Synchronization Device for Electrocardiography-gated Echo-planar Imaging[1]

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An electrocardiography (ECG) synchronization technique allowed triggering of 1.5-T echo-planar acquisitions of the heart, with high gradient slew rates. In 51 volunteers (37 men and 14 women, aged 21–48 years), the ECG signal was amplified, filtered, and converted into an optical signal directly above the heart and was transmitted optically outside the bore. Reliable and artifact-free ECG tracings were obtained in all cases, regardless of the gradient switching speed.

Index terms: Heart, flow dynamics, 51.121416 • Heart, MR, 51.121416 • Magnetic resonance (MR), echo planar, 51.121416

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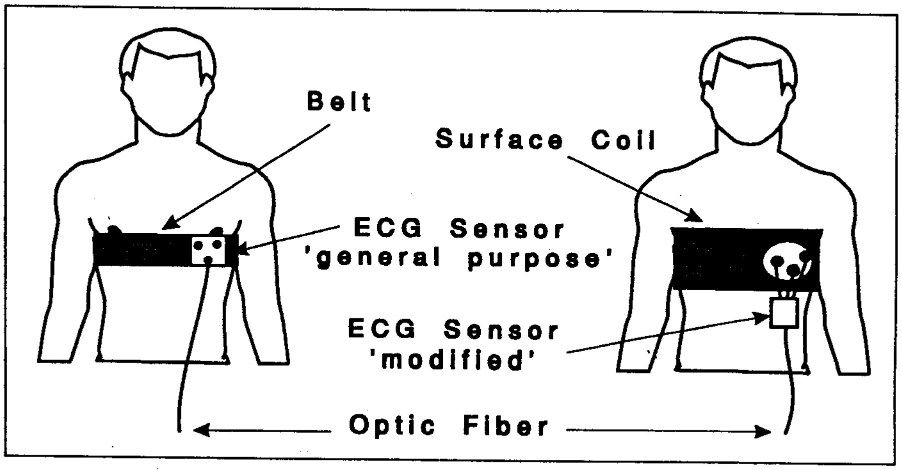

Figure 1. Diagram of the optical ECG (**a**) general-purpose device and (**b**) modified cardiac device for imaging with a torso surface coil. In both cases, the leads are placed directly on the chest wall above the heart. The leads feed into the amplifier, which is placed directly on the chest wall (in **a**) or 10 cm caudal (in **b**) or cranial (not shown). In both cases, the ECG signal is amplified and filtered close to the origin of the signal and transmitted outside the magnet bore via optical fiber.

The inherent motion sensitivity of magnetic resonance (MR) imaging mandates the synchronization of data collection to the periodicity of the heart beat during cardiac MR imaging. Such synchronization may be based on findings at electrocardiography (ECG) or on the pulsatile wave detected with a peripheral optical pulse oximeter (SaO_2). The unpredictable delay between the contraction of the heart and the peripheral pulsatile wave limits the usefulness of synchronization based on SaO_2. In addition, the SaO_2 curve is rounded and somewhat variable in its form, making it difficult to define a single "peak" from which to trigger. Hence, use of the ECG-based R-wave trigger is preferable.

Recording of the ECG signal in the MR imager with electrodes placed on the chest wall is complicated by a variety of factors. Apart from the Hall effect in the aorta, which causes an abnormal ECG tracing in the presence of a static magnetic field, use of rapidly changing gradients and radio-frequency power depositions interferes with detection of the rather weak physiologic cardiac signal. These difficulties are increased if ultrafast echo-planar sequences are employed, since they are based on faster and more powerful gradient configurations. The great changes in magnetic flux per unit time (measured in decibels per unit time) inherent in echo-planar imaging enhance the interactions with the ECG signal, making it virtually impossible to acquire a readable R-wave trigger signal while data is being collected.

In this study, we determined the efficacy of a triggering device based on an optical ECG transmission link that enables analogous R-wave synchronization of echo-planar acquisitions.

Materials and Methods

Optical ECG triggering system.—The triggering system is based on ECG amplification and conversion into an optical signal close to the patient's heart. Three fixed carbon electrodes (15-mm-diameter, 1-mm-thick carbon EK47; Steinemann, Chur, Switzerland) record the ECG signal. Cleaning of skin and electrodes with alcohol ensures excellent conductivity. Carbon wires connect the electrodes via a 40-kΩ resistor and low-pass radio-frequency filter input to the ECG amplifier, which is located within a small shielded box mounted on a Plexiglas support (Fig 1) taped to the patient's chest (1).

The ECG amplifying unit consists of an instrumentation amplifier with a gain of 400. The signal is further filtered with a 1–20-Hz bandpass filter. The signal is encoded with pulse-width modulation, which permits data transmission via an optical fiber from the shielded box located close to the patient's chest to outside the magnet bore. Here the optical signal is converted back to an analog electrical signal, demodulated, and fed into the standard ECG amplifying and triggering circuitry of the MR imager (Fig 2).

To perform echo-planar imaging of the heart with this triggering device, two problems needed to be addressed: *(a)* The susceptibility artifacts in the vicinity of the shielded box obscure cardiac morphology, and *(b)* the electrodes cannot be placed directly on the chest wall if a torso surface coil is used. Hence, the general-purpose triggering device was modified (Fig 1) by adding three 10-cm-long carbon wires interposed between the electrode lead wires (MS Cardio-Medical, Hünenberg Switzerland) and the ECG amplifier box. To minimize electromagnetic interference, the electrodes need to be positioned in a small area overlying the heart. In this precordial region, the electrodes were separated by less than 2 cm. With use of a plastic support, the shielded sensor box could be placed 10 cm craniad or caudad to the electrodes. Thus, susceptibility artifacts can be avoided in the region of the heart itself.

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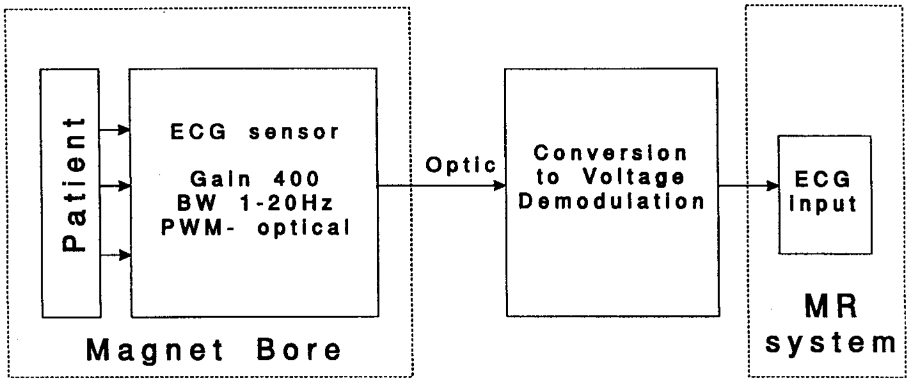

Figure 2. Schematic drawing of the ECG trigger system. The ECG is amplified by a factor of 400 (*Gain*) and filtered (bandwidth [*BW*]). The signal is encoded with pulse-width modulation (*PWM*), which permits data transmission via an optical fiber from the shielded box located on the patient's chest to outside the magnet bore. Outside, the optical signal is converted back to an analog electrical signal, demodulated, and fed into the standard ECG amplifying and triggering circuitry.

Standard ECG triggering system.—The ECG acquisition system available on standard MR imagers consists of carbon electrodes connected with a 1.5-m-long ECG cable to the ECG amplifier, which is placed outside the bore. Impedances are added at 60-cm intervals along the ECG cable, to reduce radio-frequency interactions and the risk of burning. On the MR imager, the ECG is amplified, digitalized, filtered, and plotted on the console.

MR imaging.—MR imaging was performed on a 1.5-T unit (Signa; GE Medical Systems, Milwaukee, Wis) equipped for echo-planar imaging with a nonresonant gradient configuration. Additional prototype hardware included a strengthened whole-body gradient coil, a 1-MHz bandwidth receiver, and a gradient-acceleration unit (2). The echo-planar imaging gradient is characterized by a maximum slew rate of 200 T/m/sec and a maximum amplitude of 18 mT/m.

After giving written consent, a 30-year-old male volunteer with a heart rate of 58 beats per minute was placed in the imager in the supine position. A flexible receive-only surface coil was attached to his chest. The ECG leads were attached to the chest through two holes contained within the coil (Fig 1). After a localizing MR image was obtained, transaxial multiphase echo-planar images were acquired through both ventricles of the heart, with use of a two-shot gradient-echo-planar sequence. With this acquisition strategy, the echo train is divided into two packages, each of which is collected after a single radio-frequency pulse. The two shots were collected nonsequentially (ECG-triggered) over two successive RR intervals in an interleaved k-space fashion (3). Thus, one interleaved k-space data set (shot) was obtained for each image per RR interval. Since two shots constituted a total image data set, each image contained data collected during the same acquisition window over two cardiac cycles.

Images (10-mm thick) were acquired with a repetition time of 54 msec, an effective echo time of 7.7 msec, and a flip angle of 45°. A 256 × 128 matrix with a 36 × 18-cm rectangular field of view rendered an in-plane resolution of 1.4 mm^2. To achieve this resolution, 72 data lines were acquired per image with a fractional k-space (0.5 signals acquired) acquisition. Twenty equally spaced images (phases) were acquired per cardiac cycle. Imaging was performed over 20 RR intervals, for a total of 10 multiphase image sets. The signal bandwidth was ±125 kHz.

With identical parameters, the echo-planar acquisition was repeated three times, each with a different trigger device. The first set of images was collected with the conventional trigger leads placed on the chest of the subject; the second and third sets of images were collected with the newly constructed general-purpose and modified optical ECG triggering devices (Fig 1), respectively. The leads were adjusted to ensure a ratio of R peak to T wave higher than 70% with the subject inside the magnet. Standard ECG triggering technique was used in all three cases. To record artifacts, a plotter was added outside the Faraday cage.

To validate the reliability of the new triggering device, the modified version of the optical triggering device was used at imaging in 51 volunteers (37 men and 14 women, aged 21–48 years), with various echo-planar sequences that necessitated cardiac gating.

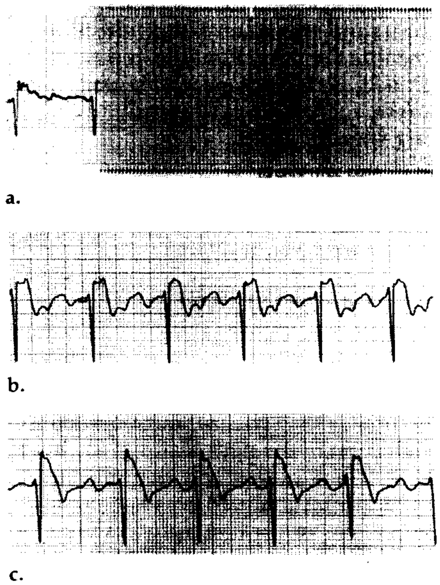

Figure 3. ECG tracings were obtained just prior to and during echo-planar data acquisition with **(a)** standard ECG signal transmission, **(b)** the general-purpose optical transmission device, and **(c)** the modified optical transmission device. Prior to data acquisition, the quality of the ECG signal is comparable. After the onset of echo-planar gradient switching, the ECG signal in **a** is no longer interpretable, whereas the ECG signal obtained in **b** and **c** remains virtually free of artifacts.

Results

Conventional ECG leads.—Prior to data collection, the ECG signal was well visualized with conventional leads. During data acquisition, signal interference from the radio-frequency and gradient pulses prohibited collection of an ECG that was suitable for triggering (Fig 3a). The images were characterized by blurring, reflecting the lack of synchronization between cardiac motion and data acquisition (Fig 4a). Since the data were obtained in two shots acquired nonsequentially in different heart beats, the lack of synchronization implies that the collections occurred at different times in the cardiac cycle.

Optical ECG triggering systems.—The ECG signal remained free of artifacts throughout the echo-planar acquisition when the optical ECG systems (both variants) were employed (Fig 3b, 3c). The radio-frequency and gradient pulses had no bearing on the quality of the R-wave triggering. Whereas there was no difference in the quality of QRS detection with the two variants, differences in image quality were apparent. The general-purpose device caused some susceptibility-induced spatial distortion of the anterior chest wall and of portions of the anterior myocardial wall (Fig 4b), whereas the dedicated cardiac device did not affect image quality in any way (Fig 4c).

With the modified device, gating was possible in conjunction with various echo-planar sequences in all 51 volunteers.

Discussion

Use of the gating method with optical ECG signal transmission provides a ro-

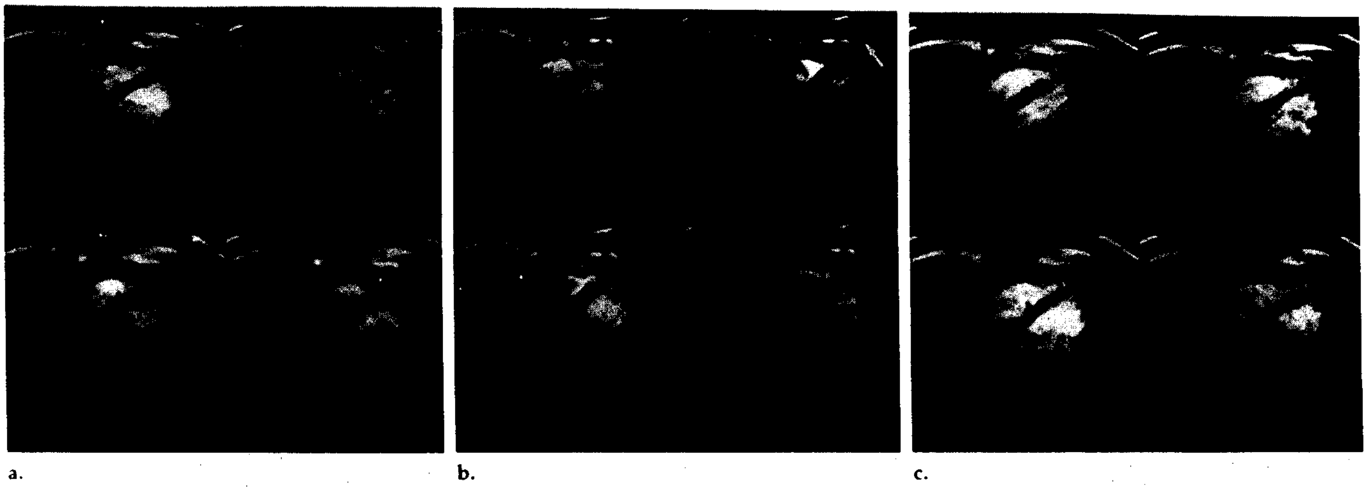

Figure 4. ECG-triggered transaxial images that traverse the ventricles were acquired with a two-shot nonsequential echo-planar sequence. Triggering was achieved with **(a)** conventional signal transmission and optical transmission, with the **(b)** general-purpose and **(c)** modified optical devices. In **a**, blurring reflects the lack of synchronization between cardiac motion and data acquisition. In **b** the general-purpose device caused susceptibility-induced spatial distortion of the anterior chest wall and portions of the anterior myocardial wall, whereas in **c** the dedicated cardiac device did not affect image quality at all.

bust strategy for cardiac synchronization of echo-planar acquisitions, without any conversion-induced time delays. The device is easily attached to the patient and is compatible with most existing MR imagers.

Although echo-planar imaging was initially considered a snapshot technique that would not necessitate synchronization to cyclic motion processes, echo-planar velocity mapping techniques designed to quantitate pulsatile flow necessitate simultaneous recording of the ECG signal (4). Triggering has also been found to be useful in echo-planar MR angiography (5). For optimal arterial imaging, the data acquisition window should be limited to periods of maximal systolic flow. Furthermore, findings in a recent study showed that two- and four-shot echo-planar acquisitions render cardiac image quality far superior to that achieved with single-shot echo-planar imaging (6). When the echo train is broken into two or four data packages (referred to as "shots"), the high-frequency k lines, which contain the high-resolution spatial information, are acquired much earlier and, hence, at a higher signal level on the T2* decay curve. Ensuing improvements in image quality include superior visualization of internal mammary and coronary arteries and more complete delineation of the myocardial margins (6).

Conventional ECG triggering strategies necessitate use of long wires to transport the electrical signal outside the bore of the scanner. However, radio-frequency and gradient switching produce transient voltages in these wires that cause interference. The longer the wires that carry the electrical signal, the greater the opportunity for signal distortion.

When the ECG signal is converted into an optical signal close to the heart, the distances covered by wires are greatly reduced. The ECG amplifier was placed either directly over the precordial region or 10 cm craniad or caudad. From this point, the electrical signal was converted into an optical signal and transmitted via optical fiber outside the magnet bore. Use of the considerably shortened electrode lead reduced the possibility that unwanted signal induction would corrupt the ECG signal. These hypotheses were supported by findings in the volunteers. Triggering was impossible with conventional leads, but conversion of the ECG signal into an optical signal close to the patient's chest wall allowed robust triggering throughout the echo-planar acquisition (Fig 3). The beneficial effects of consistent triggering on image quality are also clearly documented (Fig 4).

This approach to cardiac gating was first developed for use in patients with critical disease (1), in whom monitoring of a consistent and undistorted ECG signal is essential. Results in this study show that this approach can be used equally successfully in ultrafast gradient imaging. We now use the optical ECG sensor routinely in all echo-planar imaging examinations performed in our laboratories that necessitate cardiac synchronization. In 51 volunteer studies, no triggering difficulties have occurred.

The device is constructed in a manner to ensure maximal safety for the patient. Replacement of long electrical wires with optical fibers virtually eliminates the risk of heating, burning, or other hazards of electrical stimulation, and results in transmission of the ECG signal in an analogous fashion, without time delay.

Whereas both variants of the optical triggering device provide uncontaminated ECG tracings, only the adapted device should be employed in cardiac echo-planar MR imaging. With this device, susceptibility-induced artifacts can be totally avoided and robust triggering maintained. ■

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Letters to the Editor

■ MR Imaging in the Diagnosis of Aortic Dissection

From:
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Editor:

Dr Laissy and his colleagues are to be congratulated on their carefully conducted comparative study of magnetic resonance (MR) imaging and transesophageal echocardiography (TEE) (1). This study confirms the accuracy of spin-echo MR imaging in the diagnosis of aortic dissection. They report one false-positive diagnosis of dissection, giving a specificity of 95%. This case is illustrated and is an example of aortic atheroma being incorrectly diagnosed as aortic dissection. I believe that the spin-echo images they have provided suggest the first diagnosis (their Fig 2). It is unfortunate that, although the authors state that gradient-echo cine MR angiographic images were used in some patients, these images were not used to clarify the anatomy and abnormality in this particular patient.

As we have reported (2), the use of MR angiography in addition to conventional spin-echo sequences allows accurate definition of aortic disease. I believe that in the false-positive case in question, cine MR angiography in the oblique sagittal perspective would have clarified the abnormality and led to a correct diagnosis. The use of cine MR angiography in a similar case is shown in the Figure. It should also be noted that there are some linear artifacts on other parts of their Figure 2a (ie, in the ascending aorta) that may lead to a false-positive diagnosis of dissection on spin-echo images. This may be related to the authors' use of thicker than necessary imaging sections (they used a thickness of 7–10 mm, while we normally recommend a 5- or 6-mm thickness to reduce partial-volume effects). When such thin apparent dissection flaps are demonstrated, we advise that cine MR angiography be performed both in the same plane and orthogonal to that plane to confirm that these apparent flaps represent true dissection flaps and not artifacts due to noise or other sources of error.

Combining spin-echo with cine MR angiography, particularly to clarify less-than-definite appearances, increases the ability of MR imaging to be the most accurate method for diagnosing aortic disease, including thoracic aortic dissection.

References

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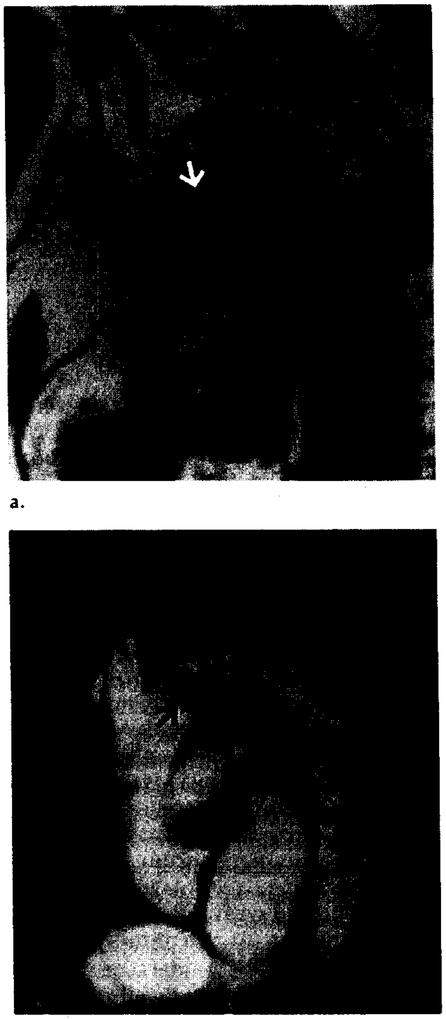
Dr Laissy responds:

We apologize to Hartnell et al that their excellent study recently published in *Radiology* (1) was not referenced in our report (2). This was because that issue of *Radiology* had not yet mailed to France at the time we submitted our study.

In his letter, Dr Hartnell insists that aortic atheroma can be easily distinguished from aortic dissection by means of cine MR imaging. Because spin-echo imaging is prone to susceptibility artifacts, in particular due to hemosiderin deposits in the case


a.

b.

(a) Oblique sagittal spin-echo MR image (repetition time msec/echo time msec = 877/26) shows a mass (arrow) projecting from the inner curve of the aortic arch into the lumen of the aorta. This was thought to represent prominent atheromatous plaque. **(b)** Cine MR angiogram (during diastole) at the same level demonstrates low signal intensity in the same mass (arrows), although on this image the mass appears to be larger than on the spin-echo image. The more extensive nature of this abnormality was confirmed by means of TEE and subsequently at surgery, which revealed a large exophytic atheromatous plaque projecting far into the aortic lumen, consistent with its appearance in **b.** It is thought that the less extensive abnormality seen in **a** is the result of susceptibility artifact due to hemosiderin in the clot attached to the surface of the plaque.