscles separately, with inclusion in the LVM calculation [9]. Based on the method used, volumetric data will significantly differ [30]. Our study had excellent interobserver variability for LV parameters but a higher variability for RV parameters. RVM (ICC = 0.94, 95% CI − 0.76–0.98) had the least agreement amongst observers. A lower agreement for RV parameters has similarly been observed by others [9].

Comparison to literature

Our study showed no association between gestational age and CMR data, although all neonates were born at term within a narrow timeframe (39–41 weeks gestation) which may preclude detection of a significant correlation. LV volumes by CMR in a preterm neonatal population has been evaluated [31]. There have been several efforts in the last decade to assess ventricular volumes and mass in healthy children. A recent study by van der Ven et al. pooled data from healthy children across three European centers to establish normal CMR values in children [12]. The median indexed LVEDV (males, 48 ml/m^2; females, 51 ml/m^2) and RVEDV (males, 47 ml/m^2; females, 54 ml/m^2) in the youngest cohort reported appear to be higher than the values we observed. However, the cohort grouped children between 0 and 6 years of age (n = 12), likely accounting for the difference. Similarly, a recent large prospective pediatric study was conducted by Olivieri et al. to assess ventricular volumes and mass in healthy children and infants [11]. The study enrolled infants ranging from 21 days to 9 months (n = 23) which reflects a different age group when compared to our study. This further highlights the paucity of normative data in newborns.

Limitations

Despite being the largest CMR study performed on healthy term newborns, the study has a relatively small sample size (n = 20) that limits detailed analysis. Of note, the study was performed on a 3T scanner. Available adult studies have shown good reproducibility in the volumetric data obtained at 1.5 and 3T, but the lack of supportive pediatric literature potentially limits the generalizability of our data [32]. All neonates included were deemed healthy based on normal newborn clinical examination. However, given that echocardiography was not performed, small shunt lesions (eg. patent ductus arteriosus, patent foramen ovale) or other congenital defects that could affect ventricular volumes and were identified on physical examination, cannot be excluded. Using biventricular SV ratios to calculate Qp:Qs, the mean RV/LV SV of the population is 1.02:1 (range of 0.87: 1.2), supportive of a lack of a significant shunt. It should be noted that all subjects were scanned prior to discharge from hospital and were less than three days of age at the time of the scan. Therefore, these data do not account for normal growth that takes place subsequently in the neonatal period and does not completely represent the neonatal age-group (0–28 days). Further, the use of free-breathing and averaged segmented imaging, particularly in newborns at high heart rates can have an impact on the image quality and measurements. Due to the small sample size and narrow BSA range, allometric normalization, as described in other normative datasets, was not performed [33]. Given that pre-term neonates have distinct clinical and hemodynamic conditions, direct extrapolation of these data to preterm infants is not recommended. Normal values of biventricular volumes and masses for a predominantly pre-term neonatal population have been previously described [17]. Importantly, the cohort described in this study consisted of neonates

born to mothers with a normal BMI in early pregnancy and excluded those whose mothers had higher BMI. This could impact on the generalizability of the data given the prevalence of obesity. As our earlier report showed the differences in CMR parameters between infants of lean and obese women, we chose to present data only on the neonates in the "lean group" [13]. Lastly, significant practice variations exist regarding the view (axial versus short-axis) used for ventriculography and the methodology used for post-processing [29]. The methods that we used are in accordance with standards used at our institution. If these data are used as a reference for comparison, we recommend that similar protocols are followed.

Conclusion

Using non-sedated, free-breathing CMR, we report the largest study of normative data on biventricular volumes and masses in a healthy neonatal population, obtained in the first few days of life. The variables in this study were highly reproducible with good inter-observer agreement. These normative data provide a reference for comparison of ventricular volumes and masses in newborns with structural and functional heart disease.

Abbreviations

BMI	Body mass index
BSA	Body surface area
bSSFP	Balanced steady state free precession
CHD	Congenital heart disease
CMR	Cardiovascular magnetic resonance
ECG	Electrocardiogram
EDV	End-diastolic volume
EF	Ejection fraction
ESV	End-systolic volume
ICC	Intraclass correlation coefficient
IOV	Interobserver variability
LV	Left ventricle/left ventricular
LVCO	Left ventricular cardiac output
LVCI	Left ventricular cardiac index
LVEDV	Left ventricular end-diastolic volume
LVEDVI	Left ventricular end-diastolic volume indexed to BSA
LVEF	Left ventricular ejection fraction
LVESV	Left ventricular end-systolic volume
LVESVI	Left ventricular end-systolic volume indexed to BSA
LVM	Left ventricular mass
LVMI	Left ventricular mass indexed to BSA
LVSV	Left ventricular stroke volume
RV	Right ventricle/right ventricular
RVCO	Right ventricular cardiac output
RVCI	Right ventricular cardiac index
RVEDV	Right ventricular end-diastolic volume
RVEDVI	Right ventricular end-diastolic volume indexed to BSA
RVEF	Right ventricular ejection fraction
RVESV	Right ventricular end-systolic volume
RVESVI	Right ventricular end-systolic volume indexed to BSA
RVM	Right ventricular mass
RVMI	Right ventricular mass indexed to BSA
RVSV	Right ventricular stroke volume
SD	Standard deviation
SV	Stroke volume

Supplementary Information

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Additional file 1: Table S1. Correlation between gestational age and ventricular variables.

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None.

Author contributions

SJ, EB, KS, YY were involved with post-processing analysis of MRI images, SJ drafted the manuscript, SJ and JC performed statistical analysis and interobserver variability, AP, EH, LP, DP, MV and PT were responsible for patient recruitment, consent, performance of CMR and image optimization, AG performed the study, provided oversight to data collection and significantly revised the manuscript. All authors reviewed data, critically revised manuscript and approved final version. All authors have approved the submitted version (and any substantially modified version that involves the author's contribution to the study); and have agreed both to be personally accountable for the author's own contributions and to ensure that questions related to the accuracy or integrity of any part of the work, even ones in which the author was not personally involved, are appropriately investigated, resolved, and the resolution documented in the literature.

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Availability of data and materials

All data generated or analyzed during this study are included in this published article.

Declarations

Ethics approval and consent to participate

The study design and protocol were approved by the UK NHS Research Ethics Committee (UK Integrated Research Application System; reference 13/LO/1108). All assessments were performed for research purposes only, written informed parental consent was obtained in all cases.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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