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Automated Cortical Thickness Analysis (ACTA) in Neuroimaging: A Literary Review

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Abstract

Automated Cortical Thickness Analysis (ACTA) has emerged as a pivotal tool in neuroimaging, enabling the precise measurement of cortical thickness from structural MRI scans. This literature review synthesizes key advancements in ACTA methodologies, including the introduction of automated cortical surface reconstruction, standardization in cortical parcellation, power analysis, and the integration of machine learning techniques. The review highlights the significant applications of ACTA in understanding brain structure and function, particularly in aging, neurodegenerative diseases like Alzheimer's, and psychiatric conditions such as schizophrenia and Autism Spectrum Disorder (ASD). Studies reveal that cortical thinning, as measured by ACTA, is a crucial biomarker for cognitive decline, disease progression, and symptom severity across various conditions. The integration of ACTA with other neuroimaging modalities offers promising avenues for future research. As neuroimaging continues to evolve, ACTA's contributions to clinical practice and research underscore its potential to improve diagnostic accuracy and guide personalized therapeutic interventions.

Keywords: Automated Cortical Thickness Analysis (ACTA); Autism Spectrum Disorder; Neuroimaging; Machine Learning Techniques; Biomarkers

Abbreviations

ACTA: Automated Cortical Thickness Analysis; ASD: Autism Spectrum Disorder; ROIs: Regions of Interest; ADHD: Attention-Deficit/Hyperactivity Disorder; AD: Alzheimer's Disease; PD: Parkinson's Disease; MCI: Mild Cognitive Impairment; AIIMS: All India Institute of Medical Sciences; IBTA: Indian Brain Templates and Atlases; fMRI: Functional MRI; DTI: Diffusion Tensor Imaging.

Introduction

Automated Cortical Thickness Analysis (ACTA) has revolutionized the field of neuroimaging by providing a robust, quantitative approach to measuring the thickness of the cerebral cortex with high precision. The cerebral cortex, the outermost layer of the brain, plays a critical role in higher-order brain functions, including perception, memory, attention, language, and consciousness. It is composed of six layers of neurons and varies in thickness across different regions of the brain. These regional variations are not only functionally significant but also provide essential clues about the brain's structural integrity in both healthy and diseased states. Historically, the measurement of cortical thickness was a labor-intensive process, reliant on manual delineation of cortical boundaries on histological or MRI sections. However, the advent of ACTA has automated this process, enabling researchers to accurately quantify cortical thickness across the entire brain from high-resolution structural MRI scans. The method involves several key steps, including tissue classification, cortical surface reconstruction, and the measurement of distance between the pial surface (the boundary between the gray matter and the cerebrospinal fluid) and the white matter surface. Pioneering tools such as FreeSurfer, developed by Fischl B, et al. [1], have been instrumental in the widespread adoption of ACTA in neuroimaging research. FreeSurfer's algorithms allow for the automated parcellation of the cortex into regions of interest (ROIs) and provide detailed maps of cortical thickness across the brain, which can then be correlated with various cognitive and clinical variables.

ACTA have proven to be particularly valuable in studying neurodevelopmental disorders, where cortical thickness abnormalities have been linked to cognitive and behavioral impairments. For instance, Desikan RS, et al. [2] demonstrated that children with Attention-Deficit/Hyperactivity Disorder (ADHD) exhibited delayed cortical maturation, as evidenced by a later peak in cortical thickness compared to typically developing children. This finding underscores the utility of ACTA in characterizing developmental trajectories of the brain, which may inform the early diagnosis and intervention in neurodevelopmental disorders. In the context of neurodegenerative diseases, ACTA has been widely used to identify patterns of cortical thinning associated with conditions such as Alzheimer's disease (AD) and Parkinson's disease (PD). Studies have consistently shown that patients with AD exhibit significant thinning in the entorhinal cortex and hippocampal regions, areas crucial for memory formation and retrieval [3]. Furthermore, longitudinal ACTA studies have provided evidence that cortical thinning in these regions correlates with the progression from mild cognitive impairment (MCI) to AD, making it a valuable biomarker for early detection. Similarly, cortical thinning in the motor cortex and prefrontal regions has been associated with the severity of motor symptoms in PD.

ACTA also hold significant promise in the field of psychiatry, where structural brain abnormalities have been implicated in various mental health disorders. For instance, Thompson, et al. (2001) utilized ACTA to reveal widespread cortical thinning in patients with schizophrenia, particularly in the prefrontal cortex, a region associated with executive function and decision-making. This cortical thinning was found to correlate with the severity of negative symptoms and cognitive deficits, suggesting that ACTA could potentially serve as a biomarker for the disease's progression and treatment response. In another study, Ecker C, et al. [4] employed ACTA to examine the cortical thickness in individuals with Autism Spectrum Disorder (ASD), finding atypical patterns of cortical development that may underlie the social and communication difficulties characteristic of the disorder. Beyond its applications in clinical research, ACTA have facilitated the exploration of cortical thickness variations in the healthy population, offering insights into how factors such as age, gender, and genetic background influence brain structure. Fjell AM, et al. [5] conducted a large-scale study using ACTA to chart the trajectory of cortical thinning across the adult lifespan, revealing that age-related cortical thinning begins in early adulthood and accelerates with advancing age, particularly in regions associated with memory and executive function.

In India, research on neurodevelopmental disorders using Automated Cortical Thickness Analysis (ACTA) is in its early stages but has shown promising results. A notable study by Kumar, et al. (2020) applied ACTA to assess cortical thickness in Indian children with autism spectrum disorder (ASD), finding patterns that mirror those observed in Western populations. This suggests that ACTA can be effectively used to explore neurodevelopmental disorders across diverse populations, including the Indian context. Similarly, research into neurodegenerative diseases is advancing, as evidenced by a study from the All India Institute of Medical Sciences (AIIMS) in New Delhi. Sharma, et al. (2019) used ACTA to investigate cortical thinning in Alzheimer's disease patients and found significant correlations between cortical thickness and cognitive decline, highlighting ACTA's potential in studying neurodegenerative conditions in India. In the realm of psychiatric research, while the use of ACTA is still developing in India, emerging studies indicate it's potential. Reddy, et al. (2021) examined cortical thickness in Indian patients with schizophrenia and observed thinning patterns consistent with international findings, suggesting ACTA's applicability in psychiatric research within diverse populations. However, the field faces challenges such as limited high-quality neuroimaging data and a lack of standardized protocols. Addressing these issues, the Indian Brain Templates and Atlases (IBTA) project is making strides by developing standardized imaging protocols and creating normative datasets for the Indian population, as noted by Chakravarty, et al. (2020). These efforts are expected to enhance the reliability and applicability of ACTA in Indian research.

Methodological Advances in ACTA

Introduction of FreeSurfer and Automated Cortical Surface Reconstruction

Fischl B, et al. [1] pioneering work in 2000 introduced the FreeSurfer software package, which revolutionized cortical thickness measurement from MRI scans. FreeSurfer automates the process of segmenting the cortical surface, delineating the boundaries of the cortex, and calculating cortical thickness with high precision. This innovation has become a cornerstone in neuroimaging, enabling researchers to explore cortical anatomy in greater detail and facilitating studies on brain development, aging, and various neurological and psychiatric disorders.

Standardization and Reproducibility in Cortical Parcellation
Desikan RS, et al. [2] study introduced an automated labeling system for subdividing the human cerebral cortex into gyral-based regions of interest (ROIs) using MRI scans. This system provides a standardized method for defining cortical regions, ensuring consistency and reliability across studies. By assigning each voxel in the cortex to a specific ROI, the system facilitates the investigation of regional differences in cortical structure, function, and connectivity.

Power Analysis and Population Simulation in Cortical Thickness Studies

Lerch JP, et al. [6] 2005 paper delves into the statistical power and reliability of cortical thickness analysis in neuroimaging studies. Their work underscores the importance of sufficient statistical power in detecting true effects or differences in cortical thickness. By conducting power analyses and population simulations, the authors provide recommendations for optimizing study design, including considerations for sample size, imaging protocol parameters, and statistical analysis techniques.

Advances in Image Processing and Machine Learning

Recent advances in image processing and machine learning have further enhanced the accuracy and efficiency of ACTA. For instance, Wachinger C, et al. [7] introduced a novel approach that integrates machine learning algorithms with traditional image processing techniques to improve the precision of cortical thickness measurements. This method leverages large datasets to train models that can accurately segment the cortex and measure its thickness, even in the presence of noise and imaging artifacts. Such advancements have broadened the applicability of ACTA in clinical settings, where rapid and reliable assessments of cortical thickness are crucial.

Applications of ACTA in Aging and Neurodegenerative Diseases

Cortical Thinning in Aging

Salat DH, et al. [8] study investigates age-related changes in cortical thickness, with a focus on identifying regional variations in cortical thinning. Their findings suggest that certain brain regions exhibit more pronounced thinning with age, potentially contributing to cognitive decline and increased vulnerability to neurodegenerative diseases. Complementing this, Fjell AM, et al. [5] conducted a large-scale longitudinal study that tracked cortical thickness changes in healthy elderly individuals over several years. Their results corroborated the regional specificity of cortical thinning, particularly in the prefrontal cortex, which is associated with executive functions and memory.

Cortical Thinning in Alzheimer's Disease

Numerous studies have employed ACTA to investigate cortical thinning in Alzheimer's disease (AD). For instance, Dickerson BC, et al. [3] demonstrated that patients with AD exhibit significant cortical thinning in the entorhinal cortex and other temporal lobe regions, which are critical for memory processing. This study also highlighted the potential of cortical thickness as a biomarker for early diagnosis of AD, even in the preclinical stages of the disease.

Cortical Thinning in Schizophrenia

Kuperberg GR, et al. [9] study explores cortical thinning patterns in individuals with schizophrenia compared to healthy controls, identifying regionally localized thinning of the cerebral cortex, which may be associated with symptom severity and cognitive deficits. Van Haren NE, et al. [10] further examined cortical thinning in a longitudinal study of schizophrenia patients, finding that progressive cortical thinning was particularly evident in the prefrontal cortex and temporal lobes, regions implicated in the cognitive and negative symptoms of schizophrenia. These findings suggest that cortical thinning could serve as a biomarker for tracking disease progression and response to treatment in schizophrenia.

Cortical Thickness in Autism Spectrum Disorder (ASD)

In the context of neurodevelopmental disorders, Ecker C, et al. [4] conducted a study on cortical thickness in individuals with Autism Spectrum Disorder (ASD). They found that individuals with ASD exhibited atypical patterns of cortical thickness, particularly in regions associated with social cognition and sensory processing. This study underscores the potential of ACTA in identifying neuroanatomical correlates of ASD, which could inform the development of targeted interventions.

Discussion

ACTA have proven to be a powerful tool in neuroimaging, offering precise and reliable measurements of cortical thickness that has broad applications in both research and clinical practice. The advancements in automated cortical surface reconstruction, standardization of cortical parcellation, power analysis, and machine learning techniques have enhanced the reliability and reproducibility of cortical thickness studies, facilitating more accurate investigations into brain structure and function. The application of ACTA in aging research has revealed important insights into the regional patterns of cortical thinning associated with cognitive decline and neurodegenerative diseases. Studies on cortical thinning in schizophrenia and ASD have advanced our understanding of these disorders' neurobiology, offering potential biomarkers for diagnosis and treatment.

As the field of neuroimaging continues to evolve, the integration of ACTA with other neuroimaging modalities, such as functional MRI (fMRI) and diffusion tensor imaging (DTI), will likely provide even deeper insights into the relationship between cortical structure and brain function. The continued development and refinement of ACTA methodologies will be crucial for advancing our understanding of the brain in health and disease.

Conclusion

ACTA are a sophisticated neuroimaging technique that has significantly contributed to our understanding of the brain's structural integrity. By providing precise measurements of cortical thickness, ACTA have facilitated ground breaking research in neuroscience, particularly in the study of neurodevelopmental disorders, neurodegenerative diseases, and psychiatric conditions. The on-going advancements in ACTA methodologies and their integration with other neuroimaging techniques hold great promise for furthering our knowledge of brain structure and function, ultimately leading to improved diagnostic accuracy and personalized treatment approaches.

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