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The Clinical Potential of Ultra-High-Speed Echo-Planar Imaging [and Discussion]

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The clinical potential of ultra-high-speed echo-planar imaging

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Ultra-high-speed echo-planar imaging (EPI) allows acquisition of a complete two-dimensional image in 64 to 128 ms devoid of movement artefact and without sacrifice of contrast due to relaxation time effects. In conventional whole-body MRI, however, obtrusive movement artefact and extended imaging time, resulting from the need to apply multiple sequences to facilitate lesion detection and pathological characterization, remain limitations. Reduced total examination time increases patient tolerance and throughput; furthermore optimization of contrast to achieve maximal conspicuity of particular features in liver or brain pathology is achieved simply and interactively by real time adjustment of the imaging parameters. The method provides the opportunity to study in real time dynamic events such as flow phenomena in the vascular and cerebrospinal fluid compartments of the brain as well as the kinetics of administered contrast agents. EPI is the only means of capturing the irregular motion of aperiodic cardiac events and bowel peristalsis.

Magnetic resonance

Conventional (MR) imaging methods typically take several minutes to acquire each set of images so that a complete examination, which may require the application of several pulse sequences and assessment in more than one plane, can take as long as an hour to complete. Because conventional whole-body MR imaging is relatively slow a variety of methods have been required to minimize the obtrusive artefacts which arise from involuntary movement of body organs. In cardiac imaging for example ECG gating has been used to eliminate motional blur but this extends the imaging time and is inapplicable in the presence of arrhythmias. Ultra-high-speed echo-planar imaging (EPI) produces snapshot images and reduces the total examination time, typically to the order of a few minutes thereby facilitating more rapid patient throughput and better patient tolerance. It eliminates the requirement for preliminary sedation of children. Furthermore this totally non-invasive method provides for the first time, the opportunity to study in real time dynamic phenomena such as flow in the vascular and cerebrospinal fluid compartments of the brain as well as the kinetics of administered contrast agents. For aperiodic cardiac studies and the assessment of peristaltic activity in the bowel ultra-high-speed methods provide the only means of capturing such irregular motion.

Method

Ultra-high-speed EPI and the several variants which have been developed allow acquisition of a complete two-dimensional image in 64–128 ms devoid of movement

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artefact and without any sacrifice of contrast due to relaxation time effects. A full description of the principles underlying EPI as well as technical details of the system will be found in the appended references (Mansfield 1977, 1988; Mansfield & Morris 1982; Howseman *et al.* 1988) and in a prior paper at this meeting.

The brief account which follows relates only to the choice of imaging parameters and their influence on contrast within the resulting images. Imaging is carried out on a 0.52 T machine using a low inductance actively screened coil system and good quality images with a matrix size of 128 × 128 and a thickness of 5–10 mm are obtained without the requirement for signal averaging. T_2 weighted images are obtained by two adaptations of EPI, the blipped echo-planar single-pulse technique (BEST) and modulus (MBEST) as well as the standard techniques. A choice of T_2 weighting in BEST and standard EP images is obtained by adjusting the value of T_E. Modulus EP images including MBEST have a high intrinsic T_2 weighting (Ordidge *et al.* 1988).

The introduction of T_1 weighting into the images produced by EP techniques is obtained either by adjustments in the value of the repetition time T_R in a saturation recovery sequence or by an inversion recovery process in which T_I is varied. In conventional two-dimensional FT imaging to capitalize on the wider range of T_1 contrast which can be achieved using an inversion recovery sequence compared to a T_1-weighted spin-echo sequence it is necessary to use a relatively long T_R which extends the imaging time. By means of a preceding 180° spin inversion pulse inversion recovery can be prefixed to the basic EPI experiment so that their respective advantages of a wide range of T_1-dependent contrast and ultra high speed are both retained in a single technique. In conventional MRI the choice of a single inversion time inevitably means that the resulting image is a compromise in providing optimal contrast between a given pathology and the normal tissue of the host organ; information on any surrounding reaction or details of any internal structure. When using the IR variant of EPI, however, optimization of contrast within the resulting images to achieve maximal conspicuity of particular features can be achieved simply and interactively by real time adjustment of the inversion time between a range of 4 ms and 9000 ms.

Chemical selection is used routinely in whole-body EPI studies (Ordidge *et al.* 1989). Excellent fat and water separated images can be achieved and the latter have been particularly useful in studying peristaltic activity in the upper bowel using water as a contrast agent.

Clinical studies

The brain

There is now general agreement that MRI has advanced to a degree that if access to it were readily available it would be the preferred initial investigation for almost all types of intracranial pathology. Its ability to depict the anatomy of the nervous system in most of the potential applications now equals or exceeds that of computed tomography and many studies have shown a clear superiority in the detection of alterations in tissue composition produced by disease particularly in the posterior fossa; it is not, however, always more specific. The problem of separating tumours from surrounding oedema (Brant-Zawadski *et al.* 1984) and the difficulty in detecting small meningiomas (Bradley *et al.* 1984) represented severe limitations to the acceptance of the method but these were overcome with the introduction of the

Figure 1

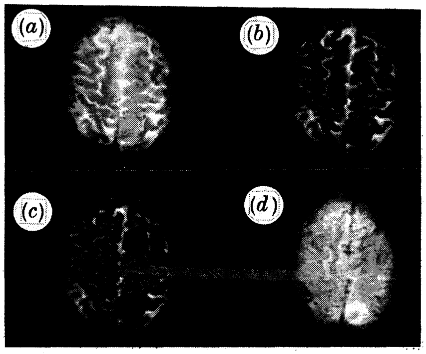

Figure 2

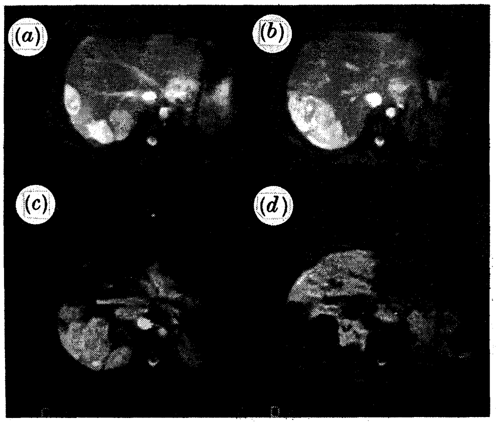

Figure 1. Four transverse axial snapshot IR EPI images at the same level in a patient with a right parasagittal meningioma showing how the conspicuity of the tumour against the adjacent brain and cerebrospinal fluid within the cortical sulci changes with alteration of the inversion time (*a*) 12 ms, (*b*) 50 ms, (*c*) 200 ms, (*d*) 3.7 s.

Figure 2. Transverse axial images through the liver of a patient with multiple hydatid cysts. MBEST images at two different levels (*a*, *b*) showing multiple cysts in the right lobe. IR EPI images at the same level with inversion times of (*c*) 180 ms, (*d*) 760 ms showing selective highlighting of the cysts and residual normal liver tissue respectively.

intravascular contrast agent Gadolinium DTPA whose mechanism of action has been extensively reviewed (Gadian *et al.* 1985).

Experience with EPI in normal volunteers and in patients with a wide range of intracranial pathology has shown that the range of T_1- and T_2-dependent contrast which is available allows excellent discrimination between grey and white matter and between the brain and cerebrospinal fluid within the ventricles and basal cisterns. Snapshot images have demonstrated an achievable resolution of better than 2 mm which has permitted excellent delineation of pathology including tiny plaques of demyelination in multiple sclerosis (Worthington & Mansfield 1990).

In the analysis of pathological appearances in the brain careful scrutiny of the altered tissue density and texture is required taking account of the pulse sequence used. Important information is also obtained from a study of the zone of transition between the abnormality and the normal brain.

Experience has shown that no single-pulse sequence is ever optimal for providing the best delineation of all the components of a complex lesion such as a necrotic tumour containing haemorrhage which is surrounded by a zone of oedema. The facility to alter the imaging parameters in real time is a valuable facility in EPI because it permits the radiologist to optimize the image to maximize the visibility of several features. Furthermore by obtaining a data-set encompassing a wide range of T_1- and T_2-dependent contrast it minimizes the possibility of overlooking a significant lesion (figure 1).

Conventional MRI like computed tomography can provide valuable morphological information about the ventricular system and the cerebrospinal fluid (CSF) spaces outside the brain which is of value is establishing the type and cause of hydrocephalus. With EPI there is the additional advantage of being able to study the dynamics of CSF flow in real time and capture moment to moment changes some of which may be lost in methods based on averaging of data acquired by cardiac gating. Observations have already been made in normal subjects and a number of pathological conditions and have been shown the potential of the method for qualitative and quantitative assessment of CSF dynamics (Stehling *et al.* 1990*a*).

The heart and great vessels

The excellent spatial resolution over a wide field of view, lack of planar restriction and inherent contrast between the blood pool and vascular wall are attributes which commend MR as an attractive method for imaging the heart and great vessels. The problem of image degradation due to heart motion and the requirement for improved temporal resolution to study dynamic events have been major obstacles to progress. The application of cardiac gating techniques has been one approach to overcome these difficulties but results in an extended imaging time and is unsatisfactory in the presence of a severe arrhythmia which is a frequent occurrence in patients with advanced cardiac disease.

EPI can produce high-quality single-shot images of the heart and great vessels in a fraction of a second which are free of motion artefact (Doyle *et al.* 1986; Stehling *et al.* 1987). Movie loops can be acquired with over 16 consecutive cardiac cycles with triggered image acquisition, or during a single cardiac cycle with ultra fast image acquisition of up to 20 frames per second using low flip angle pulses (Chapman *et al.* 1987). Movie loops derived from a single cardiac cycle permit study of cardiac morphology and function even in the face of a severe arrhythmia. EPI allows the assessment of chamber size and morphology and from contiguous sections their continuity and connections can be readily achieved. This is of particular importance in defining the abnormal anatomy in congenital heart disease (Chrispin *et al.* 1986). EPI has important advantages over echocardiography in better displaying the great vessels and their connections. Movie loops provide functional data on wall thickness and movement. The assessment of left ventricular systolic wall thickening is an excellent index of regional function and areas of dyskinesia can be readily identified. From the changing dimensions during each cardiac cycle ventricular ejection fractions can be estimated.

Complex flow patterns exist within the heart and great vessels whose precise pattern changes from one cardiac cycle to the next. EPI permits a moment to moment analysis of these both in the normal subject and in pathological conditions. The high signal returned from blood in MBEST images is relatively insensitive to in-plane laminar flow whereas turbulent flow such as that caused by valvular stenosis or regurgitation produces intra voxel spin dephasing with consequent signal attenuation which is seen as a dark void in the image.

The liver and gastrointestinal tract

The principal limitations of conventional MRI of the liver are the occurrence of obtrusive movement artefacts and the extended imaging times resulting from the need to apply multiple-pulse sequences to maximize lesion detection and facilitate pathological characterization. The prolonged relaxation times associated with neoplastic tissue compared with the relatively short T_1 and T_2 values of normal liver indicate the potential for pronounced tissue contrast. Careful work in pulse sequence optimization at mid field has shown that short T_R, short T_E T_1-weighted spin-echo sequences have the highest sensitivity in the detection of pathology; T_2-weighted sequences are also necessary to assist in tissue characterization (Stark *et al.* 1986).

The origin of motion artefacts in liver imaging is now well understood and although a number of gating techniques and software programs to compensate for movement have been developed these approaches are being superseded by the application of faster imaging régimes.

EPI produces high quality transverse axial images of the liver devoid of motion artefact and studies from patients with a wide range of pathology have shown the value of both T_2-weighted and T_1-weighted images. In the latter interactive optimization of the pulse sequence to highlight both normal liver and pathological tissue was of particular value (Worthington *et al.* 1988) and an example is shown in figure 2.

Because of the heavy T_2 weighting of MBEST images ordinary water with its long T_2 relaxation time is a suitable contrast agent for studies of gastrointestinal motility. Serial acquisition of images in the same plane during breatholding at a rate of 3 frames per second with the machine running in a free-run mode allows assessment of the frequency and wave velocity of peristaltic activity in the small bowel (Stehling *et al.* 1989*a*). The time interval between consecutive states of maximum relaxation in the same loop of small bowel was 9 s giving a frequency of peristaltic waves of approximately 6 min^{-1}. The propulsion velocity of a bolus through a segment of small bowel was found to be 40 cm min^{-1}. Transverse axial sections through the upper abdomen allow similar observations to be made in the stomach and duodenal cap (figure 3). The frequency of antral peristalsis was found to be 2.2 contractions per minute after eating a light meal with a wave velocity of 8.64 cm min^{-1}.

These results are in close agreement with manometric studies of gastric activity in individuals after a recent meal. Because it is completely non-invasive and unassociated with any known biological hazard EPI can be used in repeated and extended studies to assess the effect of drugs on bowel motility and the alteration of bowel activity in a variety of diseases.

Abnormal pregnancy

On heavily T_2-weighted MBEST images the placenta, umbilical cord and surface features of the fetus are well depicted contrasted against the high signal of the amniotic fluid (Stehling *et al.* 1990*a*). Selective imaging of water protons in MBEST eliminates the signal from the subcutaneous fat which appears as a dark black band around the fetal body and limbs. The availability of a method for reliably estimating the amount of fetal fat may mean that growth retardation will come to be better assessed by MRI than by ultrasound. In the thorax the lungs which show a high signal intensity are contrasted against the heart where the changing blood flow pattern has been observed on segmental imaging of a four chamber view. Maturation of the lung commences around 24 weeks gestation and as it develops there is an increase in water content and a rise in phospholipid concentration related to surfactant production (Thieme *et al.* 1983).

Respiratory distress syndrome secondary to pulmonary immaturity is a major cause of morbidity in premature infants. The most sensitive indicator of pulmonary maturity is the lecithin sphingomyelin ratio in the fluid obtained by amniocentesis (Hallman & Terano 1971). If MRI could be harnessed in any way to provide an indicator of lung maturity this would be a significant development.

All the major abdominal organs are well seen with structural detail apparent in the liver and kidneys (figure 4). In the limbs the diaphysis and epiphysis of long bones are noted in addition to soft tissue detail. The clear depiction of disorganised

Figure 3

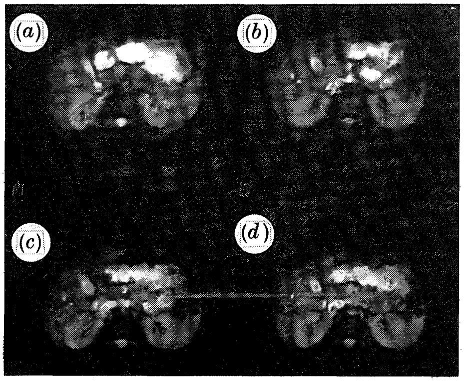

Figure 4

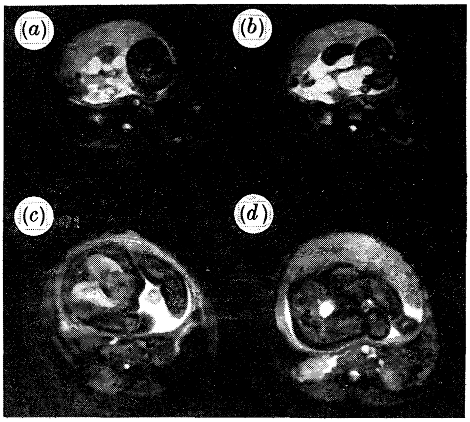

Figure 3. A sequence of MBEST transverse axial images through the upper abdomen of a volunteer (from a 32 frame data-set) taken at 3 s intervals 40 min after the injection of 10 mg of metoclopramide. Vigorous antroduodenal peristalsis has been produced accompanied by emptying of the stomach contents. (From Stehling *et al.* 1989*a*.)

Figure 4. EPI MR images through the fetus *in utero* at 36 weeks gestation. (*a*) and (*b*) show a gastroschisis with the displaced fetal intestine within the amniotic fluid and a cleft in the anterior abdominal wall. (*c*) Section through the normal thorax showing the heart and fluid filled fetal lungs, (*d*) section through the normal pelvis showing the fetal bladder and lower limbs.

anatomy in a fetus with a gastroschisis (figure 4) illustrates the potential of EPI to compliment ultrasound in the evaluation of fetal abnormalities. The cleft in the anterior abdominal wall is shown with the consequent intra-abdominal amniotic fluid collection and loops of prolapsed bowel floating in the amniotic cavity.

It is unlikely that EPI will replace ultrasound for the assessment of fetal anatomy; none the less it could become a useful ancillary technique to resolve specific problems where information is ambiguous or incomplete especially when tissue characterization or assessment of organ volume is required (Stehling *et al.* 1989*b*).

Concluding remarks

The stimulus for the development of high-speed EPI was a realization of the need to reduce and if possible eliminate obtrusive artefacts deriving from involuntary body motion. An important consequential benefit has been an enhanced patient throughput and removal of any requirement for sedation or anaesthesia. In all the areas where it has been applied EPI has provided diagnostic images with an acceptable spatial resolution and just as importantly, without any trade-off of contrast discrimination for speed. At the present level of development high quality images at 0.52 T have shown an achievable resolution of better than 2 mm. Furthermore a range of spin sequences is available which permit the introduction of differing degrees of T_1 and T_2 weighting while retaining the inherent high-speed capability.

A multislice adaptation of the method would permit the generation of a complete 16-plane three-dimensional data-set in *ca.* 2 s.

It has become apparent that MRI is a valuable tool for addressing fundamental questions relating to the pathophysiology of a range of human disorders. In this respect, the additional benefits of EPI which are not available in conventional magnetic resonance images such as the ability to study dynamic events occurring in body organs (in real time) place a premium on the technique.

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Discussion

I. R. YOUNG (*Hammersmith Hospital, London, U.K.*). I have read descriptions of CSF dynamics studies since Bill Bradley's first description of its visualization by MRI in, I believe, 1983 or 1984. As yet I have yet to hear of any direct application to the improvement of patient management arising from this work. How will patients benefit?

B. S. WORTHINGTON. It has become increasingly apparent that MRI can contribute to our understanding of normal physiology and also pathophysiology of many intracranial disorders. Magnetic resonance studies have largely confirmed the existence in the normal subject of a third ventricular pump which is secondary to cardiac-dependent cerebral perfusion. Bradley has shown that assessment of the rate of flow within the midline ventricular system can be used to distinguish between different groups of hydrocephalus and most importantly, achieve a separation between normal pressure hydrocephalus, which responds well to treatment with a shunt, and cerebral atrophy which does not. The pathogenesis of syringohydromyelia is incompletely understood, but studies of CSF dynamics such as those I showed earlier by EPI will hopefully provide further insight that will lead to more effective management and better prediction of response to treatment. In patients with narrowing of the CSF spaces around the spinal cord in the cervical region, which can result from a variety of causes, CSF pulsation may be reduced or may be absent, and this has been shown to be a useful indicator of significant compression.

Figure 1

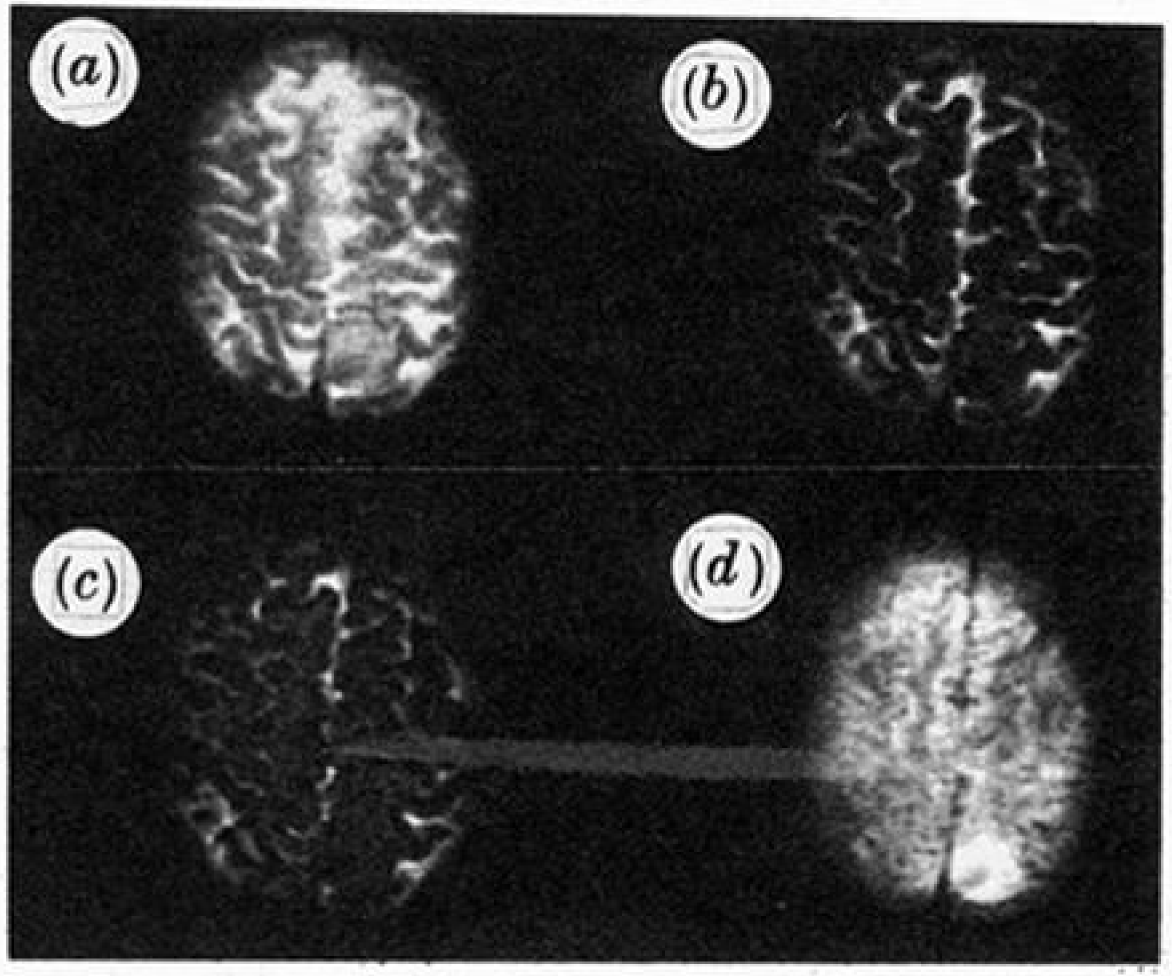
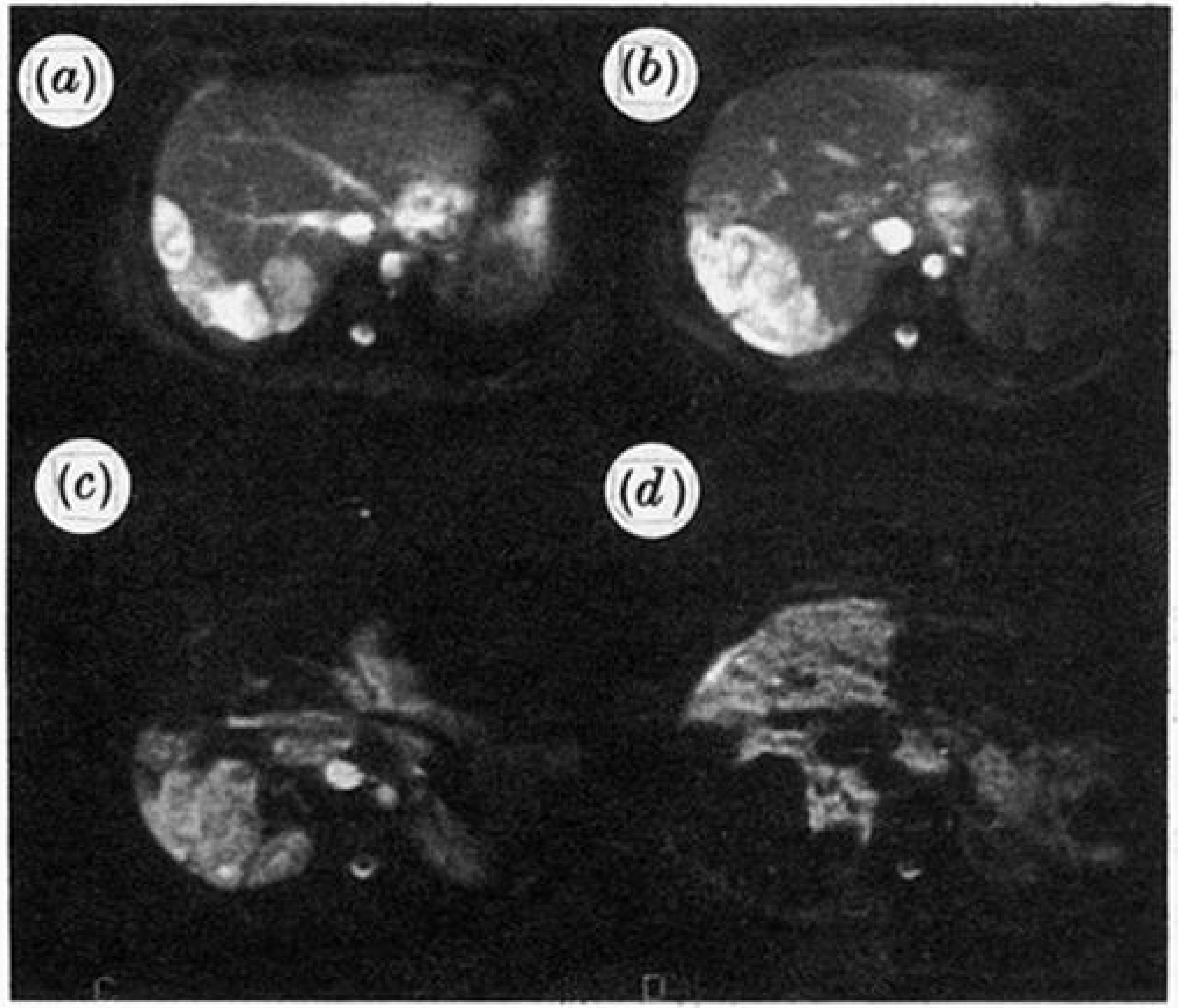


Figure 2



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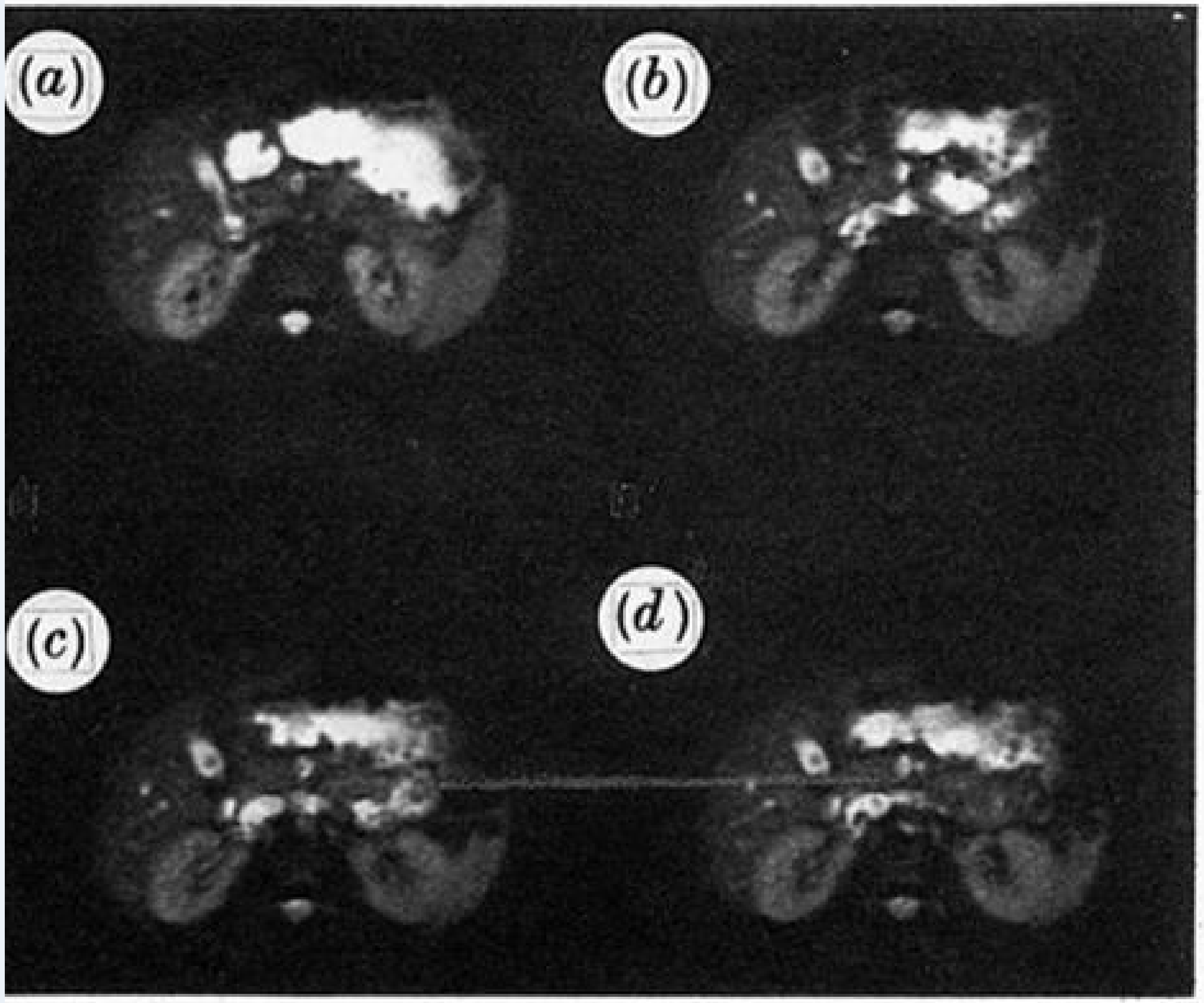
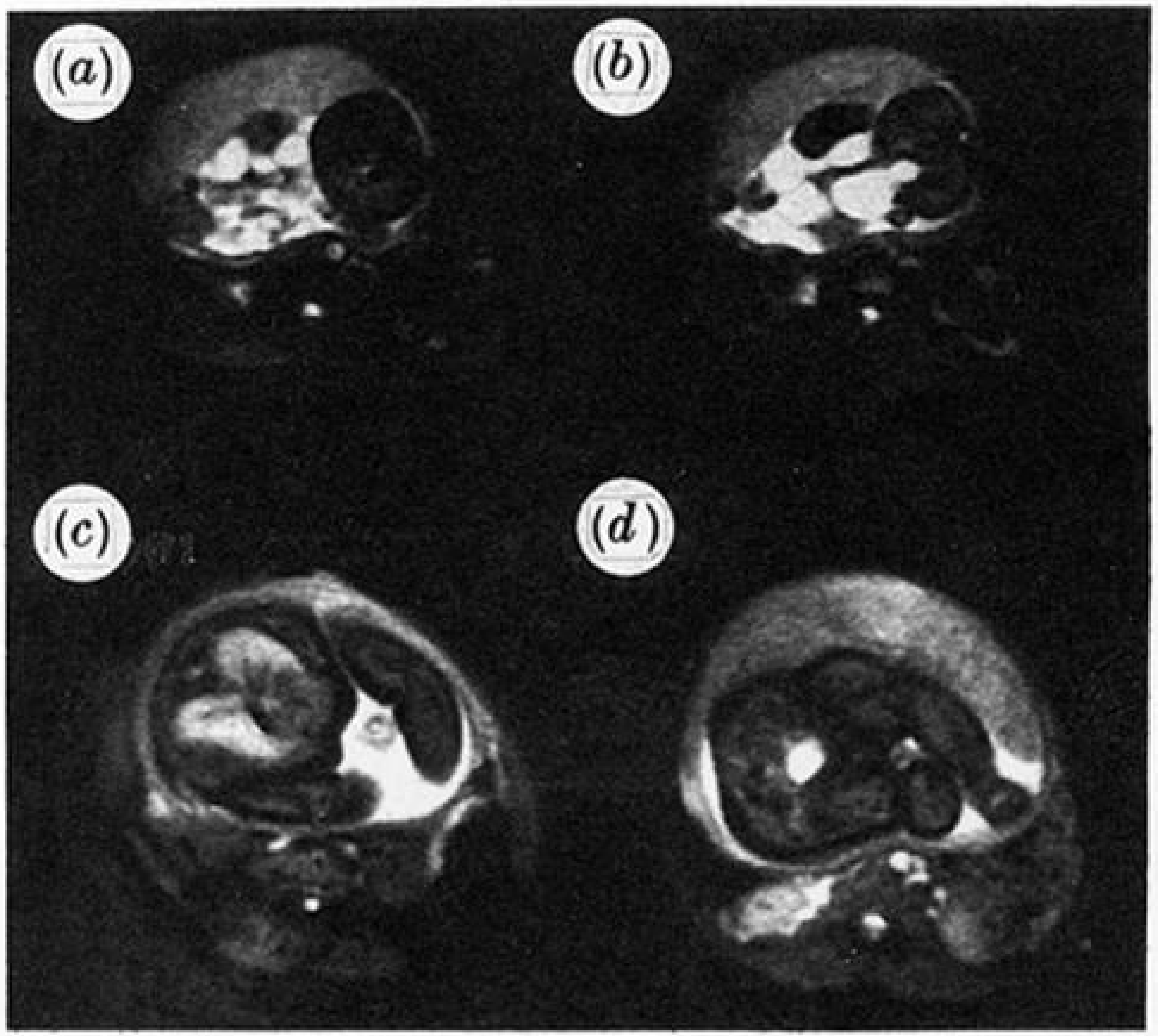


Figure 4



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