Medical Image Analysis 33 (2016) 50–55

Contents lists available at ScienceDirect

Medical Image Analysis

journal homepage: www.elsevier.com/locate/media

Editorial

From clinical imaging and computational models to personalised medicine and image guided interventions

David J. Hawkes*

Centre for Medical Image Computing, UCL, London, UK, WC1E 6BT, United Kingdom

ARTICLE INFO

Article history:
Received 13 April 2016
Revised 10 June 2016
Accepted 15 June 2016
Available online 29 June 2016

Keywords:
Medical image analysis
Image registration
Image guided interventions

ABSTRACT

This short paper describes the development of the UCL Centre for Medical Image Computing (CMIC) from 2006 to 2016, together with reference to historical developments of the Computational Imaging sciences Group (CISG) at Guy's Hospital. Key early work in automated image registration led to developments in image guided surgery and improved cancer diagnosis and therapy. The work is illustrated with examples from neurosurgery, laparoscopic liver and gastric surgery, diagnosis and treatment of prostate cancer and breast cancer, and image guided radiotherapy for lung cancer.

1. A brief history of quantitative medical imaging, some personal observations

Digital medical imaging has transformed medicine in the last 40 years. The 3D imaging methods CT, PET and SPECT were invented just over 40 years ago, MRI about a decade later. CT, in particular, had an immediate and dramatic impact on healthcare with rapid and widespread adoption in less than a decade. I was fortunate to be part of that pioneering work, undertaking my PhD on one of the first whole body CT scanners (EMI–CT5005) at the Royal Marsden Hospital, London, UK (Husband et al., 1982). My 10 years in hospital based clinical nuclear medicine coincided with the introduction of computerised analysis of time series of images to understand function in, for example, the kidney, heart, lung or liver.

From these early days it was clear to me that imaging had the potential to provide 3D measurements of a wide range of physical properties and not just a pictorial representation for the radiologist. An image could be used for guiding therapy and surgical navigation. Dynamic imaging would enable measurement of motion and physiological and pathological processes. For imaging to be a measurement tool it must be calibrated, the link between physical parameter and tissue status established, and confounds such as patient motion and measurement uncertainty characterised. An imaging technique must be validated for measurement of normal and pathological processes in order to become an "imaging biomarker" (O'Connor and seventy seven others, 2016).

1.1. Computational modelling and simulation

An image in isolation cannot provide a measurement or means for navigation. Context is needed. If an image is to provide clinically useful information of, say, the calibre of a blood vessel, size of a tumour, function of the beating heart etc. then that structure must first be identified in the image. This implies the existence of a model or representation of that structure that can be informed by the image data. These models may comprise simple geometric or iconic entities (tubes, volumes etc), but over the last 2 decades, complex, multiscale models have been developed combining geometry relating to anatomy and function relating to physiology, as well as pathological processes. Some of these models are sufficiently well advanced to conduct basic physiological research, but most still only capture certain types of information over limited ranges of scale. Nevertheless, representations are now sufficiently detailed to provide a basis for building patient specific representations that can be informed by medical imaging data. Image derived information, from a single individual, is by definition patient specific. Information derived from population or patient cohorts represent the average individual and variations across the population. Knowledge embedded in the model can be used to interpolate, extrapolate or interpret image derived information.

1.2. Image registration

Core to combining multiple imaging sources, and using image data to inform patient models and simulations, is the ability to co-register or align different data sources and those data sources with models or with the physical coordinates of the patient. When we started our work in image registration in the early 1990s we

* Corresponding author.
E-mail address: d.hawkes@ucl.ac.uk

http://dx.doi.org/10.1016/j.media.2016.06.022
1361-8415/

had some pragmatic needs to combine information from different modalities (Hill et al., 1994) and to analyse time series without the confounding effect of patient motion. Our study of information theoretic approaches to automate image registration provided robust tools for image alignment, initially assuming transformations of rigid body motion (Studholme et al., 1996, 1997, 1999) and later non-rigid using free-form deformations (Rueckert et al., 1999). It also paved the way for a much more rigorous approach to model or atlas construction. These early discoveries have opened up a large and still expanding branch of computational imaging science.

1.3. Clinical translation and defining computational science challenges

Underpinning my motivation in this exciting area is the observation from my 10 years in clinical medicine that so much disease progression is poorly understood and healthcare delivery is inadequate. Despite major advances in healthcare many patients still succumb prematurely to common diseases such as cancer or cardiovascular disease, or suffer for many years from neurological disorders or other chronic disease. While the most significant breakthroughs are still likely to be based around improved understanding of molecular, metabolic and physiological mechanisms, these are inextricably tied up with structure at multiple scales. Our vital organs function because of the molecular processes contained within, but it is their spatial relationship that enables distribution of function and these processes. It is the whole that enables our well being. Structure and spatial distributions of metabolism and physiology can be imaged and can be influenced by interventions based on engineering principles.

An effective collaborative environment between healthcare providers, industry and academic research enables translation of new ideas to improve healthcare, including creation of the pipeline from ideas, to engineered solutions, clinical trial, regulatory approval and production of healthcare solutions. My early experience in delivery of healthcare has convinced me that there is also a fruitful “reverse translation” of potentially answerable scientific questions that can be posed in the clinic to inform basic research in imaging sciences and healthcare engineering.

Many of these ideas are encapsulated now as personalised and quantitative medicine. We are at the threshold of a new revolution in medicine in which biomedical engineering and in particular imaging and its combination with computational modelling will be at the heart of many new advances in healthcare.

1.4. The centre for medical image computing (CMIC) and imaging in London, UK

CMIC was formed in 2006 when Derek Hill and myself moved from Guys Hospital, KCL to join Danny Alexander and Simon Arridge at UCL. Both institutions are in central London. Previously I had formed and led the Computational Imaging Sciences Group (CISG) at Guys Hospital, 1988 to 2004 (Hawkes and Hill, 2003).

There is now a vibrant community of medical imaging scientists working across London with a strong tradition of effective collaboration over many decades and a tradition of translation of our research findings into the clinic. The key labs work very closely with their clinical partners and with industry. The labs are well connected with the research arm of the NHS, the National Institute of Healthcare Research (NIHR) funded Academic Health Science Partnerships (UCL Partners, Kings Health Partners, Imperial College Health Partners).

The remainder of this short paper will describe a personal account of the developments I have been involved with in this area over the last 10 or so years and how these have informed the development of our overall strategy.

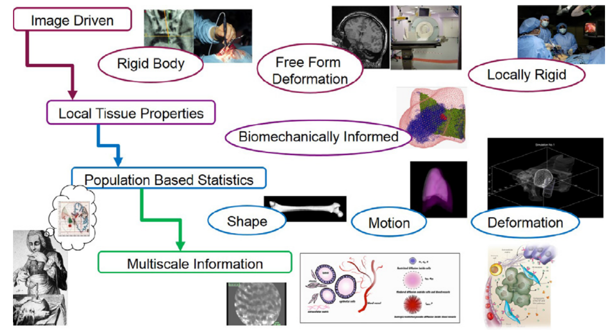

Fig. 1. A hierarchical approach to multiscale computational anatomy for image guided interventions

2. Selected research achievements

The basis for much of our research was the registration technologies developed over the previous decade (e.g. Studholme et al. (1999), Rueckert et al. (1999)). By 2000 we were developing a strong interventional image guidance programme as well as the means to combine anatomical models with image derived data. This allowed us to develop a hierarchical approach to computational anatomy in image sciences and image guided interventions. This is summarised diagrammatically in Fig. 1 showing how applications have moved from the purely data driven to static large scale (mm) models of anatomy (colon, liver, stomach), large scale models of tissue deformation and shape variation across the population (breast, prostate, orthopaedics), models that include motion (lung) and finally models that encapsulate pathological changes seen at cellular scale (prostate, breast).

2.1. Image guided surgery, microscope assisted guided interventions, the MAGI project

One of our early successes in image guided surgery was the system for Microscope Assisted Guided Intervention (MAGI) that injected images into the optics of a binocular surgical operating microscope, Fig. 2. The binocular optics of the Leica M500 surgical microscope (Heerbrugge, Switzerland) were carefully calibrated. The 3D images, primarily from MRI were carefully corrected for geometric distortion and segmented. Point based registration was used to align image and microscope coordinates (Edwards et al., 2000). An initial trial on patients with complex skull base lesions showed that critical structures such as major blood vessels could be identified with a target registration error of better than 2mm. Subsequently the concepts have found their way into other surgical devices, telemanipulators and as a display system for interventional MRI.

2.2. Image guided laparoscopic surgery

We are extending some of the concepts described above to laparoscopic surgery. Laparoscopy has transformed abdominal surgery, with less per-operative pain, lower blood loss and significantly faster recovery times. These new methods do however place significant demands on the surgeon. Field of view is restricted and the surgeon loses most of the sense of touch. Image guidance can alleviate this by providing spatial context. We have developed a system for image guided laparoscopic liver surgery based on a carefully calibrated stereo laparoscope to provide contact free 3D visible surface reconstructions, and subsequent alignment of the visible surface to pre-operative models. These are then augmented