ESC European Heart Journal (2026) **00**, 1–14
https://doi.org/10.1093/eurheartj/ehag343

CLINICAL RESEARCH
Congenital heart disease

Right aortic arch and double arch assessed by prenatal echocardiography: a population-based study

Anna N. Seale [1,2,*], Trisha V. Vigneswaran [3], Lindsey E. Hunter [4], Sandrine Foldvari[1], Esther Poole[1], David Black [5], Stacey Boardman[6], Bernadette Brent [7], Elspeth Brown [6], Patricia Caldas[8], Victoria Doughty [9], Khaled Hadi[10], Caroline Jones [10,11], Victoria Jowett [12], Joyce Lim [10], Katie Linter [13], Jane Bromilow[8], Paul Moran[14], Chris Oakley [3], Alan Pateman [15], Leila Rittey [12], Rebecca Tothill[14], Orhan Uzun [15], Joanne Wolfenden[12], Vita Zidere [3,16], Julene S. Carvalho [9,17,18], and Groups: The British Fetal Cardiology Association, British Congenital Cardiac Association

[1]Cardiac Department, Birmingham Women's and Children's Hospital, Steelhouse Lane, Birmingham B4 6NH, UK; [2]Institute of Cardiovascular Science, Birmingham University, Birmingham B15 2TT, UK; [3]Department of Congenital Heart Disease, Evelina London Children's Hospital, London, UK; [4]Department of Paediatric Cardiology, Royal Hospital for Children, Glasgow, UK; [5]Department of Paediatric Cardiology, University Hospital Southampton, Southampton, UK; [6]Leeds Congenital Heart Unit, Leeds Teaching Hospital NHS Trust, Leeds, UK; [7]Department of Paediatric Cardiology, Oxford University Hospitals NHS Foundation Trust, Oxford, UK; [8]Paediatric Cardiology Department, Bristol Royal Hospital for Children, Bristol, UK; [9]Brompton Centre for Fetal Cardiology, Royal Brompton Hospital, Guy's and St Thomas', NHS Foundation Trust, London, UK; [10]Department of Paediatric Cardiology, Alder Hey Children's Hospital NHS Foundation Trust, Liverpool, UK; [11]Department of Paediatric Cardiology, Manchester Children's Hospital, Manchester, UK; [12]Cardiology Department, Great Ormond Street Hospital, London, UK; [13]East Midlands Congenital Heart Centre, University Hospitals of Leicester NHS Trust, Leicester, UK; [14]Department of Obstetrics and Gynaecology, Royal Victoria Infirmary, Newcastle-Upon-Tyne, UK; [15]Department of Paediatric Cardiology, University Hospital of Wales, Cardiff, UK; [16]School of Biomedical Engineering and Imaging Sciences, Kings College Hospital, London, UK; [17]Fetal Medicine Unit, St George's University Hospitals NHS Trust, London, UK; and [18]Cardiovascular and Genomics Research Institute, City St.George's, University of London, London, UK

Received 19 May 2025; revised 1 September 2025; accepted 16 April 2026

Abstract

Background and Aims Introduction of the three-vessel trachea view to the second trimester foetal anomaly screening programme increased detection of right (RAA) and double (DAA) aortic arch. Aim was to investigate incidence, associations, and medium-term outcome of RAA/DAA.

Methods Retrospective, population-based, multicentre, observational study of foetuses diagnosed with RAA/DAA between 1 April 2015 and 31 March 2019. All cardiology units in England, Scotland and Wales participated. Foetuses with major congenital heart disease were excluded.

Results Overall, 1046 foetuses were diagnosed with RAA (n = 898, 85.9%) or DAA (n = 141, 13.5%), uncategorized in seven (0.6%). Estimated incidence of RAA and DAA was 17.98 and 4.58 per 10 000 pregnancies screened/year (0.23%). Nine hundred forty cases (89.9%) were isolated, with prenatal extracardiac anomaly (ECA) and/or minor cardiac difference in the remainder. Genetic results were abnormal in 80 of 1046 (7.6%): 22q11.2 microdeletion (n = 28, 35%). Prenatal ECAs increased the risk of genetic anomaly (risk ratio 3.39, 95% confidence interval 1.89–5.73, P < .0001). Nine hundred eighty six (94.3%) were liveborn, while five died postnatally from unrelated problems. Mean follow-up is 4.1 years (standard deviation 1.4), and symptoms of tracheoesophageal

* Corresponding author. Email: A.N.Seale@bham.ac.uk

compression were found in 278 of 986 (28.2%). Vascular ring relief was performed in 234 of 986 liveborn (23.7%) with no deaths. There was variation in management pathways. Surgery was performed in 74.6% with DAA, 24.4% with RAA–left arterial duct (LAD)–aberrant left subclavian artery (ALSA); median age at surgery was 5.29 months [interquartile range (IQR): 2.99–11.26 months] and 12.62 months (IQR: 8.68–17.32 months), respectively ($P < .0001$).

Conclusion Incidence of RAA/DAA is higher than previously reported. Genetic anomaly is identified in at least 7.6%, particularly in the presence of ECA. Liveborn with DAA have earlier and more surgical intervention compared to those with RAA–LAD–ALSA.

Structured Graphical Abstract

Key Question

What are the incidence, associations, and medium-term outcomes of right (RAA) and double (DAA) aortic arch in the general population?

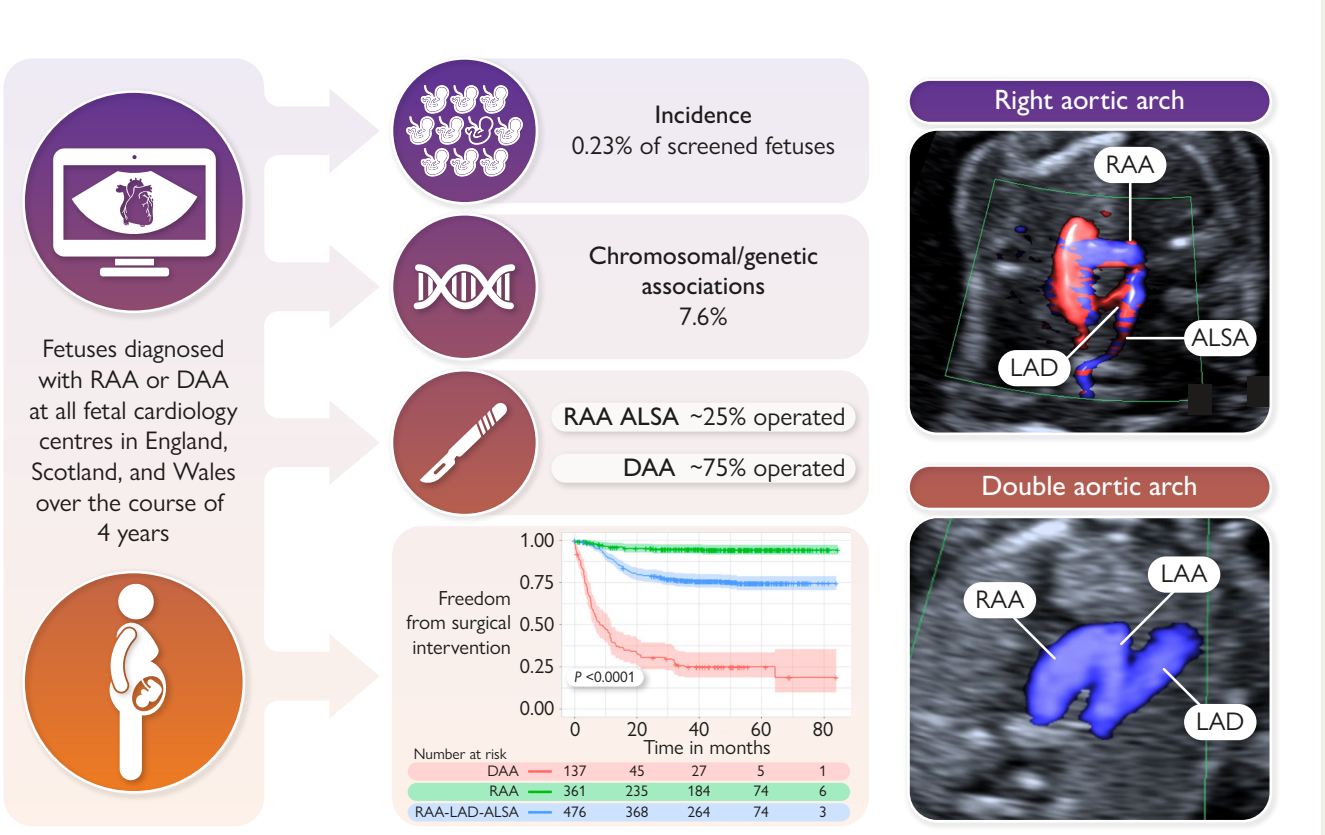
Key Finding

In this retrospective, population-based, multicentre, observational study of fetuses diagnosed with RAA/DAA:

- incidence of RAA/DAA was higher than previously described
- genetic results were abnormal in 7.6%
- most DAA required intervention, compared to a quarter of RAA-left arterial duct-aberrant left subclavian artery in the first 4 years
- there was a wide variation in how patients were managed

Take Home Message

Prospective studies are needed to understand the natural history of aortic arch anomalies, and the indications for intervention.



ALSA, aberrant left subclavian artery; DAA, double aortic arch; LAA, left aortic arch; LAD, left arterial duct; RAA, right aortic arch

Seale AN, *et al. European Heart Journal.*

Keywords Aorta • Vascular ring • Prenatal diagnosis • Heart defects • Congenital • Population • Genetics

Introduction

In the UK, all pregnancies are offered a foetal anomaly screening ultrasound between 18 and 22 weeks, as part of the foetal anomaly screening programme (FASP).[1] In 2015, the three-vessel trachea view (3VT)[2–4] was added to the FASP protocol further to improve prenatal detection of critical congenital heart disease (CHD). The impact of this change was reflected positively in the National Institute for Cardiovascular Outcomes Research (NICOR) with more patients undergoing cardiac intervention having received a prenatal diagnosis.[5] However, this change in practice concurrently increased prenatal detection of isolated right aortic arch (RAA) and double aortic arch (DAA).

Double aortic arch and RAA can form a complete or partial vascular ring around the trachea and oesophagus, the latter only when the arterial duct/ligament is present on the left of the trachea.[6] A vascular ring can lead to symptoms in some patients.[7] The prenatal incidence of RAA/DAA identified in routine first trimester screening[8] and in perinatal settings[9] has been reported, but recent experience of the foetal cardiologists in the British Fetal Cardiology Association indicates this might be underrepresentative.

Genetic associations reported in postnatal studies suggested a common association particularly with 22q11 microdeletion,[10,11] whereas in prenatal series, the association is less common. However, all series were from specialist tertiary foetal medicine units which might not reflect all cases diagnosed.[12–14] Understanding genetic associations following prenatal diagnosis is an important facet of foetal cardiology as this influences parental decision-making for invasive testing.

Furthermore, the early natural history of prenatally diagnosed cases is poorly understood as many cases were not monitored postnatally if deemed well. As centres established postnatal follow-up pathways for prenatally diagnosed patients, their data have been reported,[8,12,13,15,16] but few multicentre studies have been published.[17] Developing an understanding of RAA/DAA will allow us to accurately counsel patients prenatally and provide consistent and appropriate postnatal management.

The aim of this study was to identify foetuses who were prenatally diagnosed with a RAA or DAA since the introduction of the 3VT view to the National FASP to address the following: (i) to define the incidence of prenatal RAA and DAA; (ii) to describe the incidence of genetic and extracardiac anomaly (ECA); (iii) to describe frequency of vascular ring symptoms in early childhood and number of patients undergoing surgery for a vascular ring; (iv) to define medium term outcomes; (v) influence of the type of vascular ring on the above; and (vi) to describe current postnatal management strategies.

Methods

This was a population-based retrospective, multicentre, observational study of all foetuses diagnosed with a RAA or DAA. All foetal cardiology centres in England, Scotland and Wales (n = 19) contributed data. Inclusion criteria were prenatal diagnosis made by a foetal cardiologist or foetal cardiac specialist of a RAA or a DAA, between 1 April 2015 and 31 March 2019 (4 years). Excluded from the study were foetuses with prenatal diagnosis of coexistent major forms of CHD and patients visiting the UK solely for foetal consultation. Foetuses with small muscular ventricular septal defects (VSDs), left superior vena cava (LSVC), were included as these are minor forms of CHD which do not require surgical intervention.

Local collaborators identified patients from their centre, collecting, validating, and submitting data to the investigating team. No patient identifiable data were submitted. Variables collected included gestation at prenatal diagnosis, presence of ECA, prenatal/postnatal genetic testing, postnatal presentation, and postnatal management. Variables collected are presented in Supplementary data online, *Table S1*. Standard genetic testing was with microarray during the study period as availability of whole exome sequencing was limited during this era in the UK.

The type of arch abnormality and aortic branching pattern of the head and neck vessels used in the analysis was ascertained by a combination of prenatal and postnatal findings. When there was discordance between these, the postnatal computed tomography/magnetic resonance imaging (CT/MRI) diagnosis was used; if postnatal CT/MRI was not available, they were described as conflicted/unclassifiable.

To calculate the estimated incidence, the following factors were utilized, based on the financial year 2018–2019: (i) national data (mandatory submissions) of the number of pregnant women screened—this data is only available for England;[18] (ii) percentage of children with CHD requiring cardiac surgery or catheter intervention in the first year of life that were antenatally diagnosed, reported from NICOR;[19] and (iii) type of arch anomaly (RAA or DAA) based on combined prenatal and postnatal data.

Ethical approval was obtained. Individual informed consent was not required as data were extracted by the direct clinical care team using information previously collected during routine care and did not influence ongoing management.

Statistical analysis

Observational, retrospective study was used, describing all patients prenatally diagnosed with RAA or DAA in England, Scotland and Wales during the study period. Continuous data were recorded as median and interquartile range (IQR) or mean and standard deviation (SD). Normality was assessed using the Kolmogorov–Smirnov test. Categorical data were presented as frequencies and percentages within the category. Global Pearson's chi-squared test was used to compare proportion of prenatally diagnosed arch anomaly in the different geographical regions; the Wilson method was used for the binomial estimation of confidence intervals (CIs). Incidence was described in number per 10 000 births per year. Agreement between prenatal diagnosis of aortic arch abnormality and anatomy assigned by the study methodology was described as percentages, and the Kappa test was used to adjust raw data for chance. A modified Poisson regression model was used to investigate predictors of genetic anomaly. Differences were considered statistically significant when $P < .05$. Kaplan–Meier empirical curves were generated to plot freedom from surgery or symptoms over time, with zero reflecting birth and cases censored at time of last know follow-up; hazard ratios and 95% CI were reported; the log-rank test was used to compare curves. The proportion of liveborn having surgical relief of a vascular ring for each surgical centre was compared against all the remaining centres using the Pearson chi-squared test with Bonferroni correction and the binomial estimation of the CIs using the Wilson method. Statistical analysis was performed using R (version.4.3.2).

Results

Prenatal diagnosis of RAA or DAA was submitted for 1107 foetuses. Sixty-one cases were excluded for postnatal diagnosis of

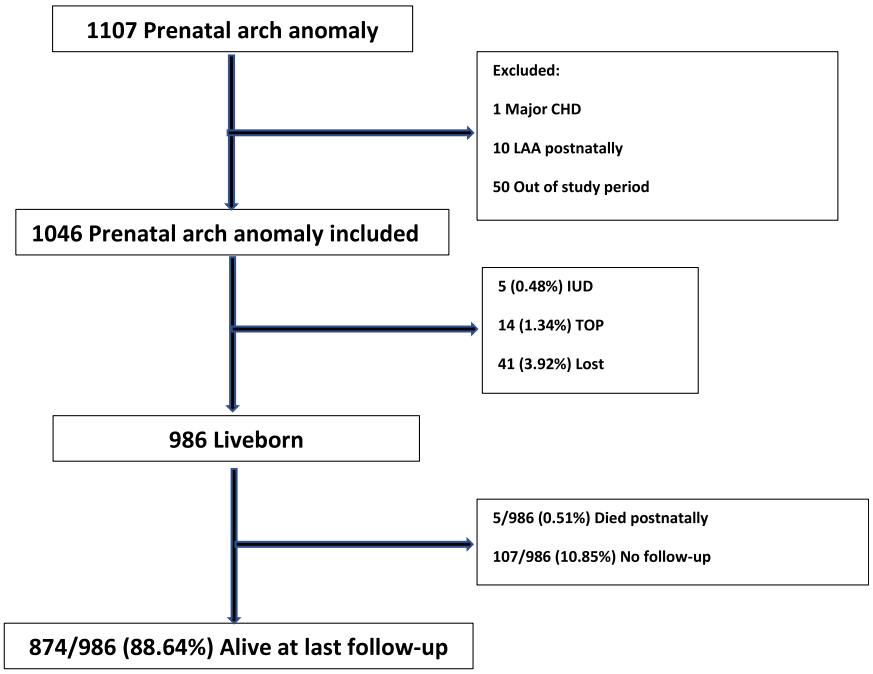


Figure 1 Flow chart of the cohort with prenatally diagnosed RAA and DAA

a single left aortic arch (n = 10), detection out of the study period (n = 50), and prenatal detection of major CHD (n = 1). Thus, a total of 1046 cases were identified during the study period (*Figure 1*), 898 with a single RAA, 141 with a DAA, and seven the type was not categorized. Pregnancy was discontinued in 14 (1.34%) of which half had a prenatally diagnosed chromosomal/genetic anomaly. *In utero* death occurred in five (0.48%) cases, and 41 (3.92%) were lost to follow-up. Therefore, 986 (94.26%) were liveborn, with only five subsequent deaths in the study period.

Incidence

During the study period, the number of foetuses with RAA or DAA diagnosed per financial year increased (see Supplementary data online, *Figure S1*). To reflect this trend, the last year of the study (2018–19) was used to estimate the incidence. Prenatal detection of RAA/DAA demonstrated statistical geographical difference across regions in England (P < .0001) which was reflective of the variation in prenatal detection between regions (see Supplementary data online, *Table S2*).[5] The London region had the highest prenatal detection (0.13% of all foetuses screened) and, therefore, was used as a benchmark to estimate incidence of RAA or DAA in the wider population.

The number of pregnancies where second trimester screening was accepted in England in 2018–19 was 519 890 (99.1%), and in the London area it was 115 653 (99.0%).[18] London detection was 54.8%, and overall UK detection was 50.0% of all major CHD requiring catheter or surgical intervention within the first year of birth.[19] This information was extrapolated to estimate the incidence of RAA or DAA in the general population, assuming 54.8% of all RAA/DAA would be detected in the London region. Therefore, the incidence per year of DAA was estimated at 4.58 per 10 000 foetuses and RAA 17.98 per 10 000 foetuses, equating to 0.23% of screened foetuses.

Minor cardiac and extracardiac anomalies

A minor cardiac anomaly was identified in 3.92% (41 of 1046) of foetuses, of which muscular VSD was the most common (2.96%). Left superior vena cava was seen in 0.86% of cases. Five with a minor cardiac anomaly also had an ECA.

An ECA was diagnosed prenatally in 6.69% (70 of 1046) cases, and in 0.48% (5 of 1046), two or more were identified. Gastrointestinal tract and brain anomalies were the most common, 18.57% (n = 13) and 15.71% (n = 11), respectively, of those with ECA.

In total, 106 (10.13%) foetuses had an ECA or minor cardiac anomaly identified in the prenatal period. In the remaining 940 (89.87%) foetuses, RAA/DAA was the only structural abnormality seen.

Type of aortic arch abnormality

There were 141 of 1046 (13.48%) cases of DAA, 860 of 1046 (82.22%) cases of RAA and left-sided arterial duct (LAD), and 38 of 1046 (3.63%) cases of RAA and right-sided arterial duct (RAD). In 7 of 1046 (0.67%) cases, pre- and postnatal ultrasound data were conflicting regarding anatomy with no CT/MRI data available.

Aortic arch branching pattern

The branching pattern of the head and neck vessels of those with a single RAA–LAD was defined pre- or postnatally in 653 of 860 (75.93%) cases using study methodology. In 185 of 860 (21.51%), branching pattern was unknown both pre- and postnatally, and in 22 of 860 (2.56%), pre- and postnatal

Table 1 Comparison of the prenatal diagnosis of the aortic arch abnormality and the anatomy assigned by the study methodology

Prenatal diagnosis (n = 1046)	Anatomy assigned by study methodology		Raw agreement between prenatal diagnosis and anatomy assigned by study methodology, % (95% CI)	Confidence interval according to kappa test's chance adjusted agreement, % (95% CI)
RAA–LAD–MIB	RAA–MIB	94	63.51	57.50
(n = 148)	RAA–ALSA	19	(55.16–71.15)	(49.91–65.09)
	RAA–RAD	0		
	DAA	17		
	Conflict/unclassifiable	18		
RAA–LAD–ALSA	RAA–MIB	3	93.95	75.57
(n = 430)	RAA–ALSA	404	(91.15–95.94)	(71.58–79.55)
	RAA–RAD	0		
	DAA	15		
	Conflict/unclassifiable	8		
RAA–RAD	RAA–MIB	0	100.00	100.00
(n = 38)	RAA–ALSA	0	(88.57–100.00)	(100.00–100.00)
	RAA–RAD	38		
	DAA	0		
	Conflict/unclassifiable	0		
DAA	RAA–MIB	0	88.78	69.42
(n = 98)	RAA–ALSA	8	(80.41–93.99)	(62.22–76.62)
	RAA–RAD	0		
	DAA	87		
	Conflict/unclassifiable	3		
RAA–LAD, head and neck branching pattern unknown (n = 332)	RAA–MIB	51	NR	NR
	RAA–ALSA	74		
	RAA–RAD	0		
	DAA	22		
	Unknown	185		

Column 3 reports the percentage of cases where the prenatal diagnosis matched the diagnosis assigned using the study methodology. Column 4 reports agreement using the kappa test to adjust for chance.
ALSA, aberrant left subclavian artery; CI, confidence interval; DAA, double aortic arch; LAD, left arterial duct; MIB, mirror image branching; RAA, right aortic arch; RAD, right arterial duct; NR, not relevant.

ultrasound data were conflicting regarding branching pattern of the head and neck vessels. RAA–LAD–ALSA was found in 505 of 653 (77.34%) where branching pattern was defined and RAA–LAD–mirror image branching (MIB) in 148 of 653 (22.66%).

Prenatal description of aortic arch branching pattern was only available in 578 of 910 foetuses (63.52%) which were thought to have a single RAA–LAD prenatally (*Table 1*). When described prenatally, agreement between the prenatal description and the anatomy assigned by study methodology, which used additional postnatal ultrasound and CT/MRI data, was 498 of 578 (86.16%).

Table 1 compares the prenatal diagnosis of the aortic arch abnormality and branching patterns with the anatomy assigned by the study methodology. The RAA–LAD–MIB demonstrated the poorest rate of agreement, 94 of 148 (63.51%) foetuses. Conversely, prenatal diagnosis of RAA–LAD–ALSA demonstrated highest agreement, 404 of 430 (93.95%) foetuses. For DAA, there was agreement in 87 of 98 (88.78%) foetuses.

Genetic associations

A prenatal genetic result was available in 262 of 1046 (25.05%), of which 26 of 262 (9.92%) had an abnormal result reported. A

Table 2 The number of cases and the percentage with genetic abnormality for the whole cohort and the subsets of arch abnormality

Aortic arch type	N.	Genetic result (*n*)	Normal genetic result (*n*)	Abnormal genetic result[a] (*n*)	Percentage with genetic result	Genetic abnormality in those with result (%)	Genetic abnormality if those with no result assumed to have normal genetics
Risk of genetic anomaly in each anatomical group							
RAA–LAD–MIB	148 (14.14%)	61	56	5	41.22%	8.20%	3.38%
RAA–LAD–ALSA	505 (48.28%)	259	215	44	51.29%	16.99%	8.71%
RAA–RAD	38 (3.63%)	16	12	4	42.11%	25.00%	10.53%
RAA–LAD	860 (82.22%)	386	323	63	44.88%	16.32%	7.33%
DAA	141 (13.48%)	88	75	13	62.41%	14.77%	9.22%
All[b]	1046	493	413	80	47.13%	16.23%	7.65%
Risk of genetic anomaly if additional extracardiac anomaly or minor[c] cardiac anomaly detected prenatally							
RAA–LAD–MIB	13	4	3	1	30.77%	25.00%	7.69%
RAA–LAD–ALSA	49	32	22	10	65.31%	31.25%	20.41%
RAA–RAD	6	4	2	2	66.67%	50.00%	33.33%
RAA–LAD	87	49	33	16	56.32%	32.65%	18.39%
DAA	13	11	8	3	84.62%	27.27%	23.08%
All[b]	106	64	43	21	60.38%	32.81%	19.81%
Risk of genetic anomaly if no other differences detected prenatally							
RAA–LAD–MIB	135	57	53	4	42.22%	7.02%	2.96%
RAA–LAD–ALSA	456	227	193	34	49.78%	14.98%	7.46%
RAA–RAD	32	12	10	2	37.50%	16.67%	6.25%
RAA–LAD	773	337	290	47	43.60%	13.95%	6.08%
DAA	128	77	67	10	60.16%	12.99%	7.81%
All[b]	940	429	370	59	45.64%	13.75%	6.28%

ALSA, aberrant left subclavian artery; DAA, double aortic arch; LAD, left arterial duct; MIB, mirror image branching; RAA, right aortic arch; RAD, right arterial duct.
RAA–LAD includes cases where branching pattern of the head and neck vessels was not described.
[a]22q11 deletion in 35%.
[b]Includes cases with conflicted pre- and postnatal diagnosis.
[c]Minor cardiac anomalies include 29 muscular VSD, 7 bilateral SVC ± muscular VSD, 2 single LSVC, 3 other.

prenatal or postnatal genetic result was available in 493 of 1046 (47.13%), with an abnormal genetic result in 80 of 1046 (7.65%) and a normal genetic result in 413 of 1046 (39.48%). No genetic result was available either prenatally or postnatally in 553 of 1046 (52.87%).

The genetic abnormalities identified in the 80 cases included 22q11.2 microdeletion (*n* = 28, 35%), trisomy 21 (*n* = 9, 11.25%), and CHARGE syndrome (*n* = 3, 3.75%). A mixture of other types of genetic difference was identified in 30 of 80 (37.50%) cases. A further 10 (12.50%) had a genetic variant reported at the time as 'of unknown significance', four of which had significant ECAs postnatally. The 10 cases were described and included in the analysis. Of the 80 cases with genetic abnormality, 58 (72.5%) had no additional anomalies detected prenatally with the RAA/DAA being the only structural prenatal marker of anomaly. Of the cases with 22q11.2 microdeletion, 16 (57.14%) had no additional structural anomalies detected prenatally. Of the 493 cases with a genetic result, 28 (5.68%) had 22q11 deletion, or 2.68% of the whole cohort. Details of cases with genetic abnormality are in Supplementary data online, *Table S3*.

Thirty-three patients in the cohort underwent both prenatal and postnatal genetic testing, of which six had a reported normal prenatal result but subsequently received an abnormal postnatal result, after clinical examination and guidance towards specific genetic testing these included CHARGE syndrome (*n* = 1), Rubinstein-Taybi syndrome (*n* = 1), ALG8 gene variant (*n* = 1), Noonan's syndrome (*n* = 1), 15q11.2 deletion (*n* = 1), and Robinow syndrome (*n* = 1).

Prenatal risk factors for genetic anomaly

Table 2 describes the number of cases and the percentage with genetic abnormality for the whole cohort and the subsets of

DAA, RAA–RAD, RAA–LAD—according to the origin of the left subclavian artery, prenatally detected ECA, and associated minor cardiac anomalies. Those that had genetic testing are described, and the whole cohort where those not tested are assumed to be genetically normal. Having an ECA prenatally diagnosed in addition to the RAA–DAA increased the risk further of having a genetic abnormality (risk ratio 3.39, 95% CI 1.89–5.73; $P < .0001$) (*Table 2* and Supplementary data online, *Table S4*).

Postnatal outcomes

Of the 986 liveborn, 5 (0.51%) died secondary to causes unrelated to the aortic arch anatomy; these included prematurity and complications arising from the ECAs. A further 107 (10.85%) were lost to follow-up. Mean postnatal follow-up period was 4.11 years (SD 1.38 years) for DAA and 4.08 years (SD 1.37 years) for RAA–LAD.

Table 3 describes postnatal findings in liveborn infants (n = 986). Postnatal ECA was identified in 112 of 845 (13.25%). Of 891 liveborn in whom no additional anomalies were identified during prenatal examination, 78 (8.75%) were identified postnatally to have an ECA or cardiac abnormality. In five infants, more than one anomaly was identified.

A cardiac anomaly was present postnatally in 136 of 735 (18.50%). Most were minor defects. Sixteen cases were identified to have a restrictive perimembranous VSD that was not detected prenatally and not requiring intervention. Among these, three (18.75%) were also confirmed postnatally to have a genetic anomaly (trisomy 21, 22q11.2 deletion, and 8q24.3 deletion). The infant with 8q24.3 deletion was known to have an absent kidney before birth.

Prenatally undetected major CHD requiring surgery in the first year of life was found in four liveborn: tetralogy of Fallot (n = 1), aortopulmonary window (n = 1), pulmonary valve stenosis (n = 1), and absent/small left pulmonary artery (n = 1). In these four cases, there was no identifiable genetic anomaly, and no ECA was detected in the prenatal period.

Symptoms

Of the 986 liveborn cases, 278 (28.19%) patients were documented postnatally to have symptoms/signs (*Table 4*). *Figure 2A and B* and Supplementary data online, *Table S5* show freedom from symptoms for RAA–LAD–ALSA, DAA, and RAA. Supplementary data online, *Figure S2* illustrates the symptomology. Upper and lower airway symptoms were the most common presenting complaints. There were 168 patients with one reported symptom and 80 with two or more symptoms (total 370). Symptoms/signs were reported more commonly in patients with a DAA (58.70%) than a RAA–LAD–ALSA (35%) or RAA–LAD–MIB (11.25%) and present earlier.

Surgery

Surgery was performed in 103 of 138 (74.64%) patients with a DAA, 117 of 480 (24.38%) patients with RAA–LAD–ALSA, four of 133 (3.01%) patients with RAA–LAD–MIB, and one patient with a RAA–RAD (*Table 4*). This latter patient had bilateral ducts and an isolated left brachiocephalic artery diagnosed prenatally, which was reimplanted into the aorta postnatally. In nine, details of arch anatomy were not available.

Table 3 Postnatal data in liveborn

	Number (% of complete data)	Complete data
Liveborn	986 infants	
Gestational age at birth (weeks + days)	Median 39 + 4 IQR 38 + 2 to 40 + 3	n = 953 (96.65%)
Premature (<37 weeks gestation)	108 (11.33%)	n = 953 (96.65%)
Abnormal genetic test	72 infants (15.13%)	n = 476 (48.28%)
ECA present postnatally[a]	112 infants (13.25%)	n = 845 (85.70%)
Gastrointestinal	22	
Musculoskeletal	20	
Brain	13	
Renal	10	
Other	55	
Cardiac anomalies present postnatally. Major[b]	136 infants (18.50%)	n = 735 (74.54%)
Tetralogy of Fallot	1	
AP window	1	
Valvar pulmonary stenosis	1	
Absent/small LPA	1	
Minor[c]		
Small perimembranous VSD	16	
Others	116	
Aortic arch type		n = 979 (99.29%)
RAA right duct	35 (3.58%)	
RAA left duct	806 (82.33%)	
RAA–MIB	133 (13.59%)	
RAA–ALSA	480 (49.03%)	
RAA Unknown branching pattern	193 (19.71%)	
DAA	138 (14.10%)	

ALSA, aberrant left subclavian artery; AP, aortopulmonary; DAA, double aortic arch; ECA, extracardiac anomaly; LPA, left pulmonary artery; MIB, mirror image branching; RAA, right aortic arch; RAD, right arterial duct; VSD, ventricular septal defect.
[a]Postnatal extracardiac anomaly: 8 of 112 infants had two or more ECA.
[b]Major congenital heart disease only identified postnatally, requiring intervention.
[c]Minor cardiac anomalies not needing intervention, including patent foramen ovale, small atrial septal defect, mild pulmonary valve or branch pulmonary artery stenosis, bicuspid aortic valve, Wolff–Parkinson–White/supraventricular tachycardia, anomalous left upper pulmonary vein to innominate vein, and muscular VSD and left superior vena cava.

Table 4 Symptoms and surgery according to anatomical type of RAA–DAA

	Symptoms	Surgery cohort
All (986 liveborn)	278 (28.19%)	234 (23.73%)
RAA–LAD–MIB (*n* = 133)	15 (11.25%)	4 (3.01%)
RAA–LAD–ALSA (*n* = 480)	168 (35.00%)	117 (24.38%)
RAA–RAD (*n* = 35)	1 (2.86%)	1[a]
DAA (*n* = 138)	81(58.70%)	103 (74.64%)
RAA unknown branching and uncategorized (*n* = 200)	13 (6.5%)	9 (4.50%)

ALSA, aberrant left subclavian artery; DAA, double aortic arch; LAD, left arterial duct; MIB, mirror image branching; RAA, right aortic arch; RAD, right arterial duct.
[a]Prenatally found to have isolated left brachiocephalic artery with left arterial duct joining LPA, bilateral ducts. Had reimplantation of left brachiocephalic artery to the aorta postnatally.

Of those patients having an operation for DAA, 73 of 103 (70.87%) had reported symptoms, and 94 of 129 (72.87%) with RAA–LAD had reported symptoms. Cross-sectional imaging was performed in 91.80% (mainly CT) and bronchoscopy in 34.43% of the asymptomatic patients; only 10.4% of these investigations were performed in centres outside the London area. Median age at surgery for patients with a DAA was 5.29 months (IQR: 2.99–11.26 months), and median age at surgery for patients with a RAA–LAD–ALSA was 12.62 months (IQR: 8.68–17.32 months) ($P < .0001$).

The 30-day mortality was 0%, 59 of 234 (25.21%) had a postoperative complication, and the most common were chylothorax (*n* = 24, 10.26%) and vocal cord palsy (*n* = 12, 5.13%). Median length of hospital stay was 4 days (IQR: 3–6 days). *Figure 2C and D* and Supplementary data online, *Table S5* show freedom from surgery for RAA, RAA–LAD–ALSA and DAA. A greater proportion of patients with DAA underwent surgical intervention compared to RAA–LAD–ALSA, 74.64% vs. 24.38% ($P < .0001$) (see Supplementary data online, *Table S6*). Another 107 cases were reported to have symptoms/signs suggestive of tracheoesophageal compression but did not undergo surgical intervention. A small number were listed for surgery but not undertaken due to symptomatic improvement.

Table 5 demonstrates the differences in the preoperative investigations and surgical rates between the surgical centres in the UK. Centre E undertook the most surgical interventions with 38.1% ($P < .0001$, 95% CI 30.6–46.2) and Centre H the least with 5.4% ($P < .0001$, 95% CI 2.3–12.0). A higher proportion of patients had investigations in Centre E.

Discussion

This is the largest study of prenatally diagnosed RAA–DAA reported in the literature and describes the estimated incidence of a RAA as 0.18% and DAA 0.05% of screened pregnancies. Extracardiac anomaly was present in 6.69% and genetic abnormalities in 7.65%. A RAA–LAD was seen more commonly than a RAA–RAD, but despite this, genetic conditions were noted in both groups. The most common variant of branching pattern of the head and neck vessels in RAA–LAD was an ALSA, which was present in 75% of cases. Symptoms or signs suggestive of tracheobronchial compression were reported in ~28% liveborn with median follow-up of 4 years. Overall, 24% underwent surgery for relief of a vascular ring. Cases with a DAA were more likely to undergo surgery than those with RAA–LAD variants (*Structured Graphical Abstract*).

Incidence

This study has demonstrated that the combined estimated incidence of RAA–DAA (0.23%) is higher than previously reported. Historic data estimated a RAA–DAA to affect 0.1% of the population[20] but predated improvements in prenatal scanning and widespread utilization of the 3VT during screening. The findings are unlikely to represent a true increased incidence in the general population over time.

The incidence we report is higher than recent studies describing first trimester foetal incidence of RAA–DAA as 6.9 per 10 000 (0.07%)[8] and higher than findings by Evans *et al.*[9] who reported RAA prevalence at birth (5.8 per 10 000). The latter study did not include RAA–RAD or cases where pregnancy was discontinued. Cases of RAA–RAD account for few in our series. The detection of RAA–RAD by screening sonographers is challenging as these cases do not have the 'U' shape seen in RAA–LAD, so it may be that RAA–RAD cases are underrepresented in this cohort as they may go undetected.

Our findings may be an overestimate if aortic arch abnormalities are more likely to be detected prenatally than other forms of major CHD. We believe this is unlikely as detection on screening is still disappointing for other arch anomalies such as aortic coarctation. Data on antenatal detection of coarctation in England in 2018 is not reported but was 36.6% on local audit in the West Midlands;[21] detection of transposition of the great arteries was 75.8% in England in 2018[5]; both would still give a higher incidence than previously described (0.17–0.34%). We found that detection rates increased with each year following routine inclusion of the 3VT, most likely representing the learning curve of local obstetric screening units, which may also underestimate the true number of foetuses with RAA–DAA. A limitation may be that cases diagnosed by screening sonographers are not referred to foetal cardiology; however, we believe this is unlikely due to NHS audited pathways, and acceptance of FASP is at least 99%.

Genetic abnormalities and extracardiac anomalies: implications for clinical practice

Extracardiac anomalies have been reported in approximately 15% of foetuses with a RAA or DAA, and therefore, specialist foetal medicine ultrasonography is required as part of the holistic assessment of foetuses once a RAA–DAA has been detected.[22] As regards chromosomal/genetic differences, in our cohort 7.46% of RAA and 9.22% of DAA and overall, a minimum of 6.28% were identified to have a genetic difference (if assumed that all untested foetuses did not carry a genetic abnormality). This is similar to the meta-analysis described by Luo *et al.*[23] who found that the overall rates of chromosomal anomalies and 22q11 deletion in isolated RAA are 7.5% (95%

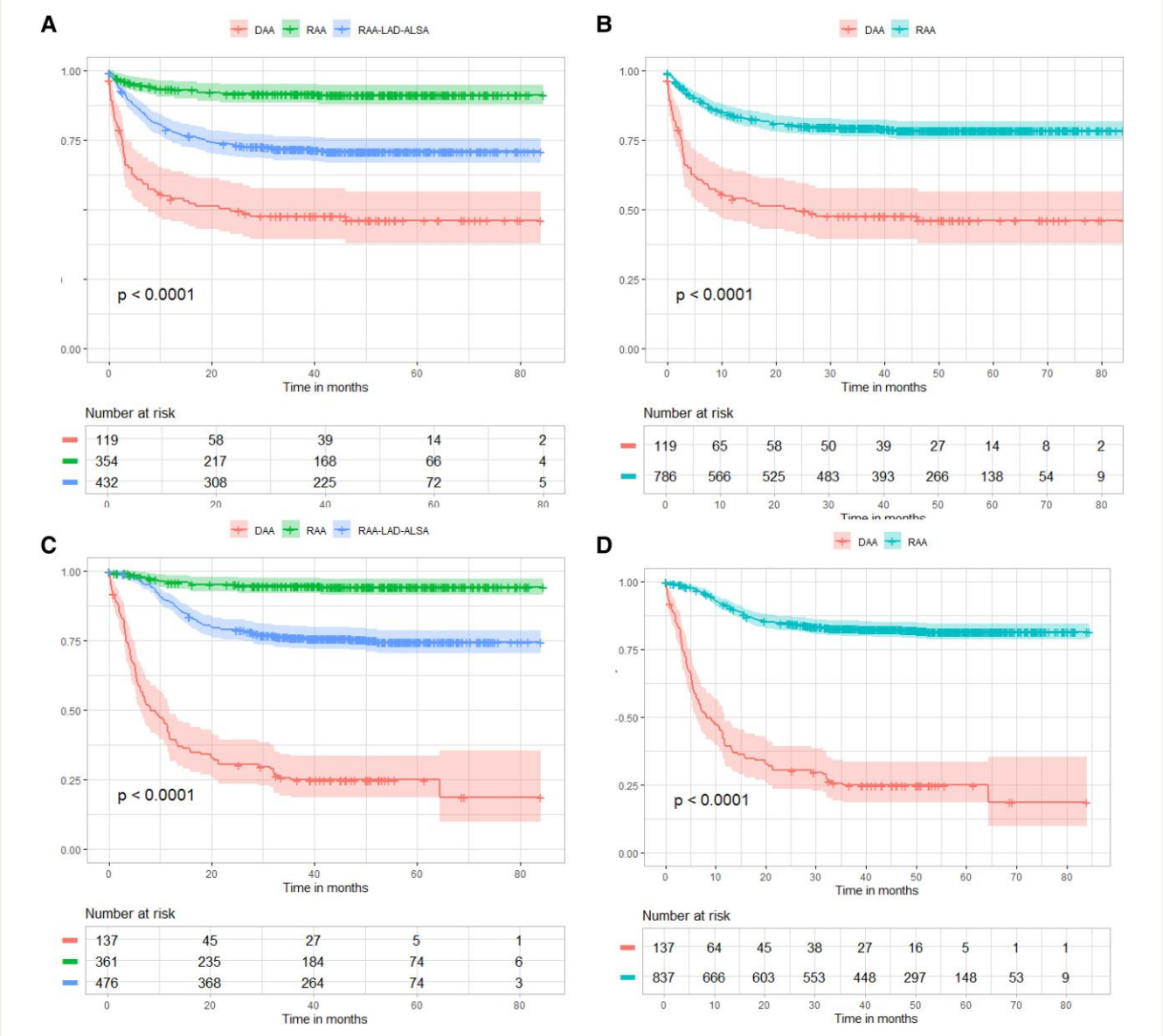


Figure 2 Kaplan–Meier curves; cases were censored at the time of last known follow-up. Time 0 = birth. (*A*) Freedom from symptoms for liveborn prenatally diagnosed with RAA–LAD–ALSA, DAA, and all remaining RAA. For 74 cases, the age at symptoms onset was unknown, so they were removed from the analysis, as were the seven cases where arch type was uncategorized. The shaded areas are the 95% confidence intervals. (*B*) Freedom from symptoms for all RAA and DAA. (*C*) Freedom from surgery for liveborn prenatally diagnosed with RAA–LAD–ALSA, DAA, and all remaining RAA. For five cases, date of surgery was unknown, so they were removed from the analysis, as were the seven cases where arch type was uncategorized. (*D*) Freedom from surgery for liveborn prenatally diagnosed with RAA and DAA

CI 4.7–10.8%). Luo also found, like us and others,[23,24] that ECA increases the risk of genetic anomalies. The risk of a genetic difference may be lower in the presence of RAA–LAD–MIB but was not significant on multivariable analysis; 2.96% had genetic difference in the absence of any additional foetal differences.

The most common genetic abnormality was 22q.11.2 deletion which is in keeping with other series.[10,13,17,24–27] We found that 5.68% of foetuses having genetic testing, and 2.68% of all foetuses had 22q11 deletion; this compares to the meta-analysis of D'Antonio *et al.*[12] who found 22q11 deletion in 5.1% (95% CI 2.4–8.6%), although that study was not population-based. The criticism of many previous studies[12,13,26] was that they were conducted in highly specialized foetal medicine centres and referrals were more likely to comprise complex foetuses with associated genetic abnormalities. However, the current study still shows an important genetic association.

The first trimester study noted that *in vitro* fertilization was associated with an eightfold increase in RAA–DAA.[8] Unfortunately, this and nuchal translucency (NT) were not documented in this study, and a limitation of our data as NT is an important indicator of genetic abnormality in the foetus.[26,28] The

Table 5 Details of liveborn in 11 surgical centres representing 19 participating centres; postnatal investigation and surgery

	Centre										
	A	B	C	D	E	F[a]	G	H	I	J	K
Liveborn, n	50	122	18	148	147	89	28	93	44	159	88
DAA, n (% liveborn)	7 (14)	19 (16)	3 (17)	25 (17)	24 (16)	6 (7)	4 (14)	7 (8)	3 (7)	31 (19)	9 (10)
Investigations											
None, n (%)	21 (42)	60 (49)	7 (39)	39 (26)	30 (20)	40 (45)	20 (71)	48 (52)	16 (36)	51 (32)	49 (56)
Barium swallow, n (%)	8 (16)	7 (6)	0 (0)	1 (1)	21 (14)	0 (0)	1 (4)	2 (2)	5 (11)	17 (11)	4 (5)
Bronchoscopy, n (%)	5 (10)	8 (7)	0 (0)	1 (1)	109 (74)	0 (0)	0 (0)	3 (3)	19 (43)	3 (2)	0 (0)
CT angiography, n (%)	15 (30)	44 (36)	11 (61)	86 (58)	112 (76)	28 (31)	8 (29)	10 (11)	22 (50)	93 (58)	22 (25)
Surgery											
Surgery, % of liveborn (n)	20.0 (10)	23.0 (28)	27.8 (5)	25.0 (37)	38.1 (56)	27.0 (24)	17.9 (5)	5.4 (5)	27.3 (12)	21.4 (34)	20.5 (18)
P-value	1.00	1.00	1.00	1.00	<.0001	1.00	1.00	<.0001	1.00	1.00	1.00
Lower 95% CI (%)	11.2	16.4	12.5	18.7	30.6	18.8	7.9	2.3	16.4	15.7	13.4
Upper 95% CI (%)	33.0	31.2	50.9	32.6	46.2	37.0	35.6	12.0	41.9	28.4	30.0

The proportion of liveborn having surgical relief of a vascular ring for each surgical centre was compared against all the remaining centres.
CI, confidence interval; CT, computed tomography; DAA, double aortic arch.
[a]Centre F: In seven cases that had surgery, details of the arch anatomy were not reported, so percentage of DAA cases may not reflect the true situation in this centre.

RAA–DAA was the only structural prenatal marker of genetic difference in 72.5% of affected cases in our cohort.

Genetic differences were seen more commonly if there was an additional difference in the foetus, although genetic testing was commonly undertaken in the presence of an additional ECA, potentially elevating the percentages. However, even when we assumed all phenotypically normal cases had a normal genetic result, genetic difference was still found in 6.28%. We believe, like others,[29] that given the strong association with genetic differences, regardless of the presence of an intracardiac anomaly or ECA, prenatal counselling should include discussing risk and benefits of invasive genetic testing. Due to the current limitations of noninvasive prenatal testing, this is not an adequate test. Amniocentesis, quoted to carry a 0.5% risk of pregnancy loss,[30,31] is notably an order lower than the association with genetic difference.

The majority of genetic testing in this study was by microarray; however, with the wider implementation of more advanced techniques such as whole exome sequencing and whole genome sequencing, an increasing number of genetic anomalies may be identified.[32–34] As standard microarray should be offered to all patients with an isolated finding of a RAA or DAA. It would be appropriate to offer further testing according to local policies, particularly if there are extracardiac abnormalities, dysmorphic features, or developmental delay. Postnatal assessment should include offering postnatal genetic testing if not performed prenatally.

It is reported that genetic conditions such as 22q11 microdeletion may be under-recognized in non-Caucasian populations due to lack of knowledge regarding dysmorphic features.[35] Other features of chromosomal/genetic abnormalities may become more apparent over time, such as neurodevelopmental differences, and might not have contributed to counselling towards postnatal genetic testing. Indeed, due to these factors, it is possible that we may have underestimated the genetic risk.

Although 22q11 microdeletion was the most frequent anomaly found, we encountered a myriad of other differences, including 10 cases of variant of unknown significance (VUS) of which four had important ECA. This replicates what has been described by other studies.[36,37] It is challenging to know whether a genetic finding is clinically relevant. Some VUS may be reclassified as clinically relevant in the future; however, the opposite is also true. We have described all differences identified; but the study was limited by granularity of the genetic data. When offering genetic testing, it is critical to explain to the pregnant woman the entity of VUS and the uncertainty of some findings.

Limitations of foetal echocardiography and prenatal ultrasound

An important finding of our study was that about 9% of babies were found to have an ECA or intracardiac anomaly that was not detected prenatally. Therefore, it is important to counsel and communicate the potential limitations of prenatal scanning to the pregnant person. Of note, there were four major forms of CHD not identified prenatally and 16 restrictive perimembranous VSDs, three of which had a genetic anomaly identified. Small perimembranous VSDs can be particularly difficult to detect prenatally. We suggest postnatal follow-up be offered to all babies to ensure normal intracardiac anatomy in all cases of RAA and DAA.

Impact of branching pattern in RAA–LAD

It appears that the risk of genetic anomaly is similar for DAA and RAA–LAD–ALSA but may be less in RAA–LAD–MIB (~3%). This is lower than previously published data for this group where 19% of RAA–LAD–MIB who underwent genetic testing had an abnormal result, or 12% of all cases of RAA–LAD–MIB.[26] The RAA–LAD–MIB is reportedly more common in foetuses with associated major CHD such as tetralogy of Fallot and, in this context, has a strong association with genetic anomalies, but this is likely to be influenced by the coexistent major CHD.[38–40]

Foetal echocardiographic assessment of the aortic arch branching pattern was noted to be challenging; in this cohort, one-third of cases had undefined branching pattern prenatally. In addition to the challenges that were faced by some in differentiating the branching pattern of the head and neck arteries, it is acknowledged that differentiation between a DAA and a RAA–LAD–MIB can be difficult both prenatally and postnatally.[41,42] Indeed, in our cohort, some cases of prenatally diagnosed RAA–LAD–MIB were found to have DAA on postnatal cross-sectional imaging (n = 17). The reason for this overlap is that in both DAA and RAA–LAD–MIB, an artery which gives rise to the left common carotid and left subclavian artery passes anterior to the trachea, and in addition, the distal region of the left arch may be hypoplastic prenatally.[15,26,41,43] This is often confounded by constriction of the arterial duct after birth which leads to complete atresia of the distal left arch and can render similar appearance to that of a RAA–LAD–MIB.[15,42]

We found that RAA–LAD–MIB was the branching pattern most difficult to diagnose prenatally with the least agreement between prenatal and postnatal diagnosis; it was also the least likely branching pattern diagnosed prenatally to have postnatal CT/MRI performed which is an important limitation to our findings. The ARCADE study also compared prenatal and postnatal diagnosis of head and neck vessel branching pattern and found reduced concordance regarding distribution of the brachiocephalic vessels.[17] Foetal cardiac MRI[42,44–46] and other ultrasound methods[47] may become helpful in differentiating these morphological groups; however, foetal cardiac MRI is not universally available.

Postnatal presentation of vascular rings

Of the liveborn, tracheo-oesophageal compression symptoms were present in 59% of those with a DAA, in 30% by 3 months of age. This is slightly less compared to recent studies which reported 65% of DAA showed symptoms/signs by 3 months of age.[15,43] Symptoms/signs of tracheo-oesophageal compression were seen in 35% with RAA–LAD–ALSA which is higher than that reported in the early meta-analysis of prenatal cohorts when systematic postnatal follow-up may not have been introduced[12] and higher than in a recent series of 112 children.[48] The lowest proportion of symptoms/signs was present in in RAA–LAD–MIB (11%), although similar to a previously published series,[48] both may be under-sampled due to the incomplete follow-up in these patients.

Children with RAA–LAD–MIB are at less risk of developing symptoms of tracheo-oesophageal compression and so prior to anomaly screening may never have presented to the paediatrician. In our cohort, only 3.01% of patients with RAA–MIB pattern had surgical relief of the ring; these patients do have vessels encircling the oesophagus and trachea, but the pattern rarely causes symptoms of compression which may be related to the absence of a Kommerell diverticulum.

There was wide variation in how patients were investigated and whether surgery was performed, with the lowest surgical rate for RAA–DAA anomaly being 5% and highest being 38% within the study period. Some units electively investigate patients with a known vascular ring to look for radiographic or airway compromise on bronchoscopy to help decide whether surgical intervention should be offered. This reflects a UK national survey showing regional variation in assessment and management of patients.[49] Like others,[50] we found that there were no deaths directly attributable to the aortic arch surgery; however, there is important morbidity with a quarter experiencing postoperative complications. Whether surgical intervention is beneficial in the long term is beyond the scope of this study.

Overall, 24% of patients with RAA–LAD–ALSA underwent surgery which is higher than described by D'Antonio *et al.* (17.1%)[12] and the ARCADE study (8%), although follow-up period was longer in this study. Our data suggest that units have a low threshold for operating on children with potential tracheobronchial compression. The frequency of surgical intervention was regional and in those with higher surgical rates investigated patients more with CT +/- bronchoscopy and thus were more likely to reveal occult compression of the trachea. A limitation of this study is assessing the impact upon the respiratory system and oesophagus, as patients were predominantly monitored by paediatric cardiologists,[49] rather than health professionals with specific expertise in assessment of swallowing or airway pathology. This practice may result in milder symptoms/signs being overlooked by a cardiologist. Alternatively, symptoms might have been falsely attributed to the arch anomaly. Symptoms secondary to palatal dysfunction may have been wrongly explained by the aortic arch difference. Capturing meaningful data on symptoms is challenging due to its subjective nature; future studies should focus on protocolized objective assessment to avoid institutional bias.

In summary, this is the largest and first study to evaluate the incidence of a prenatal RAA–DAA in the population and to highlight the varied management of patients with this anatomy. We have shown an important association with genetic anomaly; an arch anomaly may be a surrogate for a difference within the foetus. In the presence of prenatally detected arch anomaly, we recommend a complete foetal survey be performed and genetic testing offered. As recommended by Depypere *et al.*,[51] there is need for prospective, follow-up studies to document the long-term outcomes of patients with prenatally diagnosed vascular rings, to understand natural history and which patients may benefit from early intervention, informing future trials. This would aid decision-making in those asymptomatic patients or those presenting with minor symptoms. We suggest that until we understand the true significance of these lesions, centres develop a robust follow-up pathway for patients with a prenatal RAA–DAA.

Limitations

The study is limited by its retrospective nature. Cases diagnosed by screening sonographers may not be referred to foetal cardiology. Anatomical aortic arch details were not always available. Not all cases underwent genetic testing. Despite being a large data set, the analysis may be limited by sparse data bias.[52] There may be factors that we have not investigated which may influence outcome.

Acknowledgements

Teams participating in collecting data, British Congenital Cardiac Association (BCCA) and British Fetal Cardiology Association.

A.N.S., T.V.V., L.E.H., J.S.C., and S.F. devised the study protocol and contributed to manuscript writing. A.N.S. and S.F. had access to the data and performed analysis. All authors participated in data collection +/-editing of manuscript.

Some of the data have been part of previously published single centre studies which cover different time periods to this study.

Supplementary data

Supplementary data are available at *European Heart Journal* online.

Declarations

Disclosure of Interest

A.N.S. is Treasurer of the Fetal Working Group for the European Association of Paediatric Cardiology (AEPC).

T.V.V. received a grant from King's Health Partners Research Development Fund. Honorariums received for lecturing with Canon Medical.

V.J. received an honorarium for lecturing for GE Healthcare. She is the President for the British Congenital Cardiac Association.

V.Z. received an honorarium for lecturing for Canon Medical.

Data Availability

The data underlying this article will be shared on reasonable request to the corresponding author.

Funding

£5000 award from the British Congenital Cardiac Association (BCCA) for study set-up (Birmingham Women's and Children's Hospital NHS Foundation Trust) and data analysis (SF).

A.N.S. received funding from Birmingham Health Partners for a CARP Fellowship.

V.D. was supported in part by the 'Elliot Shinebourne Research Fund', Royal Brompton & Harefield Hospitals Charity, Registered Charity number 1053584.

Ethical Approval

Ethical approval was obtained (IRAS project ID 262525). Individual informed consent was not required as data were extracted by the direct clinical care team using information

previously collected during routine care and did not influence ongoing management.

Pre-registered Clinical Trial Number

Not applicable.

References

1. 20-week screening scan—GOV.UK (www.gov.uk) Date accessed 18 July 2024.
2. Donofrio MT, Moon-Grady AJ, Hornberger LK, Copel JA, Sklansky MS, Abuhamad A, *et al.* Diagnosis and treatment of fetal cardiac disease: a scientific statement from the American Heart Association. *Circulation* 2014;**129**: 2183–242. https://doi.org/10.1161/01.cir.0000437597.44550.5d
3. Yagel S, Cohen SM, Achiron R. Examination of the fetal heart by five short-axis views: a proposed screening method for comprehensive cardiac evaluation. *Ultrasound Obstet Gynecol* 2001;**17**:367–9. https://doi.org/10.1046/j.1469-0705.2001.00414.x
4. Yagel S, Arbel R, Anteby EY, Raveh D, Achiron R. The three vessels and trachea view (3VT) in fetal cardiac scanning. *Ultrasound Obstet Gynecol* 2002;**20**: 340–5. https://doi.org/10.1046/j.1469-0705.2002.00801.x
5. National Congenital Heart Disease Audit (NCHDA). www.nicor.org.uk.
6. Edwards FR. Vascular compression of the trachea and oesophgus. *Thorax* 1959;**14**:187–200. https://doi.org/10.1136/thx.14.3.187
7. Worhunsky DJ, Levy BE, Stephens EH, Backer CL. Vascular rings. *Semin Pediatr Surg* 2021;**30**:151128. https://doi.org/10.1016/j.sempedsurg.2021.151128
8. Vigneswaran TV, Jabak S, Syngelaki A, Charakida M, Simpson JM, Nicolaides KH, *et al.* Prenatal incidence of isolated right aortic arch and double aortic arch. *J Matern Fetal Neonatal Med* 2021;**34**:2985–90. https://doi.org/10.1080/14767058.2019.1676413
9. Evans WN, Acherman RJ, Ciccolo ML, Lehoux J, Berthoty D, Montes A, *et al.* Isolated vascular rings are common cardiovascular malformations. *World J Pediatr Congenit Heart Surg* 2023;**14**:21–3. https://doi.org/10.1177/21501351221122972
10. McElhinney DB, Clark BJ, Weinberg PM, Kenton ML, McDonald-McGinn D, Driscoll DA, *et al.* Association of chromosome 22q11 deletion with isolated anomalies of aortic arch laterality and branching. *J Am Coll Cardiol* 2001;**37**: 2114–9. https://doi.org/10.1016/S0735-1097(01)01286-4
11. McElhinney DB, McDonald-McGinn D, Zackai EH, Goldmuntz E. Cardiovascular anomalies in patients diagnosed with a chromosome 22q11 deletion beyond 6 months of age. *Pediatrics* 2001;**108**:E104. https://doi.org/10.1542/peds.108.6.e104
12. D'Antonio F, Khalil A, Zidere V, Carvalho JS. Fetuses with right aortic arch: a multicenter cohort study and meta-analysis. *Ultrasound Obstet Gynecol* 2016;**47**:423–32. https://doi.org/10.1002/uog.15805
13. Zidere V, Tsapakis EG, Huggon IC, Allan LD. Right aortic arch in the fetus. *Ultrasound Obstet Gynecol* 2006;**28**:876–81. https://doi.org/10.1002/uog.3841
14. Galindo A, Nieto O, Nieto MT, Rodríguez-Martín MO, Herraiz I, Escribano D, *et al.* Prenatal diagnosis of right aortic arch: associated findings, pregnancy outcome, and clinical significance of vascular rings. *Prenat Diagn* 2009;**29**: 975–81. https://doi.org/10.1002/pd.2327
15. Bartsota M, Jowett V, Manuel D, Mortensen K, Wolfenden J, Marek J, *et al.* Double aortic arch: implications of antenatal diagnosis, differential growth of arches during pregnancy, associated abnormalities and postnatal outcome. *Ultrasound Obstet Gynecol* 2023;**62**:69–74. https://doi.org/10.1002/uog.26186
16. Stephens EH, Eltayeb O, Kennedy C, Rigsby CK, Rastatter JC, Carr MR, *et al.* Influence of fetal diagnosis on management of vascular rings. *Ann Thorac Surg* 2022;**113**:630–6. https://doi.org/10.1016/j.athoracsur.2021.01.025
17. Guillaumont S, Vincenti M, Thomas F, Huguet H, Picot MC, Abassi H, *et al.* Implications of right aortic arch prenatal diagnosis: the multicentric nationwide ARCADE cohort. *Arch Dis Child Fetal Neonatal Ed* 2024;**0**:F1–7. https://doi.org/10.1136/archdischild-2024-327242.
18. Antenatal screening standards: data report 1 April 2018 to 31 March 2019—GOV.UK (www.gov.uk) 2020 Date accessed 3 August 2024.
19. national-congenital-heart-disease-audit-nchda-final-1 (www.nicor.org.uk) 2020. Date accessed 03 August 2024.
20. Achiron R, Rotstein Z, Heggesh J, Bronshtein M, Zimand S, Lipitz S, *et al.* Anomalies of the fetal aortic arch: a novel sonographic approach to in-utero diagnosis. *Ultrasound Obstet Gynecol* 2002;**20**:553–7. https://doi.org/10.1046/j.1469-0705.2002.00850.x
21. Nolan O, Kavga M, Poole E, Desai T, Miller P, Harris M, *et al.* Impact of regional teaching programme and introduction of three vessels and tracheal view on prenatal detection of major congenital heart disease. 54th Annual Meeting of the Association for European Paediatric and Congenital Cardiology (AEPC); Gothenburg, Sweden: Cardiology in the Young; 2022. 32(S1): S1–212. DOI: https://doi.org/10.1017/S1047951122000087.
22. Razon Y, Berant M, Fogelman R, Amir G, Birk E. Prenatal diagnosis and outcome of right aortic arch without significant intracardiac anomaly. *J Am Soc Echocardiogr* 2014;**27**:1352–8. https://doi.org/10.1016/j.echo.2014.08.003
23. Luo Q, Chen J, Zhang Y, Li J, Su X, Wang Q, *et al.* Incidence of chromosomal anomalies in fetuses with isolated right aortic arch: a meta-analysis. *Prenat Diagn* 2020;**40**:294–300. https://doi.org/10.1002/pd.5606
24. Miranda JO, Callaghan N, Miller O, Simpson J, Sharland G. Right aortic arch diagnosed antenatally: associations and outcome in 98 fetuses. *Heart* 2014;**100**: 54–9. https://doi.org/10.1136/heartjnl-2013-304860
25. Berg C, Bender F, Soukup M, Geipel A, Axt-Fliedner R, Breuer J, *et al.* Right aortic arch detected in fetal life. *Ultrasound Obstet Gynecol* 2006;**28**:882–9. https://doi.org/10.1002/uog.3883
26. Vigneswaran TV, Allan L, Charakida M, Simpson DA, Nicolaides JM, H K, *et al.* Prenatal diagnosis and clinical implications of an apparently isolated right aortic arch. *Prenat Diagn* 2018;**38**:1055–61. https://doi.org/10.1002/pd.5388
27. Perolo A, De Robertis V, Cataneo I, Volpe N, Campobasso G, Frusca T, *et al.* Risk of 22q11.2 deletion in fetuses with right aortic arch and without intracardiac anomalies. *Ultrasound Obstet Gynecol* 2016;**48**:200–3. https://doi.org/10.1002/uog.15766
28. Nicolaides KH, Azar G, Byrne D, Mansur C, Marks K. Fetal nuchal translucency: ultrasound screening for chromosomal defects in first trimester of pregnancy. *BMJ* 1992;**304**:867–9. https://doi.org/10.1136/bmj.304.6831.867
29. Babaoğlu K, Doğan Y, Başar EZ, Uzun O. Prenatal diagnosis of the right aortic arch: change in detection rate, the Status of associated anomalies, and perinatal outcomes in 137 fetuses. *Pediatr Cardiol* 2022;**43**:1888–97. https://doi.org/10.1007/s00246-022-02929-6
30. Navaratnam K, Alfirevic Z. Gynaecologists RCoOa. Amniocentesis and chorionic villus sampling: Green-top Guideline No. 8 July 2021: Green-top Guideline No. 8. *BJOG* 2022;**129**:e1–15. https://doi.org/10.1111/1471-0528.16821
31. Salomon LJ, Sotiriadis A, Wulff CB, Odibo A, Akolekar R. Risk of miscarriage following amniocentesis or chorionic villus sampling: systematic review of literature and updated meta-analysis. *Ultrasound Obstet Gynecol* 2019;**54**: 442–51. https://doi.org/10.1002/uog.20353
32. Reilly K, Sonner S, McCay N, Rolnik DL, Casey F, Seale AN, *et al.* The incremental yield of prenatal exome sequencing over chromosome microarray for congenital heart abnormalities: a systematic review and meta-analysis. *Prenat Diagn* 2024;**44**:821–31. https://doi.org/10.1002/pd.6581
33. Mone F, Stott BK, Hamilton S, Seale AN, Quinlan-Jones E, Allen S, *et al.* The diagnostic yield of prenatal genetic technologies in congenital heart disease: a prospective cohort study. *Fetal Diagn Ther* 2021;**48**:112–9.. https://doi.org/10.1159/000512488
34. Mone F, Eberhardt RY, Morris RK, Hurles ME, McMullan DJ, Maher ER, *et al.* COngenital heart disease and the diagnostic yield with exome sequencing (CODE) study: prospective cohort study and systematic review. *Ultrasound Obstet Gynecol* 2021;**57**:43–51. https://doi.org/10.1002/uog.22072
35. Campbell IM, Sheppard SE, Crowley TB, McGinn DE, Bailey A, McGinn MJ, *et al.* What is new with 22q? An update from the 22q and you center at the children's hospital of Philadelphia. *Am J Med Genet A* 2018;**176**:2058–69. https://doi.org/10.1002/ajmg.a.40637
36. Wu X, Li Y, Su L, Xie X, Cai M, Lin N, *et al.* Chromosomal microarray analysis for the fetuses with aortic arch abnormalities and normal karyotype. *Mol Diagn Ther* 2020;**24**:611–9. https://doi.org/10.1007/s40291-020-00474-7
37. Peng R, Xie HN, Zheng J, Zhou Y, Lin MF. Fetal right aortic arch: associated anomalies, genetic anomalies with chromosomal microarray analysis, and postnatal outcome. *Prenat Diagn* 2017;**37**:329–35. https://doi.org/10.1002/pd.5015
38. McElhinney DB, Hoydu AK, Gaynor JW, Spray TL, Goldmuntz E, Weinberg PM. Patterns of right aortic arch and mirror-image branching of the brachiocephalic vessels without associated anomalies. *Pediatr Cardiol* 2001;**22**:285–91. https://doi.org/10.1007/s002460010231
39. Knight L, Edwards JE. Right aortic arch. Types and associated cardiac anomalies. *Circulation* 1974;**50**:1047–51. https://doi.org/10.1161/01.CIR.50.5.1047
40. Hastreiter AR, D'Cruz IA, Cantez T, Namin EP, Licata R. Right-sided aorta. I. Occurrence of right aortic arch in various types of congenital heart disease. II. Right aortic arch, right descending aorta, and associated anomalies. *Br Heart J* 1966;**28**:722–39. https://doi.org/10.1136/hrt.28.6.722
41. Van Poppel MPM, Zidere V, Simpson JM, Vigneswaran TV. Fetal echocardiographic markers to differentiate between a right and double aortic arch. *Prenat Diagn* 2022;**42**:419–27. https://doi.org/10.1002/pd.6104
42. Van Poppel MPM, Pushparajah K, Lloyd DFA, Razavi R, Speggiorin S, Nyman A, *et al.* Insights from fetal cardiac magnetic resonance imaging in double aortic arch. *Ultrasound Obstet Gynecol* 2020;**56**:636–9. https://doi.org/10.1002/uog.22110

43. Vigneswaran TV, Van Poppel MP, Griffiths B, James P, Jogeesvaran H, Rahim Z, *et al.* Postnatal impact of a prenatally diagnosed double aortic arch. *Arch Dis Child* 2021;**106**:564–9. https://doi.org/10.1136/archdischild-2020-318946
44. Zachary CH, Myers JL, Eggli KD. Vascular ring due to right aortic arch with mirror-image branching and left ligamentum arteriosus: complete preoperative diagnosis by magnetic resonance imaging. *Pediatr Cardiol* 2001;**22**:71–3. https://doi.org/10.1007/s002460010159
45. Zhang X, Zhu M, Dong SZ. Utility of fetal cardiovascular magnetic resonance imaging in assessing the fetuses with complete vascular ring. *Front Pediatr* 2023;**11**:1159130. https://doi.org/10.3389/fped.2023.1159130
46. Dong SZ, Zhu M. Prenatal cardiac magnetic resonance imaging of right aortic arch with mirror image branching and retroesophageal left ductus arteriosus. *J Matern Fetal Neonatal Med* 2019;**32**:1057–62. https://doi.org/10.1080/14767058.2017.1399116
47. Han J, Zhang Y, Gu X, Liu X, Sun L, Zhao Y, *et al.* The differential diagnosis of double aortic arch and right aortic arch with mirror-image branches in the Fetus: a potential novel method. *Pediatr Cardiol* 2021;**42**:1405–9. https://doi.org/10.1007/s00246-021-02625-x
48. Oakley C, Hurn A, Suckling C, Moriarty G, Simpson JM, Turcu S, *et al.* Impact on the trachea in children with prenatally diagnosed vascular ring formed by a right aortic arch. *Pediatr Pulmonol* 2023;**58**:2275–82. https://doi.org/10.1002/ppul.26463
49. Vigneswaran TV, Hunter LE, Carvalho JS, Seale AN. Management of prenatally detected vascular rings: a United Kingdom national survey. *Cardiol Young* 2023;**33**:1332–5. https://doi.org/10.1017/S1047951122002268
50. Rato J, Zidere V, François K, Boon M, Depypere A, Simpson JM, *et al.* Post-operative outcomes for vascular rings: a systematic review and meta-analysis. *J Pediatr Surg* 2023;**58**:1744–53. https://doi.org/10.1016/j.jpedsurg.2023.02.058
51. Depypere A, Proesmans M, Cools B, Vermeulen F, Daenen W, Meyns B, *et al.* The long-term outcome of an isolated vascular ring—a single-center experience. *Pediatr Pulmonol* 2019;**54**:2028–34. https://doi.org/10.1002/ppul.24490
52. Greenland S, Mansournia MA, Altman DG. Sparse data bias: a problem hiding in plain sight. *BMJ* 2016;**352**:i1981. https://doi.org/10.1136/bmj.i1981