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ORIGINAL ARTICLE

Evolution and trends in a pediatric cardiac magnetic resonance imaging program in a tertiary hospital over a 14-year period☆

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KEYWORDS
Cardiac magnetic resonance;
Pediatric radiology;
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Abstract
Objectives: 1. To review the activity in our hospital's pediatric cardiac magnetic resonance imaging (cMRI) program from its inception to the present. 2. To evaluate changes in the number of patients, in the number of studies done under anesthesia, in the number of studies done with contrast material (magnetic resonance angiography (MRA) and delayed enhancement), and in representative diseases studied. 3. To estimate trends in the parameters evaluated in objective 2.
Material and methods: The pediatric cMRI program at our hospital started on February 14, 2005. We assessed cMRI studies done between the inception of the program and December 31, 2018. The cases were entered in a calculation table that included sex, date of birth, date of examination, clinical presentation, radiologic diagnosis, sequences done, and anesthesia. For each year, we obtained data about patients' age, studies done under anesthesia, contrast-enhanced MRA, delayed enhancement studies, and postoperative studies. We also evaluated the evolution of the number of patients studied for a group of representative diseases (coarctation of the aorta; tetralogy of Fallot; dextro-transposition of the great arteries; corrections of univentricular heart; hypoplastic left heart syndrome; anomalous pulmonary venous return; and cardiomyopathy). We analyzed these data with bar graphs, evolutions of means, and logarithmic trend curves.

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Results: A total of 2606 cases were included. The number of cases per year increased gradually. The mean age of all patients was 12.5 years, and the age of the patients studied also increased during the 14-year period. Anesthesia was used in 42%. Contrast-enhanced MRA was done in 57.6% and delayed enhancement in 42.13%. The most common condition was aortic coarctation (16.39%), although the frequency of aortic coarctation and hypoplastic left heart syndrome decreased slightly during the period. By contrast, the frequency of cardiomyopathy (7.25% of cases) increased slightly, to the point where it represented 9.35% in 2018.
Conclusion: During the 14-year period in which pediatric cMRI has been done at our hospital, the conditions studied, the type of patients, and the techniques used has varied; the number of patients and patients' age has increased, where as the frequency of MRA studies has decreased. The prevalence of the different conditions studied has also changed.

PALABRAS CLAVE
Resonancia magnética cardiaca;
Radiología pediátrica;
Cardiopatías congénitas;
Miocardiopatías

Evolución y tendencias de un programa de resonancia magnética cardiaca pediátrica en un hospital terciario durante 14 años

Resumen
Objetivos: 1) Revisar la actividad del programa de resonancia magnética cardiaca (RMC) de nuestro hospital desde su inicio hasta la actualidad; 2) evaluar la evolución del número de pacientes, estudios bajo anestesia, estudios con contraste (angiografía y realce tardío) y patologías representativas, y 3) estimar la tendencia de los mismos parámetros evaluados.
Material y métodos: El programa de RMC pediátrica de nuestro hospital comenzó el 14 de febrero de 2005. Revisamos los estudios hasta el 31 de diciembre de 2018. Los casos son incluidos en una tabla de cálculo que incluye sexo, fecha de nacimiento, fecha de exploración, clínica, diagnóstico radiológico, secuencias realizadas y anestesia. Obtenemos datos por años de la edad de los pacientes, la realización de estudios bajo anestesia, realización de angiografía por resonancia magnética con contraste, estudios de realce tardío y estudios posquirúrgicos. También valoramos la evolución de un grupo de patologías representativas: coartación aórtica, tetralogía de Fallot, D-transposición de las grandes arterias, correcciones univentriculares, síndrome del corazón izquierdo hipoplásico, retornos venosos pulmonares anómalos y miocardiopatías. Realizamos gráficos de barras, evolución de las medias y curvas logarítmicas de tendencia.
Resultados: El número total de casos fue 2.606. Se registró un incremento gradual del número de casos. La media de edad de los pacientes fue de 12,5 años y también se incrementó a lo largo del periodo; el 42% de los casos se realizaron con anestesia. En el 57,6% de los casos se realizó angio-RM con contraste, y en el 42,13%, estudio de realce tardío. La coartación aórtica ha representado la patología más frecuente (16,39%), aunque su número ha descendido paulatinamente a lo largo del periodo, así como el corazón izquierdo hipoplásico. La patología del miocardio (7,25% de casos) ha aumentado paulatinamente, hasta representar el 9,35% en 2018.
Conclusión: A lo largo de estos 14 años, la patología estudiada, el tipo de pacientes y la técnica empleada han ido variando, con un aumento del número de pacientes y de su edad, una disminución de los estudios de angio-RM, y cambios en la prevalencia de los distintos grupos de patologías.

Introduction

The use of magnetic resonance imaging (MRI) to study the heart is one of the oldest indications of the technique. As early as the early 1980s, examples of ''black-blood'' imaging of the heart were being shown[1] and synchronisation with electrocardiography was suggested. It was applied to pediatric cardiology very early on[2], given its advantages in various regards and its lack of ionising radiation; however, it was used only occasionally to clarify aspects of complex heart diseases. Angiography with gadolinium, reported in 1994,[3] has been widely used in children.[4] The development of 3D steady-state sequences to study the coronary arteries and, later, the entire heart[5] enabled a

high-resolution study including cavities, valves, major vessels and coronary arteries with no need for intravenous contrast. Cine and phase-contrast MRI sequences enable functional assessment[6] of the ventricles as well as valves and short circuits.[7] Techniques for perfusion and late enhancement[8] as well as T1 and T2 maps have increased the diagnostic information available to cardiologists and radiologists. This growth has broadened the use of cardiac magnetic resonance imaging (CMRI) in pediatrics. CMRI has gone from an uncommonly used advanced tool to an integral part of the protocols for studying many heart diseases, including congenital heart diseases,[9] cardiomyopathies and cardiac tumours.

It must be remembered that, in children, echocardiography is the technique of choice for initial diagnosis and follow-up in most heart diseases. This means that most congenital heart diseases diagnosed in the prenatal or neonatal period are examined by echocardiography alone before they are treated. However, as patients grow, their sizes increase and their acoustic windows decrease (smaller thymus size, costosternal ossification, abnormalities due to surgery, etc.). In addition, post-operative changes and myocardial abnormalities are often difficult to evaluate by ultrasound. Hence, other imaging techniques are needed. CMRI enables morphological assessment of the heart and the major vessels with high spatial and contrast resolution, study of ventricular and valvular function as a reference standard and evaluation of the state of the myocardium with high specificity—all without administration of either ionising radiation or intravenous iodinated contrast. The disadvantages of CMRI are limited availability, price, need for anaesthesia in a significant proportion of children and, at present, uncertainty regarding the risks of depositing gadolinium in human tissues.

We started our hospital's pediatric CMRI program in February 2005. In December 2018, we reached a total of 2606 cases. The objective of this study is to analyse the changes over time in our activity; the demographic, technical and pathological variations of our studies; and the trends in these variations. As shall be mentioned throughout the study, it should be borne in mind that, during the study period, changes occurred in terms of hospital structure (an adult congenital heart disease unit was created); demographics (birth rates and pregnancy termination rates varied); MRI techniques (new sequences, risks and equipment came into being); and imaging techniques (3D and 4D ultrasound and multi-slice CT scans were used). As a conclusion, changes over time in terms of techniques, numbers and types of patients, and diseases are shown, and some trends are forecasted, especially with respect to the type of heart diseases that are expected to be studied in the future.

Material and methods

All CMRI studies performed from 14 February 2005 to 31 December 2018 were added to a spreadsheet, which was used to collect and analyse data as well as create graphs (Excel, Microsoft). Ours was a retrospective study of existing clinical examinations added to a spreadsheet without accompanying personal data; therefore, it required neither the approval of an independent ethics committee nor informed consent. Sex, date of birth and date of examination were included, and patient age was determined based on the latter two variables. Reason for ordering CMRI, radiological diagnosis, use of anaesthesia and technique performed, including sequences and administration of

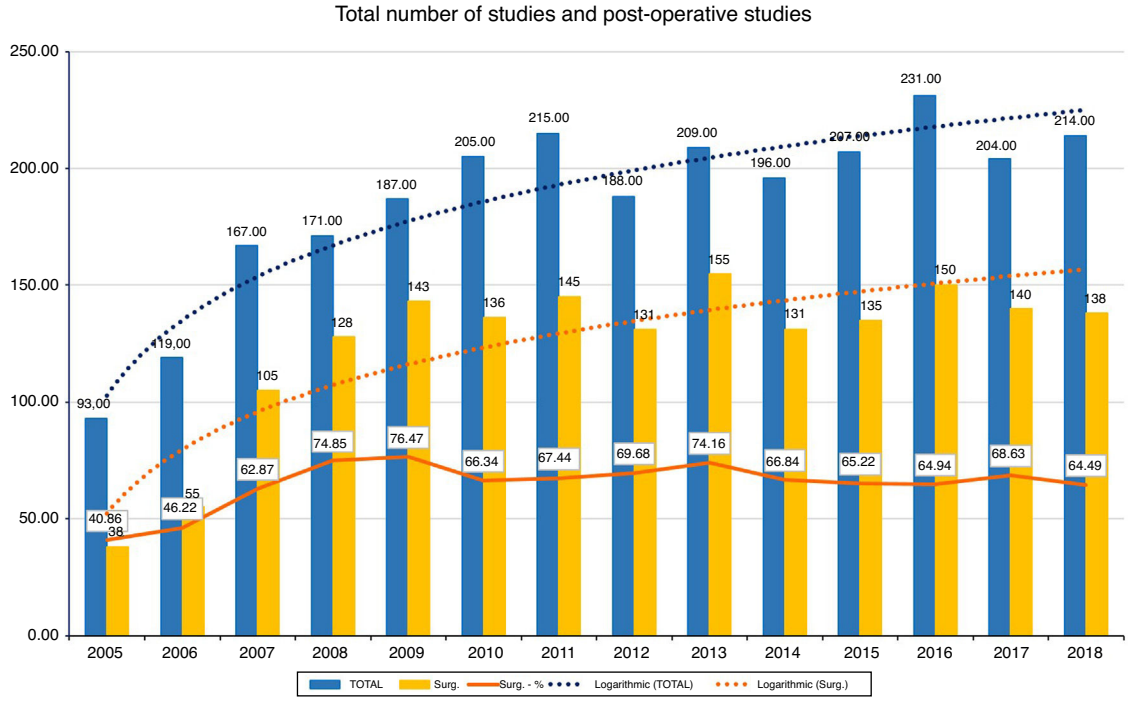

Figure 1 Bar graph showing changes over time in total numbers of studies (blue) and post-operative studies (yellow) from year to year. The dashed line shows the logarithmic trend in study numbers.

intravenous contrast, were added. Bar graphs were prepared to show changes over time in terms of numbers of studies, patient ages, use of anaesthesia and performance of angio-MRI and late-enhancement studies. We selected the following as clinical groups to examine post-operative studies: aortic coarctation (AoCo), dextro-transposition of the great arteries (D-TGA), tetralogy of Fallot (ToF), univentricular corrections, anomalous pulmonary venous return (APVR), hypoplastic left heart syndrome (HLHS) and cardiomyopathies. All graphs included the total number in bars and the logarithmic trend line. A logarithmic line was preferred to a linear line as it showed marked changes between groups. On the relevant graphs, the proportion of cases with respect to the total was included as a continuous line.

Results

A total of 2606 studies were performed during the study period (13 years and 11 months); of those, 1527 (59%) corresponded to children. The annual distribution of the total number and the post-operative studies are shown in Fig. 1. Regarding examination volume, a clear ascending trend line can be seen that gradually starts slowing down as of 2010.

Changes over time in age (Fig. 2) may be described as slightly ascending, with a range from two days old to 43 years old (adult patients gradually tapered off between the creation of the adult congenital heart disease unit in 2008 and the present time). Initially, mean age was 8.15 years, ranging between 10 and 11.5 years from 2008 to 2015.

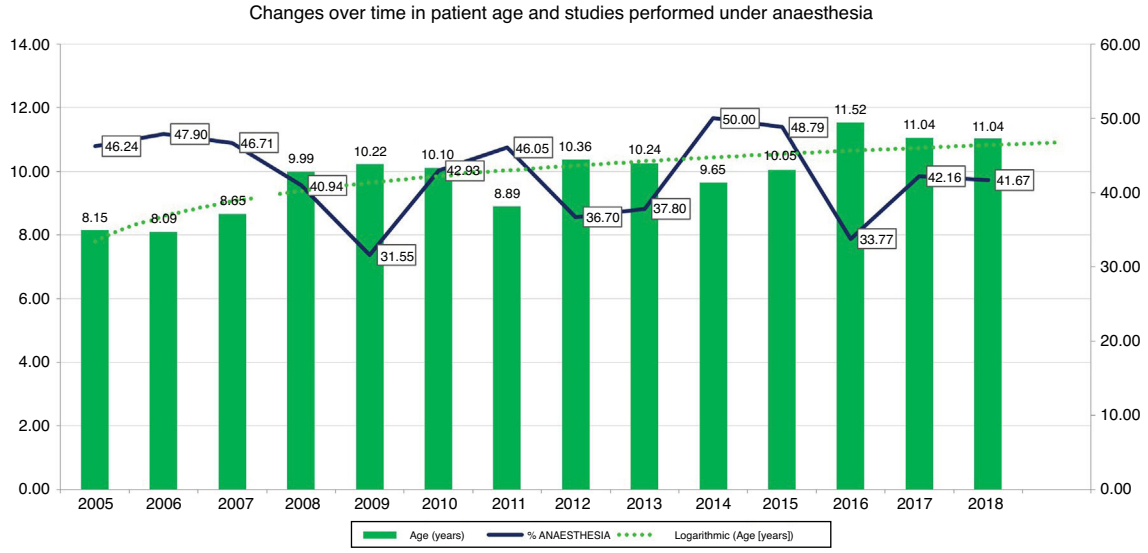

Figure 2 Bar graph showing changes over time in patient age (green) and the proportion of studies performed under anaesthesia (blue line) from year to year. The dashed line shows the logarithmic trend in age numbers.

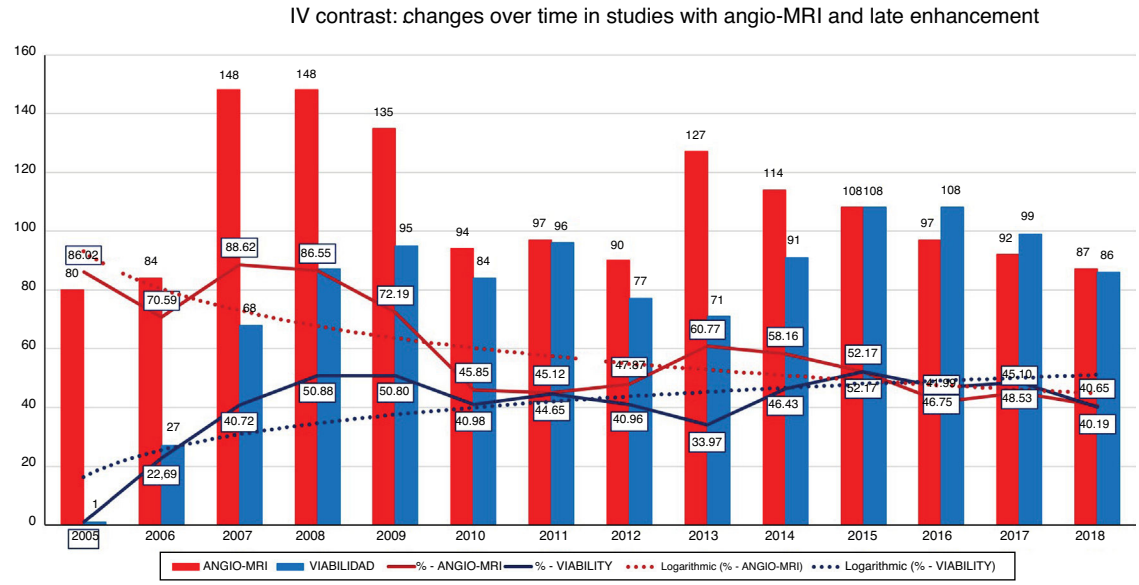

Figure 3 Bar graph showing changes over time in numbers of angio-MRIs (red) and late-enhancement or viability studies (yellow) from year to year. The solid line represents the changes over time in the mean. The dashed line represents the logarithmic trend.

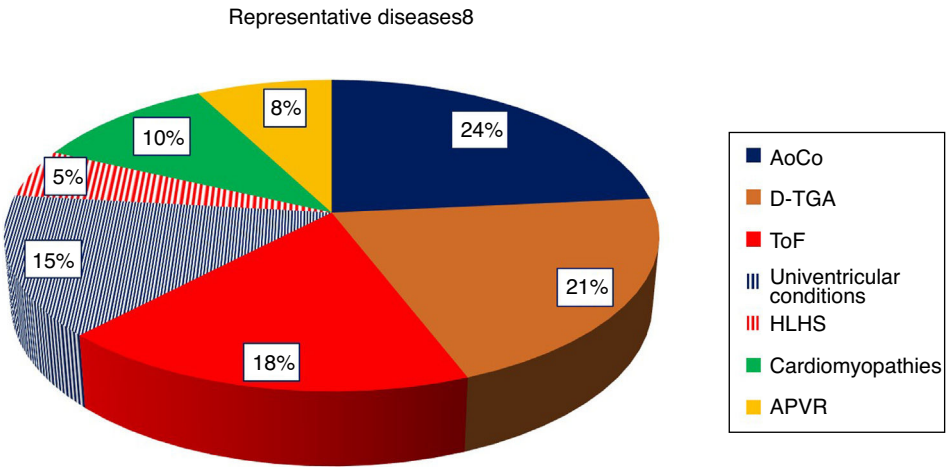

Figure 4 Graph of sectors of the most representative diseases from the series and their relative proportions (within the group). Univentricular corrections and HLHS both have a striped pattern, as both fall under univentricular physiology.

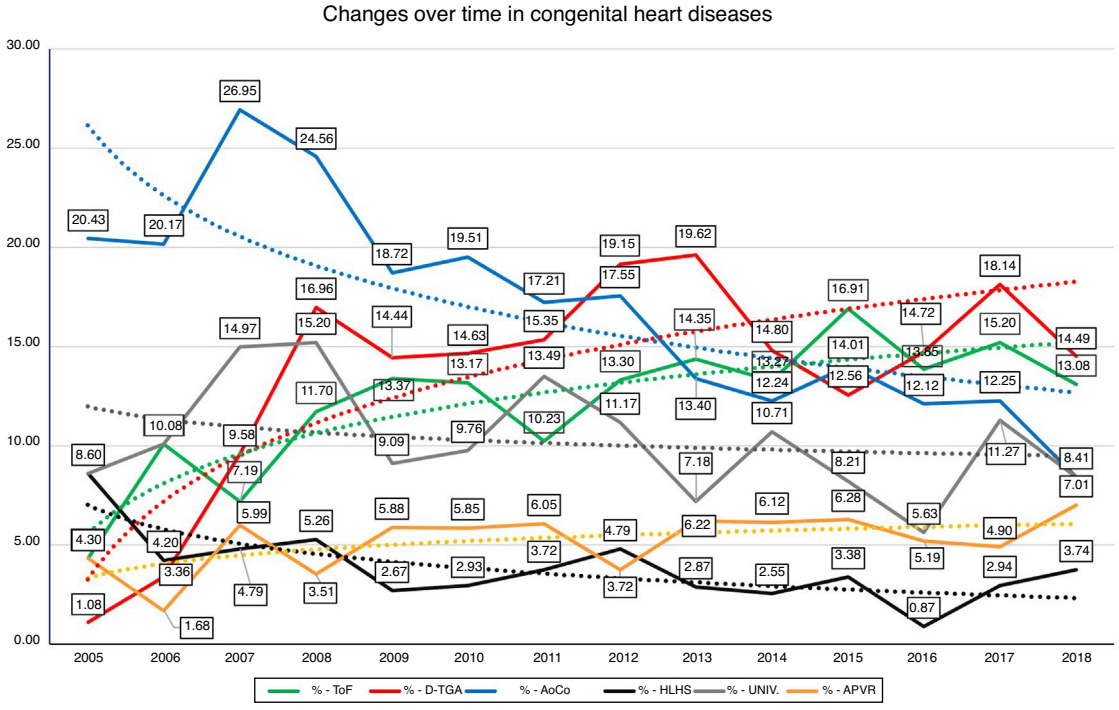

Figure 5 Line graph of the most representative congenital heart diseases from the series. The solid line represents the proportion of cases, and the dashed line, in the same colour, represents the logarithmic trend.

The absolute number of anaesthetised patients increased from 2005 to 2011, though the proportion of examinations with anaesthesia (Fig. 2) slowly decreased from an average of 44%–47% in the first few years to an average of 34%–42% in the last few years.

The use of contrast for angio-MRI (Fig. 3) was highest in 2008. The proportion of studies that included this sequence ranged between 71% and 86% in the first few years and between 40% and 42 in the last 3 years.

However, post-contrast late-enhancement studies have increased over the years (Fig. 3).

The total number of post-operative studies and the total number of studies are shown in Fig. 1. It can be seen that this number increased up to 2013, going from 41% in 2005 to 74% in 2013 and peaking at 76% in 2009. At present, it is between 60% and 70%.

Regarding the various diseases, the most representative ones are shown in Fig. 4. Given that HLHS (92 cases in total) falls under univentricular corrections, both groups are represented with a striped pattern, to indicate that cases of HLHS belong to the univentricular group.

Changes over time in congenital heart disease are shown in Fig. 5. The disease with the largest number of cases was AoCo, with 427 cases, accounting for 16.39% of the total. The volume of studies for AoCo shows a descending trend; it peaked at 27% in 2007 and is currently 8%. After AoCo,

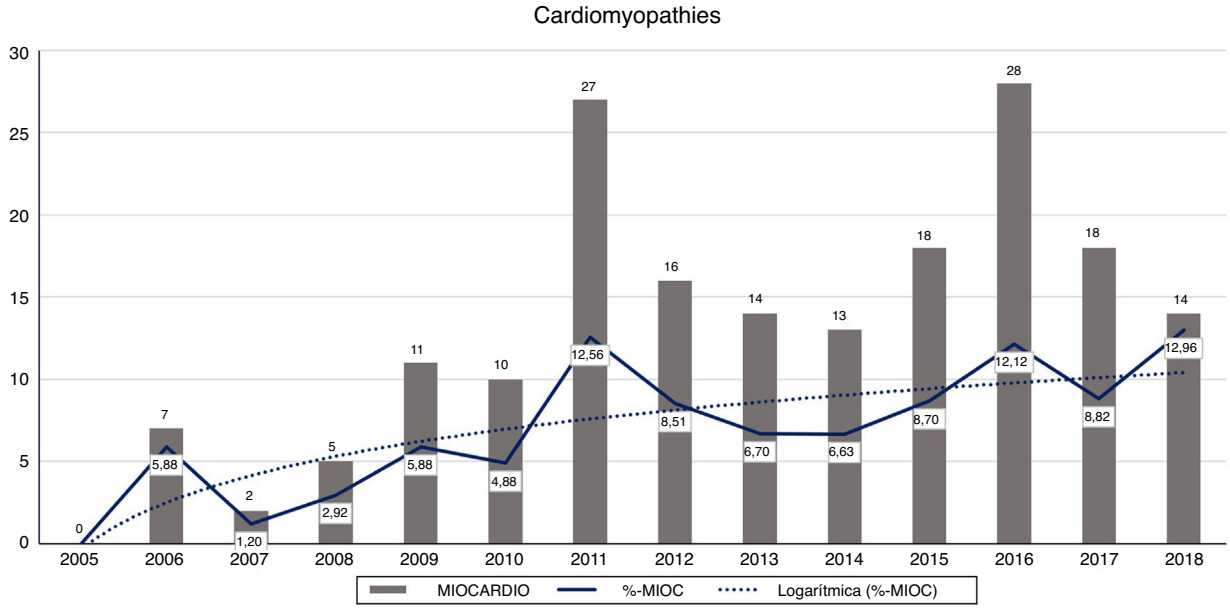

Figure 6 Bar graph showing changes over time in numbers of studies for cardiomyopathies from year to year. The solid line represents the changes over time in the mean. The dashed line shows the logarithmic trend.

D-TGA accounts for 14.35% with 374 cases; it exhibits a growing trend, having represented 18% of studies in 2017 and 14% of studies in 2018. Tetralogy of Fallot is the third most common heart disease, with 329 cases (12.62%), and shows a slight ascending trend; it accounts for a very stable percentage of cases, between 10% and 15%. Taken together, patients with univentricular hearts (including patients with single ventricles and patients having undergone univentricular correction surgery such as the Norwood, Glenn or Fontan procedure) represent 265 cases and 10.17% of all patients. They show a negative trend, peaking at 15% in 2007 and being around 8% at present. We also studied patients with hypoplastic left heart syndrome separately, even though they belong to the univentricular heart group, in order to show this disease's clear descending trend. Initially, it accounted for 9% of studies, while it now accounts for around 3%. Patients with anomalous pulmonary venous return are a rather stable group, with a very slight ascending trend. Finally, patients with cardiomyopathies (Fig. 6) exhibit a gradual ascending trend in their proportion of our studies, accounting for less than 5% in the first few years and 13% at present.

Discussion

Our hospital's pediatric CMRI program started in February 2005. The learning curve for diagnostic imaging technicians as well as radiologists, anaesthetists and cardiologists meant that somewhat longer examination times were required in the first few months, as may be seen in the changes over time in the initial number of studies. The use of black-blood sequences on the three usual orthogonal planes also required considerably prolonged examination times. This time decreased starting in 2009 when the WH3D sequence was incorporated into our equipment (Fig. 7), though the acquisition time of this sequence varies depending on heart rate and respiratory rate as well as patient cooperation, leading to variability in the efficiency of the respiratory navigator pulse. Usually, this acquisition time ranges from 5 to 15 min, though in patients who are not very cooperative, with irregular respiration and involuntary movements, it may exceed half an hour. However, one of the factors that the WH3D sequence influenced the most was the gradual decrease in angio-MRI studies (Fig. 8), which not only led to lower doses of contrast being administered to our patients, but also reduced examination times. It must be added that, in many cases, not performing an angio-MRI not only decreased sequence time, but also decreased the need for venous access in children and, on a secondary basis, for anaesthesia. Some patients are of a borderline age for performing the examination with anaesthesia; in them, the need for venous access may render the examination difficult due to anxiety, crying, etc.

Regarding patient age, although it was rather stable, it increased slightly over the years, despite the creation of the adult congenital heart disease unit in 2008. This gradual increase might be tied to the growing proportion of patients in post-operative long-term follow-up, as well as the decrease in the rates of babies born with complex congenital heart diseases resulting from a gradual increase in the rates of pregnancy termination when these heart diseases are detected, in both Spanish national[10] and international[11,12] studies. Associated with this is the decrease in the proportion of patients with anaesthesia.

The outbreak of nephrogenic systemic fibrosis in 2006 and of brain deposits of gadolinium in 2017 sparked general concern with respect to the use of contrasts in recent years, especially in children.[13] The WH3D sequence has enabled us to substantially decrease the use of intravenous contrast, resulting in a decrease in angio-MRI studies with contrast over the years. However, there is a gradual increase in late-enhancement studies with contrast. This is tied, on

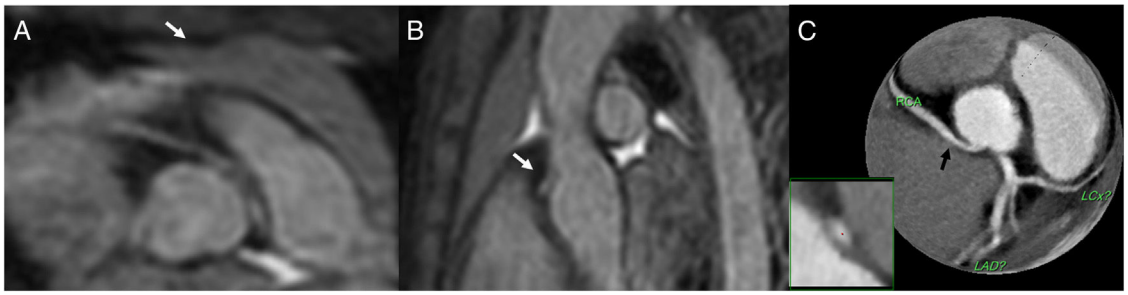

Figure 7 A 7-year-old girl with chest pain. WH3D sequence (A) axial and (B) sagittal multi-planar reconstructions show the abnormal origin of the right coronary artery from the left coronary sinus (arrows), confirmed using (C) a coronary CT scan. The fusiform or morphology or 'lentil shape' suggests the presence of significant stenosis.

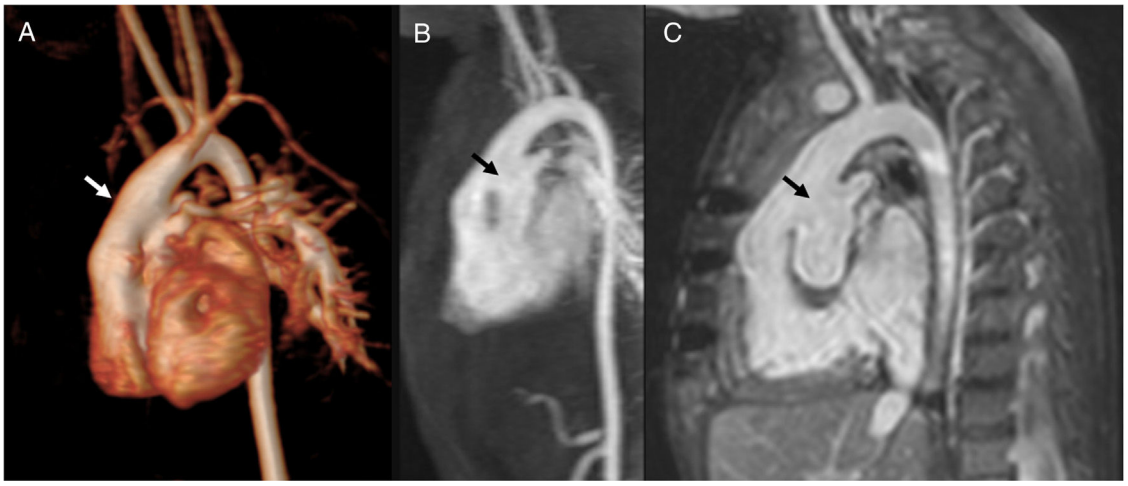

Figure 8 A 6-month-old infant with dextro-transposition of the great arteries, bibanding of the pulmonary arteries and a large aortopulmonary window (arrows). These findings are clearly demonstrated on (A) volume rendering (VR) and (B) maximum intensity projection (MIP) reconstructions of the angio-MRI with contrast. The (C) WH3D sequence shows the same anatomical abnormality with greater spatial resolution.

the one hand, to the follow-up of post-operative patients (we systematically include a late-enhancement study in the first examination following surgery) and, on the other hand, to a gradual increase in studies for cardiomyopathy. In the future, for diagnoses such as acute myocarditis, with T1 and T2 maps[14] we will probably not need gadolinium chelates either. Cardiac tumours in children are rare and account for only 14 cases in our series. Studies of myocardial perfusion, uncommon in pediatrics, are limited to 27 cases in our series, and they also do not have a significant influence on the administration of gadolinium chelates, since the late-enhancement sequence had been performed in all of them.

The disease group with the most patients is undoubtedly the post-operative group, accounting for around 60% of studies. In terms of frequency of disease groups, the most common diseases overall were AoCo, D-TGA and ToF. However, studies for AoCo have decreased over time such that in the last few years they have slipped to third place; currently, the two most common types of study are for D-TGA and ToF. Overall, patients with univentricular correction (by the Norwood, Glenn or Fontan procedure) show a constant decrease that is especially marked in the case of HLHS. This is tied to the decrease in surgical procedures for this disease, which is due to an increase in prenatal diagnosis and voluntary pregnancy termination when these diseases are detected.[15] APVR, for its part, is relatively common—especially partial APVR associated with sinus venosus atrial septal defect—and the number of cases of this condition has increased slightly over the years. The group of patients with cardiomyopathies was very much a minority group initially (accounting for 0%–5% of studies in the first few years), but currently accounts for more than 10% of studies. Increases in clinical concern as well as social respect for cardiomyopathies as a cause of sudden death in children and young people who play sports have led to increased numbers of visits and patients. These things as well as advances in CMRI and its importance in the diagnostic criteria for these diseases have led to a continuous increase in requests for CMRI. To this must be added the fact that our hospital was designated a leading Spanish national centre for pediatric cardiomyopathies in 2010. This study is not intended to comprehensively enumerate the diseases studied in our series. The most significant diseases

were included in the total number of studies; taken together, they comprise 69.44% of the studies. The remaining 30% is comprised of other diseases, including Ebstein's anomaly, double outlet right ventricle, endocardial cushion defects such as double aortic arch and interruption of other vascular rings, Kawasaki disease and cardiac tumours. Although, taken together, these groups represent a large number of patients, their changes over time are not very substantial as each represents a small population.

Our experiences have certain features in common with other published series,[16] though cases depend on hospital type, radiology department and available technology. Our hospital is a maternal-child hospital within a general hospital with an MRI machine in the pediatric radiology section. This machine is shared with all the pediatric sections (neuropediatrics, oncology, trauma, etc.) and with the women's imaging section (breast and female pelvis). This limits the availability of the MRI machine and influences indications for tests. Until July of this year, we had a four-slice computed tomography (CT) scanner that was insufficient for performing cardiac CT scans. In July 2018, a 128-slice CT scanner was installed in our section.

Due to technology and population changes, future changes in CMRI and cardiac imaging in general are to be expected. On the one hand, complex heart diseases are decreasing due to pregnancy terminations, as mentioned above, and cases of cardiomyopathies are increasing. In terms of technology, we currently have a 3D phase contrast sequence with temporal resolution (4D flow), though we do not have a suitable post-processing program due to its high cost. The value of T1 and T2 maps, which we do not currently have, has increased very significantly for the study of myocardial disease. Lastly, multi-slice CT scanning will undoubtedly lead to changes in indications. More CT scans will be performed in purely vascular or coronary examinations, which will facilitate access to CMRI for other more complex diseases and cardiomyopathies.

This study is a retrospective observational study whose limitations include patient selection bias in terms of the type of centre (leading centre) as well as the characteristics and technological equipment of the radiological diagnosis department. The number of cases, the variety of diseases and treatments and the changes over time in the technique used and the experience of the radiologists and other staff make it difficult to draw statistical inferences with respect to radiological findings, technique validity and the characteristics of the different sequences.

It may be concluded that, during the study period, the number of examinations increased, following an ascending trend, and the use of intravenous contrast was limited mainly at the expense of a decrease in angiographic studies. In addition, the number of complex and serious heart diseases was found to decrease, something that was reflected in a decreasing number of univentricular corrections as well as an increase in studies of patients with cardiomyopathies.

Authorship

1 Responsible for study integrity: CMR.
2 Study conception: CMR, TAM.
3 Study design: CMR, TAM, ALZ, YRM, JDC.
4 Data collection: CMR, ALZ, MSA, YRM.
5 Data interpretation and analysis: CMR.
6 Statistical processing: CMR.
7 Literature search: CMR.
8 Article drafting: CMR, TAM, ALZ.
9 Critical review of manuscript with intellectually significant contributions: CMR, TAM, ALZ, MSA, YRM, JDC.
10 Approval of final version: CMR, TAM, ALZ, MSA, YRM, JDC.

Conflicts of interest

The authors declare that they have no conflicts of interest.

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