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Original paper

Towards radiological diagnosis of abdominal adhesions based on motion signatures derived from sequences of cine-MRI images

John Fenner [a,*], Benjamin Wright [a], Jonathan Emberey [a], Paul Spencer [b], Richard Gillott [b], Angela Summers [c], Charles Hutchinson [d], Pat Lawford [a], Paul Brenchley [c], Karna Dev Bardhan [b]

[a] Medical Physics Group, Dept of Cardiovascular Science, University of Sheffield, Beech Hill Road, Sheffield, Sth Yorks. S10 2RX, UK
[b] The Rotherham NHS Foundation Trust, Rotherham Hospital, Moorgate Road, Rotherham S60 2UD, UK
[c] Renal Research Labs, University Dept of Medicine, Manchester Royal Infirmary, Manchester M13 9WL, UK
[d] University of Warwick, Health Sciences, Clifford Bridge Road, Coventry CV2 2DX, UK

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A B S T R A C T

This paper reports novel development and preliminary application of an image registration technique for diagnosis of abdominal adhesions imaged with cine-MRI (cMRI). Adhesions can severely compromise the movement and physiological function of the abdominal contents, and their presence is difficult to detect. The image registration approach presented here is designed to expose anomalies in movement of the abdominal organs, providing a movement signature that is indicative of underlying structural abnormalities. Validation of the technique was performed using structurally based *in vitro* and *in silico* models, supported with Receiver Operating Characteristic (ROC) methods. For the more challenging cases presented to the small cohort of 4 observers, the AUC (area under curve) improved from a mean value of 0.67 ± 0.02 (without image registration assistance) to a value of 0.87 ± 0.02 when image registration support was included. Also, in these cases, a reduction in time to diagnosis was observed, decreasing by between 20% and 50%. These results provided sufficient confidence to apply the image registration diagnostic protocol to sample magnetic resonance imaging data from healthy volunteers as well as a patient suffering from encapsulating peritoneal sclerosis (an extreme form of adhesions) where immobilization of the gut by cocooning of the small bowel is observed. The results as a whole support the hypothesis that movement analysis using image registration offers a possible method for detecting underlying structural anomalies and encourages further investigation.

Introduction

The challenge of diagnosing particular abdominal abnormalities from moving images, supported by analysis using image registration, is the focus of this article. Our interest is the abdominal cavity, which through injury can manifest adhesions. Adhesions can be likened to “internal scars”. Sometimes congenital, the majority follow infection, injury (after abdominal operations) or intestinal disease (e.g. Crohn’s). The adhesions can resemble a rope, multiple strands of varying thickness or a mesh, tethering together abdominal organs, or an organ to the abdominal wall. They may present in a broad spectrum of forms, from minor irritation to the lethal cocooning of the abdominal contents characteristic of Encapsulating Peritoneal Sclerosis (EPS) [1–4]. It is only when adhesions obstruct the intestine and require surgery that the diagnosis becomes clear; in all other instances adhesions as a cause of recurrent or continuing abdominal pain remains a possibility.

Non-invasive methods of detecting abdominal adhesions are strongly preferred, which is the rationale for the deployment of minimally invasive imaging methods for diagnosis, but this is acknowledged to be very challenging. In the domain of diagnostic imaging, plane film radiography and fluoroscopy are increasingly being replaced by more powerful techniques [5,6] – the use of CT is widely cited [7–11]. However, reliable methods for diagnosis remain illusive. The roles of Ultrasound and Magnetic Resonance Imaging are acknowledged in certain circumstances [6,12–15] and their non-invasive/non-ionising characteristics make them appealing. Recommended practice is to study the movement of the abdominal contents (sometimes enhanced with the use of a contrast medium) and infer the presence of adhesions from the disruptions that might be introduced to the patterns of movement

* Corresponding author. Tel.: +44 (0)114 271 3687.
E-mail address: j.w.fenner@sheffield.ac.uk (J. Fenner).

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[14–17]. The diagnostic reporting of scans can be time consuming for the radiologist (since the process involves the analysis of many images), so the technique is not without cost-benefit implications. Nonetheless its diagnostic value appears beyond reproach in the hands of a specialist [14], but arguably this deserves qualification since diagnosis by such methods may only be tractable in advanced stages of disease [12].

We exploit image registration as a tool to quantify anatomical movement within diagnostic sequences of images and hypothesise that movement anomalies are diagnostic of abnormalities in underlying physical structures (e.g. adhesions). We postulate that this may support disease localisation and accelerate diagnosis. This was explored using a variety of models (*in vitro*, *in silico*) and the outcomes quantitatively evaluated. Ultimately this led to application in a clinical example, and results are presented.

The participants supporting the development of this technique covered a wide range of experience and expertise, with early trials involving clinicians (radiologists, gastroenterologists, surgeons) as well as more technical participants from medical physics/imaging backgrounds. The models presented here tend to have an abdominal bias because our interest is the motion of abdominal anatomy for detection of adhesions, but this is not inherent to the method. It can readily be extended to other domains. This paper describes development of techniques that were used to explore issues relevant to the hypothesis, ultimately yielding a proof-of-concept tool that demonstrates potential in clinical practice.

Materials and methods

The diagnostic technique presented here [18] relies on image processing support to aid the tracking of characteristic features within a temporal sequence of images. Initially a simulated environment was constructed to emulate the diagnostic challenge and exercise the software algorithms. This was a vehicle for training the user and developing/quantifying the image processing aid. This was followed by a progression of increasingly demanding diagnostic scenarios, eventually leading to application in a clinical example. The sequence of technical developments is reported below.

Experiment 1: a physical model and a preliminary qualitative study

As with many dynamic, diagnostic imaging sequences, diagnosis of adhesions requires interpretation of motions captured in a 2D plane, and our interest is identification of subtle changes to that movement (introduced by small defects) that may be masked by the complexities of the anatomical image. Hence a simple test environment was constructed for proof of concept purposes, built around a 2D mechanical analogue (see Fig. 1), designed to encapsulate the principles of diagnosis through identification of disturbed movement. It also loosely acknowledges the displacement of the diaphragm at the periphery of the abdominal cavity. The observer was required to infer the presence of an underlying structural abnormality, diagnosed from anomalous movement of an overlying image. Performance with and without image processing permitted the relative effectiveness of the image processing support to be assessed.

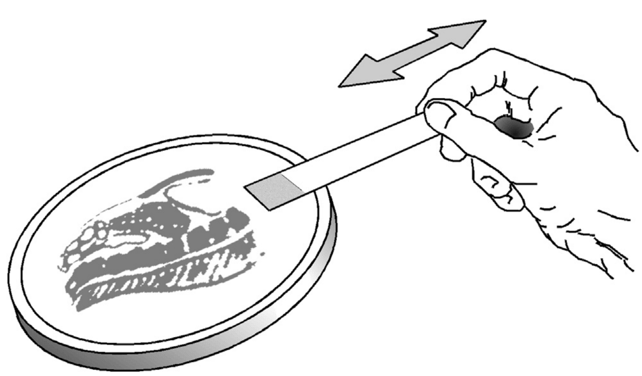

Figure 1. Physical test rig: An image was drawn onto an elastic sheet. This was tensioned over a circular frame, and distorted by pulling an attached piece of tape.

Physical model

The physical model employed an opaque and lightly tensioned elastic sheet overlaid on a sewing ring of 15 cm diameter, with an image drawn on its surface (Fig. 1). The end of a length of tape was attached near the periphery, which could be pulled to deform the sheet. A rig was constructed to enable repeated pulling and relaxation (~1 Hz) of the diaphragmatic region of the image, causing movement that distorted all parts of the image in a reproducible manner. The whole cycle was captured as a digital video using a camera operating at 15 fps, providing a baseline animation that represented 'normal' movement. In order to introduce subtle, localised disturbance to the motion, a small, square, inelastic sticky sheet (1 cm^2) was securely attached near the centre of the image on the reverse side of the elastic material that was fixed to the sewing ring (i.e. it was invisible to the camera). Therefore, when the tensioning tape was pulled to distort the elastic image within the sewing ring, the inelastic defect suffered a displacement but moderated the local elastic strain (and the implicit motion of the overlying image). The stretching cycle was again captured as a digital animation. An observer was blinded to the presence/absence of the defect, so that when presented with the video footage, he/she was required to analyse it to…

- Identify if the motion of the image was 'normal' (no defect present) or 'abnormal' (sticky tape defect present)
- Localise the defect in those cases in which it was judged to be present.

The inelastic tape responsible for the defect could be placed in different locations to generate a gamut of movement restrictions. Analysis of the video images by the observer was performed with and without image processing assistance to ascertain its effectiveness in assisting with the identification of subtle disturbances concealed within the movements of the image. Two levels of image complexity were employed separately in this experiment, the first utilising a simple image (square grid) and the second, a cartoon representation of a sagittal abdominal MRI slice (medium complexity image – Fig. 2).

Image processing

Our image processing methodology used the registration technique developed by Barber and Hose [19], which computes a mathematical transformation (non-affine) that maps a reference image to another similar image. This is ideal for quantifying movement within a collection of similar images that constitute a dynamic sequence. The mapping has its basis in a numerical variational methodology that computes a continuous vector field. This describes the local displacement needed to map every visual structure in a source image to an equivalent visual structure in a target image. Subsequent analysis of the vector field and appropriate visualisation can reveal the motion of the visual structures contained within the field of view, and yield characteristic signatures that are indicative of perturbations to that movement. Our preferred method of visualisation reduces the vector data to contour maps of vector magnitude (see Fig. 2). Numerous other data presentation strategies are possible, but our chosen method was