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Low-Cost MR-Compatible Moving Heart Phantom

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ABSTRACT

For the development and evaluation of cardiac magnetic resonance (MR) imaging sequences and methodologies, the availability of a periodically moving phantom to model respiratory and cardiac motion would be of substantial benefit. Given the specific physical boundary conditions in an MR environment, the choice of materials and power source of such phantoms is heavily restricted. Sophisticated commercial solutions are available; however, they are often relatively costly and user-specific modifications may not easily be implemented. We therefore sought to construct a low-cost MR-compatible motion phantom that could be easily reproduced and had design flexibility. A commercially available K'NEX construction set (Hyper Space Training Tower, K'NEX Industries, Inc., Hatfield, PA) was used to construct a periodically moving phantom head. The phantom head performs a translation with a superimposed rotation, driven by a motor over a 2-m rigid rod. To synchronize the MR data acquisition with phantom motion (without introducing radiofrequency-related image artifacts), a fiberoptic control unit generates periodic trigger pulses synchronized to the phantom motion. Total material costs of the phantom are US$ < 200.00, and a total of 80 man-hours were required to design and construct the original phantom. With schematics of the present solution, the phantom reproduction may be achieved in approximately 15 man-hours. The presented MR-compatible periodically moving phantom can easily be reproduced, and user-specific modifications may be implemented. Such an approach allows a detailed investigation of motion-related phenomena in MR images.

KEY WORDS: *Cardiac imaging; Moving phantom; MR compatibility; Phantom.*

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INTRODUCTION

For the development of cardiac specific-magnetic resonance (MR) imaging techniques, MR-compatible moving phantoms are often of great value (1–8). Periodically moving phantoms allow the investigation of motion-specific phenomena related to MR image acquisition. They have specifically proven to be highly valuable in the development and refinement of free-breathing coronary MR angiography sequences (2,3).

Unfortunately, because of the specific physical boundary conditions of the MR environment and the susceptibility of MR imaging to material or radiofrequency-related artifacts, the choice of phantom materials and driving units is heavily restricted. As a consequence, access to such phantoms may be limited and moving phantoms are not widely available in cardiac MR research centers.

Although sophisticated commercial solutions are available, they are relatively expensive, and user-specified modifications may not be easily implemented. Because of these mentioned restrictions, we sought to build a periodically moving MR-compatible phantom at low cost that allowed maximal flexibility. The result may easily be reproduced or further developed by others interested in the field.

METHODS

Requirements

For motion experiments in cardiac MR, a phantom with periodic motion patterns is needed. To synchronize data acquisition with phantom motion, a trigger pulse related to the periodic phantom motion and similar to the heart beat is necessary. All materials, including driving units and electrocardiographic (ECG) electronics, need to be MR compatible and must also not adversely interfere with MR data acquisition. Finally, the solution needs to be flexible, easily modifiable, and relatively inexpensive. Preferably, the flexibility should not require the use of sophisticated tools, specialized facilities, or machinery.

Solution

Considering these requirements, we used a retail K'NEX construction set (Hyper Space Training Tower, K'NEX Industries, Inc., Hatfield, PA) to build such a phantom. K'NEX are standardized plastic components that are readily available at retail toy vendors in the United States and around the world. The basic components consist of simple plastic elements (8 rods of varying lengths and 10 different connectors) and more sophisticated options such as gears and wheels. Thus, K'NEX allows a flexible design of moving structures. All the basic components are MR compatible.

The present solution includes a periodically moving phantom head (Figs. 1 and 2). The motion of this head consists of a translation (foot head direction) that optionally can be superimposed by a rotational (around anterior posterior axis) component (Figs. 1D and 2). The entire phantom is driven by a single K'NEX DC motor (12 V) over a 2-m-long semirigid rod composed of a series of linkages (Figs.1, A and C, and 2), and it is designed to carry multiple user-defined samples of MR-visible material (Fig. 1D). As samples, small containers (diameter, 30 mm) each filled with gelatin (Jell-O, Kraftsfood, Inc., Rye Brook, NY) and a tube (diameter, 3 mm) filled with corn oil (Mazola, CPC International, Inc., Englewood Cliffs, NJ) were used. An additional Jell-O container was attached to the trolley of the phantom head (Figs. 1D and 2), which may provide an interface for an MR navigator echo.

For the synchronization of the MR data acquisition with the motion of the phantom head, a versatile fiberoptic connection set (HFBR-0501, Hewlett Packard, Palo Alto, CA) was used (Figs. 1B, 2, and 3). A laser beam (660 nm, –23 dBm) transmitted over a plastic fiber was periodically interrupted by the translational motion (foot head or B_0 direction) of the phantom head (Fig. 2). This signal was transformed into a transistor-transistor logic (TTL) pulse on the receiver side of the electronic unit, which was galvanically separated from the transmitter part (Fig. 3). The transmitter was supplied by a 5-V transformer. The receiver was powered by three 1.5-V batteries connected in series. The generated TTL pulse was connected to the ECG interface of the scanner.

MR Phantom Studies

To test the developed solution, three different experiments were performed on a 1.5-T Gyroscan ACS-NT (Philips Medical Systems, Best, The Netherlands) commercial scanner. First, a multiple heart phase imaging sequence (two-dimensional, multislice, segmented echo planar imaging sequence with a factor of 7, 320-mm field of view [FOV], 256 × 256 image matrix, 10-mm slice thickness, flip angle 30 degrees, 20 heart phases with 100-msec intervals, TR 7 msec, TE 2.4 msec) was per-

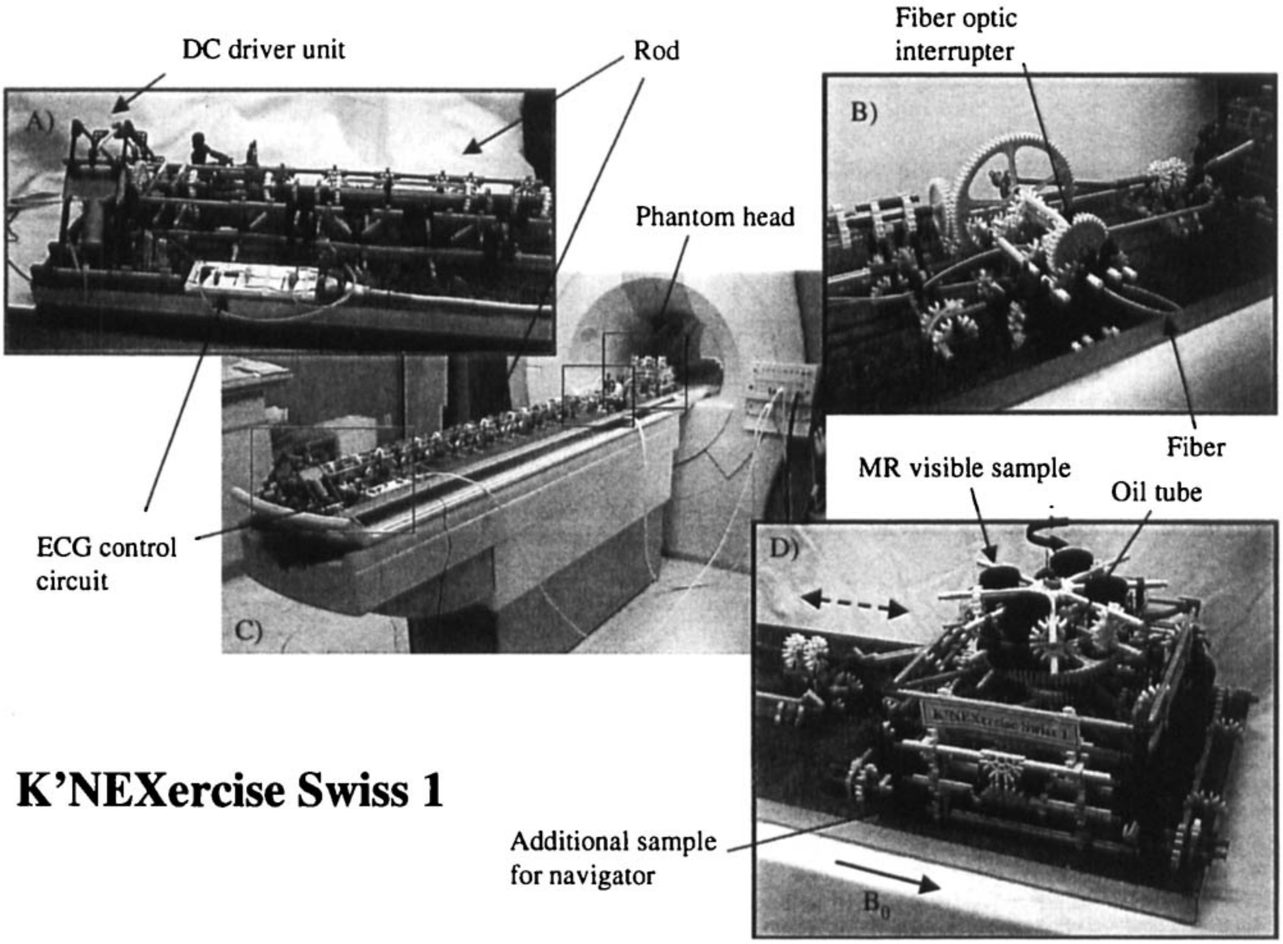

Figure 1. Moving phantom K'NEXercise Swiss 1: phantom head (C and D) with MR-visible samples (D), DC motor, and ECG control circuit (A and C), gearwheel transforming the rotation of the rigid rod into a translation of the phantom head (B). The entire construction is mounted on a flat wooden board.

formed, using the trigger generated by the phantom (Fig. 2, mode A). The four phantom head containers were loaded with Jell-O. A navigator gated scan of the motion phantom with an external trigger (Fig. 2, mode B) (two-dimensional turbo field echo sequence, 300-mm FOV, flip angle 25 degrees, trigger frequency 185 min^{-1}, TR 7 msec, TE 2.4 msec) was used to monitor the periodical translational component of the moving phantom head. To examine the utility of navigator gating at the phantom head, a navigator gated scan (two-dimensional TFE, 300-mm FOV, 256 × 256 image matrix, 4-mm slice thickness, flip angle 35 degrees, 2-mm gating window, TR 10.6 msec, TE 2.9 msec) was then compared with a nongated scan using the same sequence. Finally, to verify the MR compatibility of the present solution, two measurements of a static bottle phantom with and without running DC motor were compared.

RESULTS

The images of the multiheart phase scan demonstrate the translational and rotational movement of the phantom head (Fig. 4). Using the ECG trigger produced by the phantom (Fig. 2, mode A), we have a direct relation between the simulated heart beat and the motion of the phantom head, representing the displacement of the diaphragm.

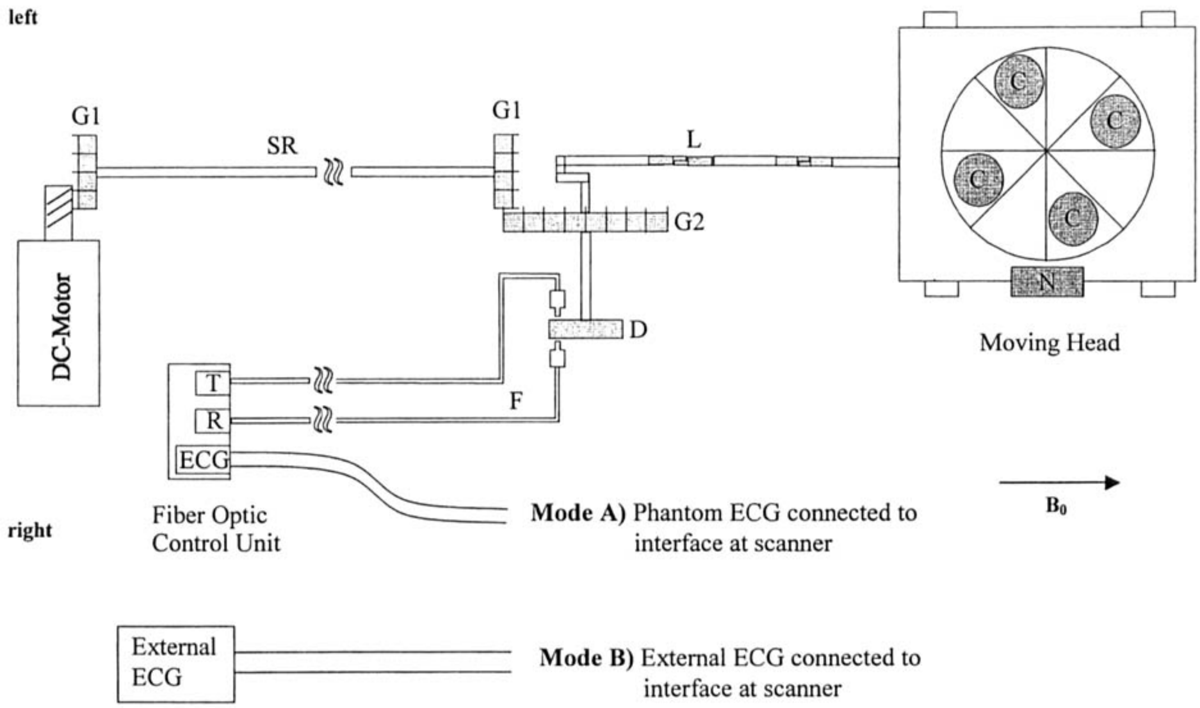

Figure 2. Schematic of the moving phantom (top view): gearwheel (G1, G2), 2-m-long semirigid rod, composed of linkages of K'NEX parts (SR), disk with hole for optical pulse (D), fiberoptical link (F), transmitter (T), receiver (R), TTL output for ECG interface (ECG), link (L), transforms the rotation of G2 into a translation. Four containers (C) filled with MR-visible material are on the rotational moving head. An additional MR-visible sample is attached to the trolley as interface for an MR navigator echo (N). On the head of the phantom, the motion pattern can be adjusted: translation or combination of translation and rotation. The moving phantom can either be used with its self-generated trigger pulse (mode A) or with an external independent ECG pulse (mode B).

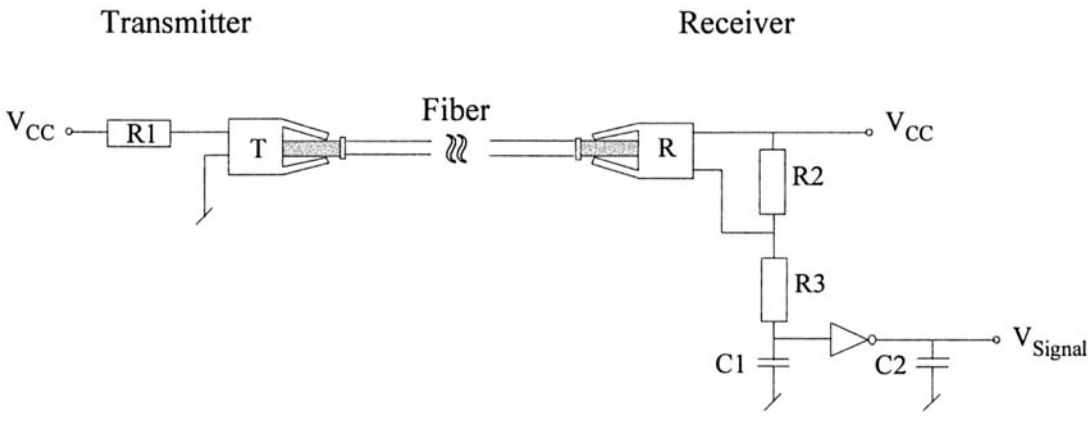

Figure 3. Control circuit schematic for fiberoptic pulse transmission. Transmitter (T): 5-V power supply (V_{CC}) by transformer. R1 = 20Ω resistance. Receiver (R): 5-V power supply (V_{CC}) by battery, R2 = 100Ω resistance, R3 = 4.7 kΩ resistance, C1 = 100 F capacitor, C2 = 0.33 F capacitor. TTL output signal (V_{Signal}) is directly fed into the MR scanner ECG interface. Note: Transmitter is galvanically separated from the TTL output signal.

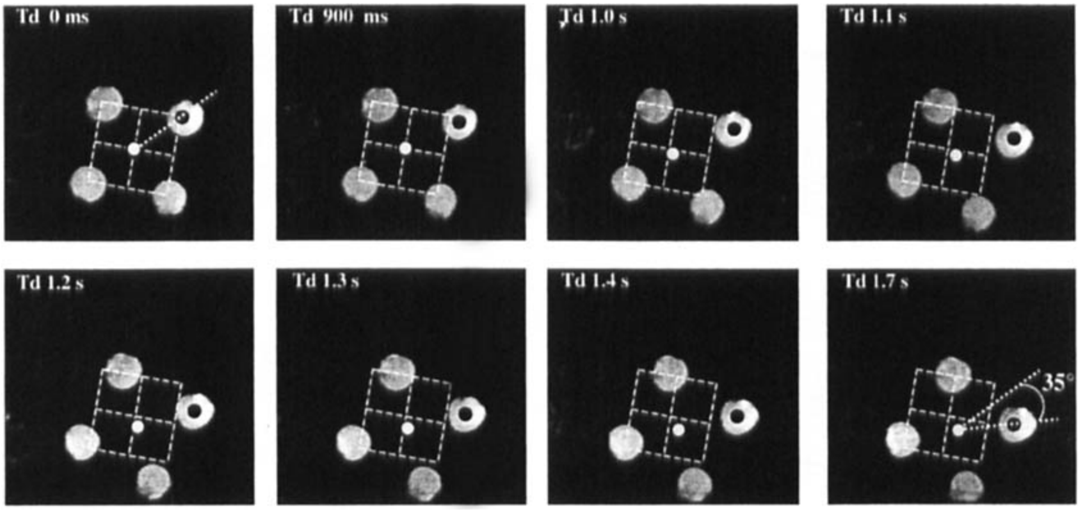

Figure 4. Motion phantom used in combination with its ECG (see Fig. 2, mode A). A multiple heart phase scan of the phantom head visualizes its translation and the superimposed rotation. The maximal rotation is 35 degrees (Td 1.7 sec).

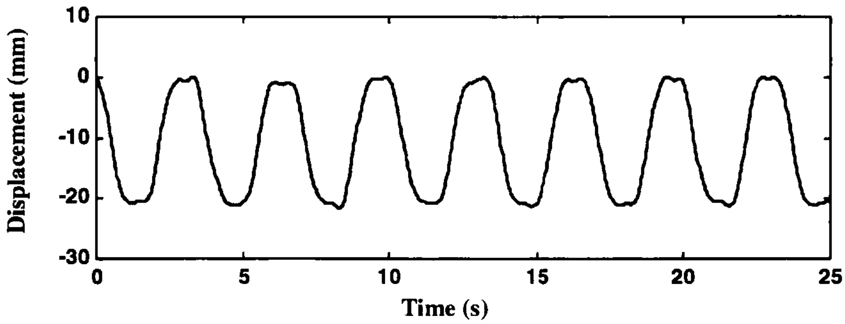

Figure 5. Navigator echo positional data regarding the translational motion of the phantom head trolley, analogous to diaphragmatic motion. The cycle length is 3.5 sec (17 min^{-1}).

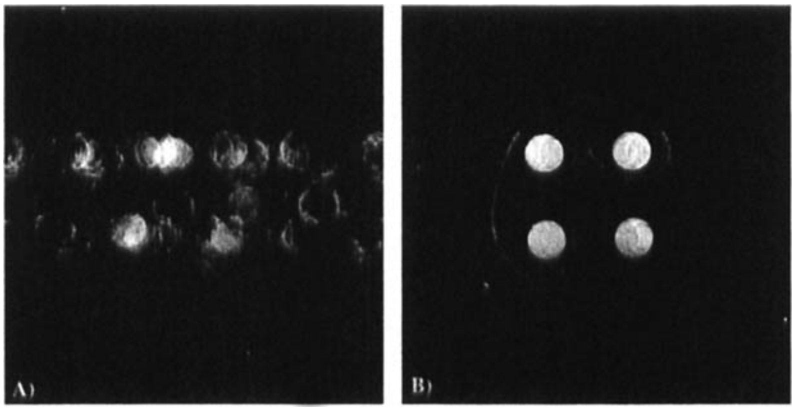

Figure 6. Image comparison of phantom head with four containers filled with Jell-O and a small tube filled with corn oil using an external ECG trigger (see Fig. 2, mode B). (A) Scan with ECG but without navigator gating. (B) Combined ECG and navigator gated scan, using a 2-mm acceptance window.

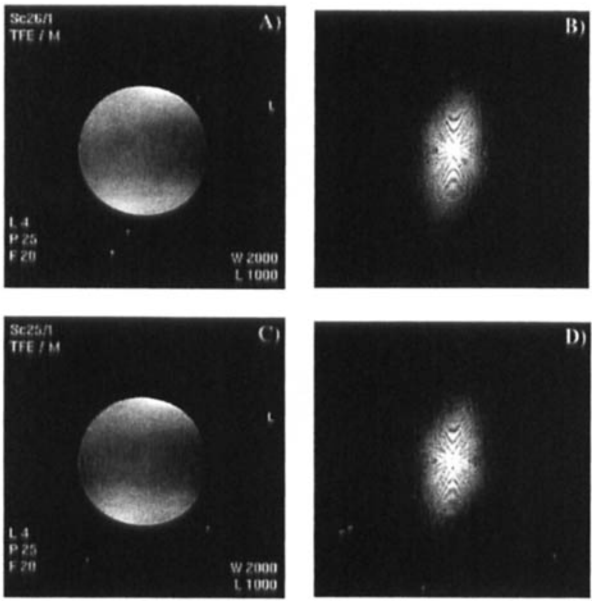

Figure 7. k-Space yields no artifacts related to the DC motor. Image (A) and k-space (B) of a circular phantom. DC motor "off." Image (C) and k-space (D) with DC motor "on."

Phantom experiments using the navigator demonstrate the periodic motion of the phantom head (Fig. 5) in a manner analogous to the diaphragm with regular respiration. The cycle length of the phantom head is approximately 3.5 seconds (RR $\cong$ 17/min) and the translational amplitude is 21 mm. The angle of the superimposed head rotation is 35 degrees (Fig. 4).

By applying an external ECG trigger (Fig. 2, mode B), the trigger pulse (ECG) and navigator echo (respiration) can be decoupled, which allows the motion phantom to be used for experiments with navigator gated ECG-triggered sequences (Fig. 6). In the absence of navigator gating (Fig. 6A), data acquisition is only synchronized to the external trigger but not to the position of the phantom head. In the navigator gated scan, the trigger pulse allows data acquisition if the measured navigator echo (reflecting the position of the moving head) is within the predefined 2-mm gating window (Fig. 6B). All measurements with the moving phantom yielded neither DC motor-related artifacts in the images nor artifacts induced by the fiberoptic control unit (Fig. 7).

Total retail material costs of the phantom are US$ < 200.00, and a total of 80 man-hours were required to design and construct the phantom. With schematics presented of the solution, a reproduction of the moving phantom may be achieved in 15 man-hours.

DISCUSSION

In this study we report on a low-cost, flexible, and easily modifiable MR-compatible moving phantom that allows detailed investigations of motion phenomena as might be anticipated with respiratory and cardiac motion. This includes intrinsic cardiac motion related to a cardiac contraction and extrinsic bulk motion due to respiration/diaphragmatic motion. The present solution may easily be reproduced or further modified or adapted at minimal expense and inconvenience. The materials are fully MR compatible, and no artifacts in the images are introduced by the DC motor or the optical ECG unit.

The phantom can be used either in combination with navigator gated and/or ECG-triggered sequences, which makes it valuable for navigator gated sequences and for real-time applications. The motion of the phantom consists of a translation and an optional rotation. With the help of a computer-controlled step motor, the range of possible motion patterns could be further extended. A potentially desirable extension of the present solution may include the addition of motion in the third dimension.

Loading the phantom head with multiple MR-visible samples of varying diameters may facilitate the assessment of motion or motion compensating techniques. Spatial resolution of small vessels, such as coronaries in an MR angiography, may also be studied.

A limitation of the current phantom description is the fixed relation between the translation (breathing) of the phantom trolley and its superimposed rotation (cardiac motion). For a more varied modeling of respiratory motion and independent cardiac contraction, an additional driving unit could be implemented that independently moves the entire phantom construction back and forth (translation), thereby simulating the extrinsic motion of the breathing. This translation would simulate the extrinsic motion of normal respiration. This extrinsic translational motion could also be simulated by applying the breathing pattern to the patient table of the scanner. Access to such a low-cost flexible moving phantom should allow improved development of MR methods and approaches for motion compensation.

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