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Reflections on the Past and Future Evolution of Quantitative Reconstruction Algorithms for Microwave Biomedical Imaging

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The different approaches that have been taken for reconstructing complex-valued permittivity images in microwave biomedical imaging are categorized. Beyond a thorough listing of these approaches, as abundantly provided by previous overviews, the purpose here is to determine, as far as possible, their relative effectiveness to fulfill the radiologists', as end-users, requirements in terms of sensitivity/specificity tradeoff. Indeed, in the absence of sufficient standardized algorithm benchmarking, this is not an easy task. Early microwave imaging systems developed in the 80's were operated in transmission mode, directly inspired by X-ray radiography or optical microscopy arrangements. Later on, multi-view, multi-frequency, and time-domain systems came on the stage to enrich the information content of the measured microwave imaging data. From the beginning, although the sensitivity of the measured microwave data to relevant physiological parameters such as water content or temperature seemed promising, the difficulty in extracting the required information from the measured data was also clear. To extract as much information as possible from the measured microwave data, many reconstruction algorithms have been developed, relying on Maxwell-based formulations, either in an approximated fashion or in the 3D full-wave form. The approximations were, for example, in the form of neglecting multiple scattering events, assuming ray-like propagation in an averaged homogeneous media (radar-based equation), or simplifying 3D full-wave propagation into 2D transverse magnetic propagation (tomographic approximation). Despite the complexity of microwave scattering within the highly inhomogeneous human body, the use of some approximations has not been shown to necessarily have a negative impact on the clinical relevance of the reconstructed image. The quality of the achievable image seems to be dependent on not only the utilized reconstruction algorithm, including the corresponding approximations being made, but also on the utilized microwave system architecture (e.g., number of antennas, calibration procedure, and dynamic range). Herein, to review different reconstruction algorithms in microwave imaging, we consider the following four factors: (i) how rich is the information content of the measured microwave data; (ii) how well the model used in the reconstruction algorithm represents the actual system (modelling error); (iii) how well multiple scattering events within the object being imaged can be retrieved (nonlinearity); and, finally (iv) how well the ill-posedness of the microwave imaging problem can be treated (regularization).

The information content of the measured data is the most fundamental aspect of microwave imaging; it significantly affects the choice of the reconstruction algorithm with 3D full-wave approaches often attempting to reconstruct many more unknowns than approximation-based approaches. When the measured microwave data only offer limited information content, an approximation-based reconstruction algorithm could yield better results (solving for two unknowns using two approximated equations may be more desirable than solving for four unknowns using three exact equations). When the information content is limited, an alternative approach is to use additional data to augment the actual measured data. For example, structural information derived from ultrasound or magnetic resonance imaging can be used as spatial prior information in reconstruction algorithms. The modelling error inherent in the inversion model being used is also critical in the performance of reconstruction algorithms as it is independent of the signal-to-noise ratio of the measured data: perfectly measured signals cannot overcome the use of poor system models. Several approaches, including different calibration techniques, and the use of lossy coupling media, have been proposed to reduce the modelling error; however, the robustness of different reconstruction algorithms against the modelling error has not been thoroughly discussed. The nonlinearity in microwave imaging algorithms is exacerbated by multiple scattering events occurring in highly heterogeneous tissues. To handle the nonlinearity, most researchers use iterative algorithms such as the contrast source inversion or Gauss-Newton inversion based approaches. All require regularization techniques, an area of intense study, to deal with the ill-posedness of the problem. Successful regularization approaches adaptively change the regularization weight in the iterative reconstruction process. In addition, the use of machine learning techniques are being adapted for microwave imaging, mimicking emerging trends being seen in other radiological modalities, such as mammography. Some such techniques can be seen as a post-processing of the reconstructed quantitative or qualitative images improving the radiologist interpretation capability, by supplying an "augmented" interpretation. Finally, reconstruction algorithms are only one component of the microwave imaging process; thus, making an assessment of their performance without taking into consideration any human and technological environment, is not ideal.