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Synopsis

Medical Signal Processing and Biomedical Imaging

In the '70s, the major research advances in biomedical signal and image processing came from the introduction of tomography (literally from [TOMOS] - SECTION and [GRAPHO] – WRITE) which was in some way a revolution compared to the current standard made of projection images (X-ray, scintigraphy …). Some of these major discoveries are CT scans and, later on in the decade, MRI, SPECT or PET scans, completed by the growing influence of electrophysiological data (MEG, EEG, ECG…). From this period, Allan M Cormack and Godfrey N. Hounsfield received the 1979 Nobel Prize in Physiology or Medicine for the "development of computer assisted tomography"[1] [1-3], and very recently, Paul C Lauterbur and Peter Mansfield received the 2003 Nobel Prize in Physiology or Medicine for their discoveries concerning "magnetic resonance imaging" [4-6][2]. This time was the early stage of the representation of in vivo slices of the human body. The major research advances in the '80s were going from 2D representations to 3D in the clinical context. The '90s, with the arrival of data fusion algorithms (mostly registration) and new sequences of Magnetic Resonance Images – MRI (especially fast ones and functional ones), added one or two more dimensions to clinical images.

As we can observe in the five papers of this section, the major current research challenges follow this evolution by adding new spatio-temporal dimensions to the anatomical and functional data produced and used, and adding new effectors and biological signal and image data during computer assisted interventional procedures (surgery, interventional radiology …).

The classical way of making use of these data, mostly based on human interpretation, becomes less and less feasible. In addition, the societal pressure for the cost effective use of equipment on the one hand, and better traceability and quality insurance of the decision making process on the other hand, makes the development of advanced computer assisted biomedical imaging and medical signal processing systems more and more essential.

It is possible today to produce anatomical (i.e structural) and physiological (i.e functional) information which are complementary on the same subject. However, this increase of available information to perform the diagnosis must be followed by an equivalent improvement of the quantity of data the user has to integrate and interpret, notably when these data are being used in a surgical environment. So, the traditional way physicians use these data is often less than optimal and an important number of valuable information is then excluded from the medical decision process.

To go forward, the doctor has to consider not only the original biomedical signals but also the processing tools to interpret and make use of them. The mechanism of understanding and managing the biomedical images and signals is still very complex and is not based on only matching these data, but also on the knowledge about the observed structures and their interactions, these interactions being of anatomical or functional nature. It comes clear today that, except the emergence of new acquisition modalities, the arrival of new algorithms, capable to jointly use all these information, will improve patient care, diagnosis, and the therapeutic plan (including the

[1] http://nobelprize.org/medicine/laureates/1979/press.html
[2] http://nobelprize.org/medicine/laureates/2003/press.html

surgical one).

Let us consider for example the recognition of complex anatomical structures such as cortical gyri as presented by Cachia et al in their paper [7], these structures have no explicit representation on the image data. Nonetheless, it is from their representation on images (i.e. MRI) that the surgeon can better elaborate his surgical strategy, or the researcher in neurosciences can better interpret the functional activations he collected.

The surgical coverage of a patient, as presented in papers [8,9], is another example which illustrates the complexity of the decision and exploitation process of biomedical images and signals (MRI data here) in order to better model the surgical procedure and to better anticipate the surgical results. This complexity is particularly connected to the heterogeneity of the data. This heterogeneity can be of geometrical nature (acquisitions as well as surgical effectors are referred to in different Euclidian spaces). This problem is addressed in two of the papers of this section [8,9] when concerning the matching of patient data with a priori anatomical model representations (Talairach and Tournoux brain atlas [10] in [9] and a biomechanical generic face model in [8]). This heterogeneity can also be related to the scale of the data (spatial and/or temporal) as illustrated in [8,11].

The joint use of these various data, defined from different spaces, different scales and with different dimensions call for more precision on a "customized" anatomical and functional mapping the physician makes to the patient data, and requires the contribution of transverse capabilities coming from the data processing domain, including signal and image processing algorithms. The five papers presented in this section propose new algorithmic methods better adapted to the clinical application context. As an example, [11,12] deal with the localization of electrical cardiac sources or the localization of electrodes and their signals around cortical gyri or sulci. These cortical features are also used as landmarks during surgical procedures [8]. On the other hand, the insertion of these computer aided diagnosis and decision making tools in the clinical and\or surgical process raises the problem of the evaluation and the validation of these methods. This issue is partially covered in these papers but will certainly stay as a constant concern in the near future.

Before commenting on each paper, it is worth noting here that these different contributions are addressing very different methodological aspects. Two of them are more concerned with the processing of electrocardiography signals, with or without the support of heart imaging data but with a common scope: catheter ablation procedures [11,12]. The three others deal with the modeling of head structures for the purpose of building a brain atlas [7] or for matching anatomical models to a patient brain or skin face [8,9], with the scope of image-guided surgery for the later two (included simulations).

The paper by Cachia et al [7] proposes a new representation of the cortical surface that may be used to study the cortex folding process. In addition, the aim behind this new representation is to exhibit potential stable anatomical cortical landmarks called *sulcal roots* supposedly hidden in the depth of the brain. This new approach can be used to better understand the variability of brain structures taking into account the variability of the brain morphogenesis. A future address would be to overcome the difficulties of template-based deformable registration methods to deal with structurally different patterns. The proposed cortical surface delineation is based on a primal sketch derived from a scale space representation computed for the mean curvature of the cortical surface. This scale-space is derived from a diffusion process, geodesic to the cortical surface. The primal sketch is made up of objects defined from mean curvature minima and saddle points. A hierarchical description of the primal sketch can be deducted from the computed representation which may lead to new hypotheses about the morphogenesis formation of cortical folds. Results show the primal sketch of the central sulcus from 10 different brains (8 adults and 2 children). These results exhibit the variability of the hierarchy decomposition of the detected sulcal roots.

The paper Chabanas et al. [9] addresses the problem of predicting facial soft tissue deformations resulting from bone repositioning in maxillofacial surgery. As shown in the references of [9], this problem was already addressed in the mid eighties by numerous authors dealing with facial reconstructive surgery, but at this time with a lack of realistic computerized numerical models to deal with deep tissue deformation. Chabanas et al. propose a new generic 3D Finite Element Model of the facial soft tissues. This generic biomechanical model is adapted to patient morphology, and then used in order to perform simulations of face deformations under muscle actions and to simulate the aesthetic and functional consequences of maxillofacial surgical procedures. This generic soft-tissue model is automatically conformed to patient morphology by elastic registration, using skin and skull surfaces segmented from a CT scan. In order to avoid any geometrical distortion of some mesh elements of the FEM after the registration process, a detection scheme followed by a regularization process is performed. The major contribution of this work concerns the prediction of the patient facial soft tissue resulting from the repositioning of the underlying bone structures, and by specifically taking into account the cephalometric and orthodontic analyses (i.e. the morphometric analysis of the face). The results show six patient models generated with the proposed method. Simulations of soft tissue deformations resulting from bone displacements planned for two patients are provided. In both cases, a qualitative evaluation is performed based on expert surgeon's validation.

The paper of Ganser et al. [8] presents a computerized atlas system based on the Talairach atlas which tries to overcome some well know limitations of classical paper-based (or even digitized) atlas books. As illustrated in this work, the utilization of a classical paper-based atlas involves three steps. The first one concerns the geometric registration between the image data to interpret and the anatomy of one or several individuals displayed on atlas plates. The second aspect concerns the segmentation and the identification of anatomical structures of the subject from the outlines and labels of the same structures within the atlas plates. The third aspects concerns the link to the semantic knowledge associated with the anatomical structures. Classical atlases are usually printed and thereby have severe limitations. This paper tries to overcome some principal drawbacks of printed anatomic atlas. As illustrated in this paper, the use of digital atlases offers a wide range of capabilities, which overcome these limitations. Among them are the capability of digital atlases to display in 3D the related images, the capability to match inter-individual data via non-rigid registration methods, the capability to expend the corpus of accessible information which can be used (images, processing tools, additional semantic knowledge, …), and finally the capability to give a flexible way of navigation between the corpus of information represented in the computerized atlas system. The developed system integrates well-established anatomical contents from different 2D or 3D sources, integrates segmentation tools, including an interface to a navigation system, and an "easy-to-handle" non-rigid matching capability being able to handle anatomies potentially being deformed due to tumours. The capability of the system is shown in three different surgical cases. The first clinical case deals with a patient having a large tumour in the right hemisphere. The second case non-rigidly matches the digitized atlas to an MR scan acquired during surgery with an open MR scanner. Finally, the third case illustrates the application of the digitized atlas for a stereotactic intervention for Parkinson disease therapy (two electrodes are inserted in the patient's thalamus for electrical deep brain stimulation). Coloured figures exhibit the capabilities of the proposed system.

The last two papers by Tilg et al. [11] and Armoundas et al. [12] address more the aspects of biomedical signal processing for cardiac electrical activation. Both papers look at similar perspectives: the guidance of catheter ablation therapy during a Right Coronary Artery (RCA) procedure.

Tilg et al. [11] proposes an imaging approach that uses a *bidomain theory*-based surface heart model applied to single-beat data of atrial and ventricular activation. This work concerns the wider domain of inverse modelling of electrocardiographic data. The authors present a method for the imaging of the activation time map on the surface of the atrium and ventricle from electrocardiography (ECG) mapping data. The individual thorax models of the patient are constructed from 3D+time MRI data. ECG and MRI are then coupled in time and space. The major contributions of this work concerns the extension of the activation time imaging approach to atrial data (single-beat data are used to calculate activation time images). This new activation time imaging is then applied to clinical data for Wolff–Parkinson–White (WPW) syndrome. Results on two patients are presented from single beat ECG mapping data for sinus and paced rhythms activation time maps.

The paper by Armoundas et al.[12] is the only one of this section that doesn't at all concern imaging data but purely biomedical signals (electrocardiographic signals here). This work uses the well known *single equivalent moving dipole* algorithm (SEMD) in order to reconstruct in space and time both the electrocardiographic signal generated by arrhythmic activity of the heart and the bipolar current pulses emanating from a catheter tip. The goal is to guide an ablation catheter to the site of origin of the arrhythmias. Conversely to the previous paper, the authors use the direct modelling of electrocardiographic data here. Both dipoles are reconstructed by the SEMD model source at each instant of the cardiac cycle. The major advance of this work concerns the fact that, so far, they were no attempts to use the fusion of signal modelling to guide ablation therapy. This advance would allow a rapid repositioning of the catheter tip which requires only a few cycles of the arrhythmia. So far, this algorithm was not validated on humans under actual ablation conditions. The most important results concern the evaluation of the accuracy and the power of separability of the algorithm from animal and computer studies (i.e. simulation).

The papers reviewed in this synopsis are just a very small samples of the huge number of studies performed in recent years – whose purpose has been to produce clinically useful information systems, this year, with a special emphasis on clinical applications dealing with computer assisted intervention procedures. It is important to note that there are still numerous unsolved problems and we are still far from a large use of these new algorithms in a world wide clinical context. The biomedical signal and imaging research community has still to work on proposing automatic, reliable, accurate, and affordable systems. Nonetheless, the efforts of the last twenty years demonstrate that major achievements have been made. Nowadays, computerized biomedical signal and imaging systems are actually available in a very large clinical context and they already participate to make medicine safer and more efficient while still trying to make these advanced tools accessible to all citizens.

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