



Paolo Tomà

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Professor Paolo Tomà qualified in medicine at the University of Genoa in 1976. He trained in both radiology and pediatrics. Between 1980 and 1994 he worked as a radiologist in the Department of Imaging at the G. Gaslini Institute in Genoa, first as a registrar and later in a more senior position. From 1992 to 1994 he was Director of Ultrasound at the institute. Between 1995 and 2009 he was Director of Radiology, and from 2005 to 2009 he also held the position of Director of the Department of Imaging.

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## Dear readers and colleagues,

I am extremely honored to be invited as editor of this issue of Siemens Healthineers MAGNETOM Flash journal. As a radiologist, I have always believed that pediatric<sup>1</sup> magnetic resonance imaging (MRI) represents a very interesting and challenging field for radiologists as well as for physicists, engineers, and technicians. Like for adults, in children MRI is today performed in a variety of medical settings, including neurological, cardiac, thoracoabdominal, musculoskeletal, and oncological. Clinical MRI applications allow us to observe structural, functional, and chemical changes in patients and to identify biomarkers of specific diseases in their early stages, which can help us to better understand typical and atypical findings. Imaging pediatric patients normally requires a variety of specific and adaptable equipment, together with dedicated software and well-trained staff. The need for specialized technology arises from several challenges of pediatric MRI, which include anatomical, developmental, physiological, and behavioral issues.

A child's anatomy is smaller than that of an adult and changes rapidly during early growth [1]. The reduced size of pediatric structures makes it difficult to obtain adequate signal-to-noise ratio (SNR). As suggested by the literature [2], this obstacle may be mitigated by choosing a compromise between reduction of the field of view and reduction of spatial resolution, respectively, at the cost of decreased SNR and less informative images. As well as a compromising strategy, many manufacturers are

adopting a customized approach with appropriate hardware, consisting of specialized coils sized to fit neonates and a narrow bore, which allows faster scans using higher gradient strength and slew rate.

It is far from simplistic to say that one of the major challenges in imaging pediatric patients is getting them to cooperate sufficiently for a diagnostic MRI study [3, 4], in the effort both to prevent motion artifacts and to obtain high-quality scans. Younger children are unable to cooperate, perform breath-holding, and frequently require sedation or general anesthesia to undergo MRI. Since sedation and anesthesia involve long-term neurocognitive effects, short-term risks related to the procedure, and require specialized staff, the chance to implement fast and motion-resistant MRI sequences is appealing [5, 6]. In the last few years, several approaches aimed at accelerating acquisition time have been developed, including parallel imaging, compressed sensing, non-Cartesian acquisition, and simultaneous multislice acquisition. Also, much has been done to ensure that parallel imaging methods reduce scan times, thus avoiding errors in coil sensitivity measurement. In this context, Wave CAIPIRINHA<sup>2</sup> has recently been introduced [7], which ensures the use of full 3D coil sensitivities to achieve high acceleration factors with small g-factor penalties and less SNR degradation. These very promising results have already been shown in adult acquisition data, but much still has to be done to extend clinical application to the pediatric population.

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<sup>1</sup>MR scanning has not been established as safe for imaging fetuses and infants less than two years of age. The responsible physician must evaluate the benefits of the MR examination compared to those of other imaging procedures. Note: This disclaimer does not represent the opinion of the author.

<sup>2</sup>WIP, the product is currently under development and is not for sale in the U.S. and in other countries. Its future availability cannot be ensured.

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Professor Tomà was appointed Professor of Pediatric Radiology at the University of Genoa's Radiology and Pediatric Postgraduate Schools in 1990. For the last 20 years, he has mentored, inspired, and led a strong and committed group of pediatric radiologists at the G. Gaslini Institute. He has held a similar position at the Bambino Gesù Hospital in Rome since 2010.

Internationally, he served as Vice-President of the European Society of Paediatric Radiology (ESPR) from 1999 to 2002, and as President from 2002 to 2003. He received the ESPR gold medal in 2016.

He has published over 200 papers in peer-reviewed journals, as well as book chapters and books.

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Novel technologies for prospective motion correction are gaining consensus. The BioMatrix Kinetic Sensor, for example, uses an in-bore camera system and a marker on the patient's skin to track head movement and correct motion as slight as normal breathing, thus producing remarkably accurate MRI scans. The scan length is a key point not only for exam quality but also for children's safety. Naturally, increasing efforts should be made to develop innovative techniques that can help to accustom children to MRI exams. Today, many new devices can provide a play-based simulation of the full MRI experience, including a motion sensor and noise simulation, providing children with the skills to cope during the actual scan. Also, making MRI rooms less institutional with playful surroundings and in-bore experience can do much to help children fully trust MRI staff.

Acoustic noise of the MRI scan remains an important challenge and is a cause of major discomfort for the pediatric population [8, 9]. Involuntary patient movements, temporary hearing difficulties, and problems in communication between patient and operator are possible issues related to acoustic noise. Evidence from the literature suggests that reducing acoustic noise can increase patient comfort and their acceptance of the procedure, which improves image quality. Several countermeasures have been proposed but there is still much to be done before MRI can really be considered a "child-friendly" experience.

The brain undergoes a period of dramatic change in the first few years of life, as sulci become deeper and numerous, and water content decreases due to progressive myelination, producing gray versus white matter contrast improvement and connectivity enhancement. Consequently, brain tissue properties such as the longitudi-

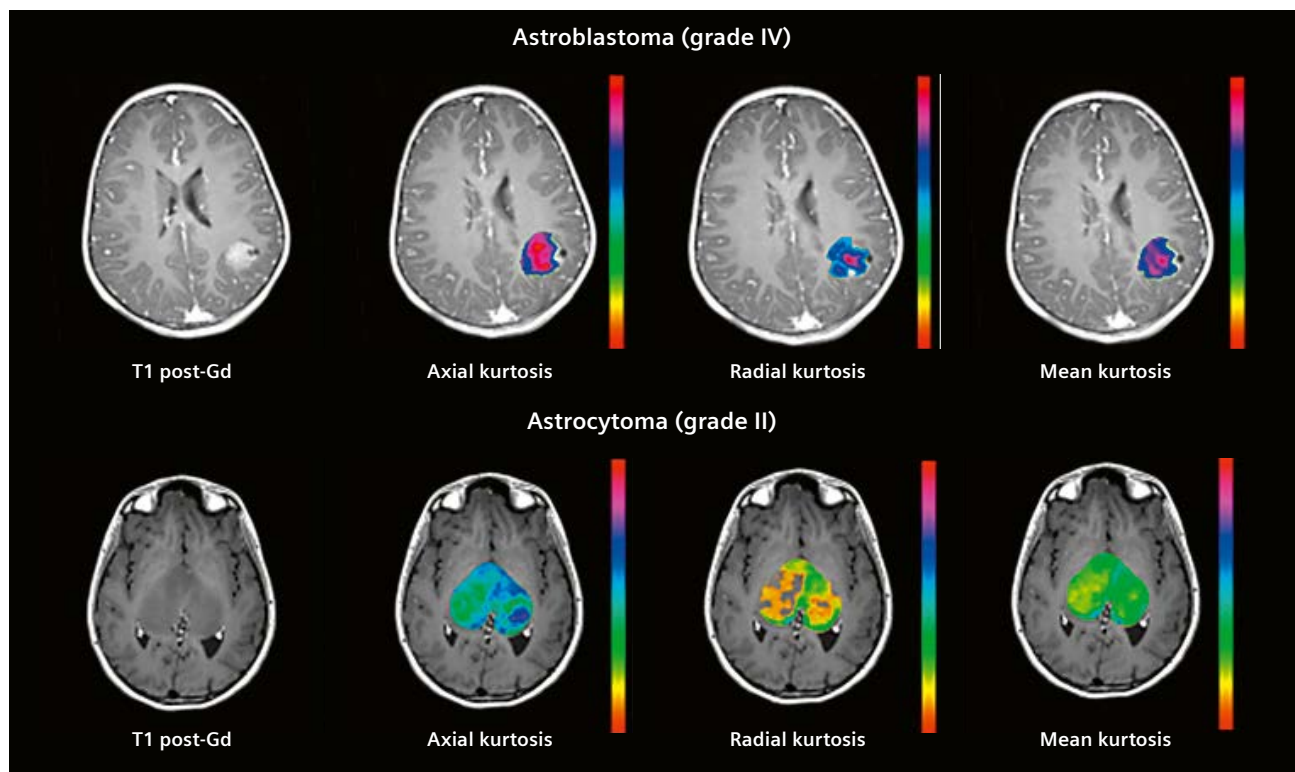
nal relaxation time (T1) and axial relaxation time (T2) differ significantly between children and adults. As myelination progresses, water diffusion within the white matter changes, creating differences at a microstructural level, thus posing a challenge for diffusion-weighted imaging (DWI) and diffusion-tensor imaging (DTI) [10–12]. Standard analysis techniques used for adult data are not directly applicable. The development of novel pipelines that deal directly with neonatal-specific issues, including high brain water content and reduced anisotropy, are necessary. Accelerating techniques have made it possible to introduce sequences such as Diffusion Kurtosis Imaging (DKI)<sup>2</sup> in a clinical setting, due to reduced acquisition time. DKI is a water diffusion technique based on a non-Gaussian water distribution model. DKI has shown great potential in exploring tissue complexity, and has produced promising results in adult glioma grading [13] (Fig. 1). Robust T1 and T2 mapping in both the brain and the rest of the body are valuable methods and are only starting to emerge in the clinical context of pediatric MRI, i.e., for monitoring brain maturation and measuring chronic liver disease over time [14]. The differences in frequency of biomedical signals between children and adults are another very sensitive issue to consider in clinical practice. Blood flow, pulse, and respiratory rates are faster in children than in adults, thus significantly affecting data from brain, cardiac, thoracic, and abdominal imaging. Cerebral blood flow (CBF) as measured by Arterial Spin Labeling (ASL) is particularly affected by physiological changes in blood flow. ASL is a low-SNR method and, even though higher mean CBF and blood flow velocity in the carotid arteries lead to a physiological improvement of SNR in children compared with healthy adults, the interpretation of pediat-

ric perfusion data is complex as it is dependent on age-related and sedation-related changes. Indeed, perfusion map templates for healthy children are extremely important to confine or broaden normal perfusion data.

In cardiac magnetic resonance (CMR), the infant heart rate (90–180 bpm) is higher than the average adult (60–100 bpm), resulting in a very short cardiac cycle. Moreover, the variability of cardiac frequency makes image reconstruction complex, since it affects temporal resolution and velocity measurements. Flow MRI<sup>2</sup> is a very useful method for assessing longitudinal changes in cardiovascular physiology in pediatric subjects and for monitoring common congenital disorders associated with complex alteration of cardiovascular physiology and flow. In this context, due to small vessel size, high heart rates and the limited capacity of children to perform breath-holding, flow MRI is challenging. Moreover, the method requires time-consuming and operator-dependent placement of multiple imaging sections in order to study multiple vessels. This can result in misalignment with respect to the flow direction and thus in underestimation of velocity. These issues in the evaluation of congenital diseases result in a long total examination time (60–90 min). In addition, pediatric flow MRI requires high spatial and temporal resolution, short imaging times, and full coverage of complex cardiovascular malformations. Generally, to benefit

pediatric CMR and flow MRI, acceleration techniques using parallel imaging were developed to allow fast, high resolution, free-breathing, 3D and 4D acquisitions [15] (Fig. 2). Along with them, the recent introduction of Compressed Sensing acquisition and reconstruction techniques has made it possible to reduce acquisition times even further, thus allowing the optimal fusion of anatomic and flow data into a single 3D dataset as well as fast cine imaging<sup>2</sup>. However, we still do not have a standardized protocol for background correction in cardiovascular MR phase-contrast imaging. This indeed represents a challenge to be considered in pediatric CMR although various correction approaches have been investigated.

A new field emerging in pediatric CMR is fetal cardiovascular MRI<sup>1</sup>. Until now, cardiac MRI of the fetus was mostly based on anatomical imaging or, at best, on low spatial and low temporal resolution functional imaging, typically employing untriggered cine real-time balanced steady-state free-precession sequences. After some attempts at obtaining a fetal ECG signal with devices such as MR-compatible electrodes and cardiocographs, the new frontier in fetal cardiovascular MRI currently involves self-gating approaches, the most common being Metric Optimized Gating (MOG). MOG is a method that can be applied to both cine and phase-contrast flow imaging. Data are retrospectively acquired with an artificial

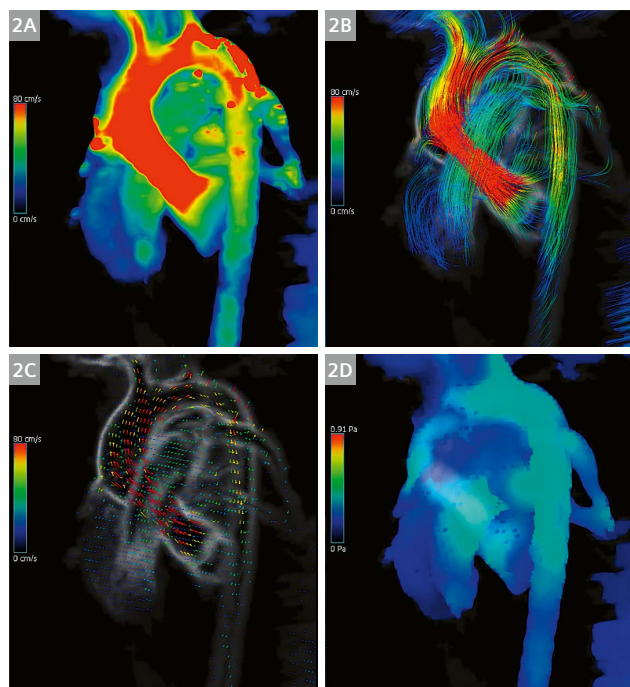


1 Example of diffusion kurtosis maps on two different pediatric brain tumors.

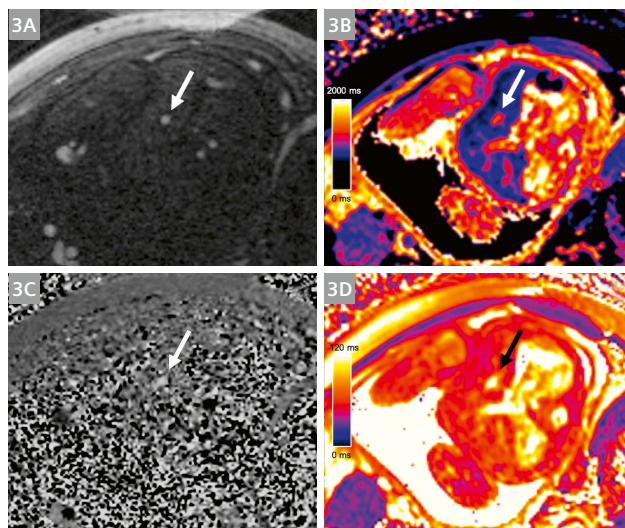
ECG-trigger and then subjected to iterative reconstruction, which performs an exhaustive search of all possible combinations of different heart rhythms until it finds the one yielding the minimum entropy due to the lack of ghosting-reconstruction artifacts. This identifies the real heart rate of the fetus [16]. Different self-gating techniques first reconstruct real-time images of limited image quality but high temporal resolution, subsequently analyzed to extract a self-gating signal that characterizes the periodic contraction of the fetal heart, which in turn is used to retrospectively sort all readouts into their corresponding cardiac phase [17]. The high-quality images that result can be used for a detailed functional assessment of the fetal heart. Another technique that is gaining favor in fetal imaging is MR oximetry, which aims to quantify oxygen saturation of the blood within the larger fetal vessels by applying mapping techniques. T2-mapping exploits the paramagnetic properties of hemoglobin, with deoxyhemoglobin shortening the T2 relaxation time, resulting in higher T2 values with higher oxygen content. However, to account for the fact that T2 measurements are also influenced by hemoglobin concentration (hematocrit), T1-mapping is additionally applied because of its strong correlation with this parameter, with lower T1 values for higher hematocrit percentages [18]. The combination of phase-contrast flow imaging and mapping oxygen

measurements (Fig. 3) can be used to calculate fetal oxygen delivery, consumption, and extraction fraction, providing the only currently available noninvasive insight into advanced fetal hemodynamics.

Recent advances and future developments in artificial intelligence and machine learning, including neural networks and deep learning, have a promising role in medical imaging [19–21]. These techniques offer numerous applications and may potentially facilitate countless aspects of radiology workflow, namely scheduling and triage, clinical decision and examination support, image acquisition, detection and interpretation of findings, postprocessing, reporting, image management and archiving, dose estimation, quality control, and integration with other medical record data [22]. In MRI, machine learning could reduce imaging time and improve characterization, for example by recognizing lesions and suggesting appropriate protocol or sequence modifications. It could also improve image reconstruction by exploiting prior information extracted from existing image datasets to compensate for missing data in *k*-space undersampling. In pediatrics, bone age assessment algorithms based on hand radiographs could soon become a clinical reality [23], and many more applications are being investigated. Machine learning can even be used to identify, predict, or categorize subtle patterns beyond the threshold of the human eye, potentially



**2** 4D Flow. Velocity (2A), vector (2B), streamline (2C), and wall-shear-stress (2D) systolic images of the aorta in a 15-year-old boy with bicuspid valve and aortic stenosis treated using the Ozaki procedure.



**3** Fetal Cardiovascular MRI<sup>1</sup>. Flow magnitude (3A) and phase (3B), T1-mapping (3C), and T2-mapping (3D) images of the umbilical vein in a 32-week-old fetus affected by transposition of the great arteries with intact interventricular septum.

extracting new valuable information. Radiomics is one such development, where a large number of quantitative features are extracted from medical images using data-characterization algorithms, with the aim of revealing disease characteristics that cannot be detected by the human eye but may prove useful for predicting prognosis and treatment response. In children, this technique has mainly been applied in (neuro-)oncology [24]. MRI remains the most common imaging modality used to evaluate central nervous system tumors. The diagnosis, prognosis, and treatment of pediatric brain tumors are now becoming more reliant on the genetic profile and histopathologic features of the tumor rather than on the histopathologic features alone, which previously were the reference standard. Grasping the principles and advances in tumor genomics is crucial to radiologists who interpret neuro-oncology imaging studies. In this scenario, quantitative radiomic data can be extracted and analyzed together with clinical and genomic data, in a process that is known as radiogenomics. This information can be used to better predict the diagnosis and outcome for children with brain tumors. Artificial intelligence may further enhance the potentialities of radiomics and radiogenomics, allowing the conversion of radiologic images into highly mineable data. For example, machine-learning algorithms trained on radiomic features have shown promising results in predicting medulloblastoma molecular subgroups [25]. The potential of these techniques lies in their ability to

inform subsequent clinical and surgical decision-making, which greatly impacts patient survival and quality of life. All this is paving the way to personalized medicine, in which variables gathered from different fields of medicine and life can be used for tailored prevention, diagnosis, and treatment approaches. Nevertheless, more work is needed to integrate novel technologies into existing systems before they can fully enter the clinical scenario. Also, these technologies are prone to bias and could potentially produce significant ethical and medico-legal issues. They are not expected to replace radiologists in the foreseeable future but rather to aid them, improving their accuracy and productivity, and enhancing their value in patient care and satisfaction. Besides, radiologists need to understand both the strengths and the pitfalls of these new tools and become actively involved in their research and development, performing critical assessment through evidence-based medicine.

In conclusion, more so than in adults, pediatric MRI challenges require the most advanced methods, hardware, and clinical staff, and I believe that pediatric MRI is now a pivotal area on which technology and new ideas must focus to improve diagnosis and care.

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**Paolo Tomà**

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