Magnetic Resonance Coronary Angiography
The Condemned Live Longer*
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Magnetic resonance coronary angiography (MRCA) has been around for several decades (1). Early reports (2) demonstrated the principal feasibility of the technique to visualize the coronary arteries and coronary artery stenoses noninvasively. Major advances were achieved by moving from breath-hold imaging to navigator-corrected datasets (3). This allowed measuring during free breathing, achieving higher spatial resolution and shorter acquisition time per cardiac cycle. The development of T2 preparation pulses to suppress the signal from the myocardium and enhance the contrast between blood and surrounding tissue (4) led to euphoric reactions in the community based on excellent preliminary data and robust image quality. As a consequence, the first multicenter MRCA trial was conducted (5). Even though this was a milestone for cardiovascular magnetic resonance (MR) imaging, being the first international multicenter study in the field, it had sobering results. Despite interpretable image quality in 84% of the proximal and middle coronary artery segments, the specificity only reached 42%. The method at this stage, however, allowed the exclusion of triple-vessel disease and left main coronary artery stenosis with a negative predictive value (NPV) of 100%.

The next years were used to improve the signal of the coronary artery lumen and further suppress the surrounding tissue. Intravascular contrast agents yielded interesting results with very good image quality in healthy volunteers; the application in patients, however, did not lead to the expected outcomes (6,7). Similar to other areas of cardiovascular MR imaging, the development of steady-state free precession (SSFP) techniques resulted in a superior signal and contrast to noise ratio of the coronary artery lumen against the myocardium compared with intravascular contrast agents and is now the established approach for MRCA (8).

The last major step toward diagnostic coronary artery imaging with MR imaging was the development of 3-dimensional data acquisition schemes covering the whole heart (7). This was made possible by the previous step, the development of SSFP techniques, because these techniques yield a high T1/T2 signal for blood, which is nearly independent of inflowing signal. Consequently, large 3-dimensional volumes, rather than thin 2-dimensional slices, could be obtained. An advantage of this approach is the higher signal-to-noise ratio obtained by 3- versus 2-dimensional imaging. By adapting the acquisition duration and time point of data acquisition to the coronary rest period, which is determined individually for each patient, the influence of cardiac motion on image quality can be minimized (9).

Again there were euphoric reactions based on excellent results in single-center studies, followed by sobering results when applied to a broader patient population. MR coronary artery imaging was dead—or was it?

Revival
The renewed interest in MRCA came from Asia, triggered by beautiful images, resembling what we are used to from computed tomography angiography (CTA). Then, excellent results were presented from single centers (10). Should we now be euphoric again?

In this issue of the Journal, Kato et al. (11) present their results from a 7-center Japanese MRCA trial. They report on 138 patients imaged with a 3-dimensional, navigator-corrected SSFP whole-heart MRCA sequence. Of the MRCA studies, 92% were completed; average imaging time was just <10 min. Sensitivity was 88%, specificity was 72%, and positive predictive value (PPV) and NPV were 71% and 88%, respectively. Left main coronary artery stenosis and triple-vessel disease were excluded with an NPV of 99%.

Kato et al. (11) optimized nearly every step in the procedure. They administered nitrates to dilate the coronary arteries, used an abdominal belt to reduce abdominal breathing motion, tailored data acquisition to cardiac motion using patient-specific acquisition windows and time points, and applied T2 preparation as well as fat suppression for better contrast and less venous signal. By stopping data acquisition after 30 min, they excluded the “bad breathers.”

Using such an optimized approach in an Asian population led to results superior to those of the cited previous multicenter study (5). When comparing the current results with those of recent multicenter computed tomography studies (CORE-64 [Diagnostic Accuracy of Multi-Detector Spiral Computed Tomography Angiography Using 64 Detectors] [12] and ACCURACY [Assessment by Coronary Computed Tomographic Angiography of Indi-
Individuals Undergoing Invasive Coronary Angiography [13]), similarities and differences can be detected (Fig. 1).

Number of patients excluded from the final analysis and reasons for exclusion. The current study population was preselected by exclusion of patients with pacemakers, atrial fibrillation, and previous bypass surgery. Patients with stents were included, but the stented segments were not analyzed. The main reason for not completing the study (8%) was drift of the diaphragm. In the CORE-64 study, patients with an Agatston calcium score of >600 (22% of the total population) were excluded from the analysis (12). Only the ACCURACY trial included all patients (13).

PPV. The PPV of CTA is superior to that of MRCA. Even though considerable progress has been made over the past few years, this significantly weakens this technique in patients with intermediate pre-test probabilities.

NPV. The NPV of the 2 MRCA multicenter trials is identical to the NPV of the CORE-64 study. All 3 studies, however, show inferior NPVs compared with the ACCURACY study. Remarkably, however, the value of MRCA in patients with a low pre-test likelihood is similar to computed tomography and can reliably rule out coronary artery disease in patients with a pre-test likelihood of <20%. These patients, who are often younger, predominantly female, and require >1 scan over their lifetime, would highly benefit from a radiation-free technique. In addition, in patients with a relatively high likelihood of coronary artery disease, it is important to rule out triple-vessel disease and left main coronary artery stenosis (achieved with 99% negative predictive value in the current study) and significant myocardial ischemia. Perfusion imaging is probably the best study for this, and even though most data are available for single-photon emission computed tomography, MR perfusion seems to be a valid and nonionizing alternative (14).

Study Limitations

Clearly, the study has its limitations, and several steps need to be taken before a new era of euphoria for MRCA might begin. 1) Patients were included in only 7 Japanese centers over a period of >2 years. A follow-up study with faster inclusion in more centers distributed around the world needs to follow. 2) Patients had a relatively low body mass index (BMI) (average 24 ± 4 kg/m²). Even though no significant differences were observed between patients with a BMI <25 and >25 kg/m², there was a tendency toward less accuracy in patients with a higher BMI. Thus, it will be interesting to see how the technique performs in a Western population. 3) The centers expended much effort performing the study. Most cardiovascular MR studies are not only directed toward the coronary arteries, but are combined with...
perfusion imaging and delayed enhancement. This combination might lead to weaker results, because cardiovascular MR is still a relatively complex technique, and small errors lead to significant reductions of image quality.

Outlook
Most likely, the future of MRCA will not demonstrate a major step change; rather, it will continue to develop slowly. In the foreseeable future, the utilization of multichannel coils (e.g., 32 channels), which yield a considerably higher signal-to-noise ratio, will lead to further improvement (or at least cover the loss expected by transferring the technique to a Western population). Similarly, higher field strengths (e.g., 3.0-T) are refined continuously, and even though preliminary results have not been superior to those with 1.5-T magnets (15), continuous improvements are made, resulting in better pre-pulses and better shimming procedures, and thus fewer artifacts. It has also been shown that the application of beta-blockers leads to favorable coronary artery images with MR. Even though the ultimate goal should be to avoid pre-medication, the doses required for MR imaging are well below those for CTA because the main effect seems to be the reduction of heart rate variability rather than the need for very low heart rates (16).

Conclusions
Compared with CTA, MRCA is still a cumbersome method with a higher failure rate, longer scan times, and less accuracy due to the lower PPV. However, the results of Kato et al. (11) show that MRCA is evolving slowly but steadily, and we should continue to look out for this method. Clearly, a noninvasive test to determine the significance of coronary artery stenosis (stress perfusion imaging) and visualizing the morphologic correlate (coronary artery imaging) in 1 examination without the use of ionizing radiation would be highly attractive. In addition, scar tissue, which is a strong prognostic parameter in ischemic and nonischemic heart disease, can be detected with excellent accuracy.

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Key Words: coronary artery • coronary artery disease • magnetic resonance angiography • national multicenter trial.