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Modern Diagnostic Approaches in Celiac Disease: Molecular Mechanisms, Biomarkers and Emerging Technologies

Aleksandra Strzewiczek¹, Karolina Szamocka^{1*}

¹ University Clinical Hospital in Poznań, 49 Przybyszewskiego Street, 60-355 Poznań, Poland

Corresponding author: Karolina Szamocka — szamockakarola@gmail.com

**Aleksandra
Strzewiczek**

ORCID: [0009-0003-2291-1032](https://orcid.org/0009-0003-2291-1032)

ola.strzewiczek@gmail.com

**Karolina
Szamocka**

ORCID: [0000-1291-8626](https://orcid.org/0000-1291-8626)

szamockakarola@gmail.com

ABSTRACT

Introduction: Celiac disease is a chronic autoimmune disorder triggered by gluten in genetically predisposed individuals. Incomplete digestion of gluten leads to immunogenic peptides that activate intestinal immune responses, causing inflammation and damage to the small intestinal mucosa. Early and accurate diagnosis is crucial to prevent complications such as malabsorption, anemia, osteoporosis, and neurological disorders.

Aim of the Study: This review aims to summarize current and emerging diagnostic methods for celiac disease, with a focus on biochemical mechanisms, molecular biomarkers, and advanced laboratory techniques, including proteomics, microRNA profiling, and nanotechnology-based biosensors.

Materials and Methods: A literature review was conducted using PubMed to identify studies on celiac disease diagnostics, molecular mechanisms, and biomarkers. Peer-reviewed clinical studies, systematic reviews, and experimental research were analyzed to provide a comprehensive overview of current knowledge and innovative diagnostic approaches.

Conclusion: Modern diagnostics combine serological, genetic, and histopathological methods, with key biomarkers such as anti-tissue transglutaminase and deamidated gliadin peptide antibodies linked to disease mechanisms. Emerging technologies including proteomics, microRNA analysis, metabolomics, and nanotechnology-based biosensors offer promising tools for early, sensitive, and non-invasive detection, improving disease monitoring and patient care.

Keywords: celiac disease; tissue transglutaminase; deamidated gliadin peptides; HLA-DQ2; biomarkers

1. INTRODUCTION

Celiac disease is a chronic autoimmune disorder characterized by inflammation of the small intestinal mucosa induced by dietary gluten proteins present in wheat, barley, and rye [10]. Gluten consists primarily of gliadin and glutenin fractions that are rich in proline and glutamine residues, which renders them resistant to digestion by gastrointestinal proteases such as pepsin, trypsin, and chymotrypsin [17].

Incomplete digestion leads to the formation of immunogenic peptides that interact with the intestinal immune system and initiate inflammatory responses in genetically predisposed individuals [18]. Among these peptides, the 33-mer gliadin fragment derived from α -gliadin is considered the most immunogenic because it contains multiple overlapping T-cell epitopes capable of activating CD4+ lymphocytes [17].

The prevalence of celiac disease is estimated at approximately 1% of the global population, although a significant proportion of cases remain undiagnosed due to atypical clinical manifestations or a silent disease course [7]. Untreated celiac disease may lead to numerous complications, including malabsorption, anemia, osteoporosis, infertility, neurological disorders, and an increased risk of intestinal lymphoma [20].

The pathogenesis of the disease involves complex interactions between environmental factors, genetic susceptibility, and immune mechanisms [19]. Genetic predisposition is strongly associated with the presence of HLA-DQ2 and HLA-DQ8 molecules encoded within the major histocompatibility complex on chromosome 6 [22].

Advances in immunology and molecular diagnostics have led to the development of modern diagnostic strategies based on serological biomarkers, genetic testing, and histopathological analysis [6]. More recently, emerging technologies such as proteomics, metabolomics, and

nanotechnology-based biosensors have been investigated as potential tools for non-invasive diagnosis and disease monitoring [31].

2. AIM OF THE STUDY

The aim of this study is to review current and emerging diagnostic methods used in the detection of celiac disease, with particular emphasis on biochemical mechanisms, molecular biomarkers, and advanced laboratory diagnostic techniques. The study also aims to discuss novel diagnostic strategies including proteomic analysis, microRNA profiling, and nanotechnology-based biosensors.

3. MATERIALS AND METHODS

This review was conducted using scientific literature available in the PubMed database. Publications related to celiac disease diagnostics, molecular mechanisms, and laboratory biomarkers were analyzed. Search terms included:

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"celiac disease diagnosis" | "tissue transglutaminase antibodies" | "deamidated gliadin peptides" | "HLA-DQ2 genetics celiac disease" | "proteomics celiac disease" | "biosensors celiac diagnostics"
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Peer-reviewed clinical studies, systematic reviews, and experimental molecular research articles were included in the analysis [3]. A total of 40 publications were selected and used to prepare this review.

4. STATE OF KNOWLEDGE

4.1. Immunopathogenesis of Celiac Disease as the Biochemical Basis of Diagnostics

The pathogenesis of celiac disease is closely related to the biochemical interactions between gluten peptides, intestinal enzymes, and immune cells [16]. A crucial role in disease development is played by tissue transglutaminase type 2 (tTG2), a calcium-dependent enzyme belonging to the transglutaminase family [37]. This enzyme catalyzes post-translational modifications of proteins through transamidation and deamidation reactions [16].

In the intestinal mucosa, tTG2 modifies gliadin peptides by converting glutamine residues into glutamic acid residues in a process known as deamidation [17]. This modification increases the negative charge of gliadin peptides and significantly enhances their affinity for HLA-DQ2 and HLA-DQ8 molecules present on antigen-presenting cells [23].

The resulting peptide-HLA complexes are recognized by CD4⁺ T lymphocytes in the lamina propria of the small intestine, which leads to T-cell activation and production of pro-inflammatory cytokines such as interferon- γ and tumor necrosis factor- α [19]. These cytokines promote intestinal inflammation and damage of the epithelial barrier, ultimately leading to villous atrophy and crypt hyperplasia [18].

Another important biochemical factor involved in celiac disease pathogenesis is increased intestinal permeability regulated by the protein zonulin [21]. Gluten exposure stimulates zonulin release, which disrupts tight junctions between epithelial cells and facilitates translocation of immunogenic gliadin peptides across the intestinal barrier [21].

The formation of tTG-gliadin complexes also plays a key role in autoantibody production [37]. B lymphocytes internalize these complexes and present gliadin peptides to T helper

cells, which provide signals required for B-cell activation and antibody production [16]. This mechanism leads to the generation of characteristic autoantibodies used as diagnostic biomarkers.

4.2. Serological Diagnostics of Celiac Disease

Serological testing represents the first-line diagnostic approach for suspected celiac disease due to its high sensitivity and specificity [26].

4.3. Anti-Tissue Transglutaminase Antibodies

Anti-tTG antibodies are currently considered the most sensitive serological marker of celiac disease [11]. These antibodies are directed against tissue transglutaminase, which acts as the primary autoantigen in the disease [37].

Detection of anti-tTG IgA antibodies is typically performed using enzyme-linked immunosorbent assay (ELISA) techniques that utilize recombinant human tTG antigen [13]. ELISA assays provide high analytical sensitivity and allow quantitative measurement of antibody concentrations.

High levels of anti-tTG antibodies correlate strongly with intestinal mucosal damage and the severity of villous atrophy [11]. Studies have demonstrated that antibody titers exceeding ten times the upper limit of normal may allow diagnosis without biopsy in selected pediatric patients according to international guidelines [4].

4.4. Anti-Endomysial Antibodies

Anti-endomysial antibodies (EMA) represent another highly specific serological marker of celiac disease [11]. These antibodies target endomysial connective tissue surrounding smooth muscle fibers, although their primary antigen was later identified as tissue transglutaminase [37].

Detection of EMA antibodies is performed using indirect immunofluorescence microscopy with primate esophagus or human umbilical cord substrates [11]. Although this method has very high specificity approaching 100%, it requires experienced laboratory personnel and is more labor-intensive compared with ELISA assays [26].

4.5. Antibodies Against Deamidated Gliadin Peptides

Antibodies against deamidated gliadin peptides (DGP) represent an important advancement in serological diagnostics [15]. Unlike older assays detecting antibodies against native gliadin, DGP tests target gliadin peptides modified by tissue transglutaminase through deamidation [17].

These modified peptides contain negatively charged glutamic acid residues that form stronger interactions with HLA-DQ2 molecules and induce stronger immune responses [23]. IgG DGP tests are particularly useful in patients with selective IgA deficiency, which occurs more frequently among individuals with celiac disease than in the general population [5].

4.6. Genetic Diagnostics

Genetic testing plays an important role in the diagnostic process by identifying individuals genetically predisposed to celiac disease [22]. Approximately 90–95% of patients with celiac disease carry HLA-DQ2 haplotypes encoded by the DQA1*05 and DQB1*02 alleles [38]. Most remaining patients carry the HLA-DQ8 heterodimer encoded by DQA1*03 and DQB1*03:02 alleles [22].

These molecules form peptide-binding grooves that preferentially bind negatively charged peptides produced during gliadin deamidation [23]. The stability of these complexes determines the efficiency of antigen presentation and activation of gluten-specific T lymphocytes [19]. Although these genetic variants are common in the general population, their absence virtually excludes celiac disease because more than 99% of patients carry either HLA-DQ2 or HLA-DQ8 haplotypes [7].

4.7. Histopathological Diagnostics

Histological examination of duodenal biopsy specimens remains an important diagnostic method in many clinical cases [25]. Typical histological features of celiac disease include:

villous atrophy

crypt hyperplasia

increased intraepithelial lymphocyte infiltration

These morphological changes are commonly classified using the Marsh-Oberhuber classification system, which describes progressive stages of mucosal damage [25]. Advances in digital pathology and artificial intelligence have enabled automated image analysis systems capable of quantifying morphological parameters such as villous height-to-crypt depth ratios and lymphocyte density [24].

4.8. Proteomic Diagnostics

Proteomics is an emerging field that studies the complete set of proteins expressed in biological systems [31]. In celiac disease research, proteomic techniques are used to identify protein biomarkers associated with intestinal inflammation and immune activation.

Mass spectrometry-based techniques such as liquid chromatography coupled with tandem mass spectrometry (LC-MS/MS) enable highly sensitive detection of protein expression changes in biological samples [32]. Proteomic studies have identified altered expression of proteins involved in immune responses, oxidative stress, and epithelial barrier function in patients with active celiac disease [31]. These proteins include heat shock proteins, complement system components, and enzymes involved in inflammatory signaling pathways [32].

4.9. MicroRNA Biomarkers

MicroRNAs are short non-coding RNA molecules that regulate gene expression at the post-transcriptional level [39]. They bind to messenger RNA molecules and inhibit translation or promote mRNA degradation.

Recent studies have demonstrated altered expression of several microRNAs in intestinal tissue and blood samples from patients with celiac disease [39]. These microRNAs are involved in the regulation of immune responses, epithelial barrier integrity, and inflammatory signaling pathways. Specific microRNA profiles may therefore serve as potential biomarkers for early detection and monitoring of disease activity.

4.10. Metabolomic Biomarkers

Metabolomics involves the analysis of small molecules produced during cellular metabolism [39]. Changes in metabolic profiles may reflect alterations in intestinal microbiota composition and immune activity in celiac disease.

Metabolomic studies have identified differences in amino acid metabolism, lipid metabolism, and short-chain fatty acid production between patients with celiac disease and healthy individuals [39]. These metabolic signatures may provide additional diagnostic information and help monitor adherence to gluten-free diets.

4.11. Biosensors and Nanotechnology-Based Diagnostic Tests

Nanotechnology has enabled the development of highly sensitive biosensors capable of detecting disease-specific biomarkers at extremely low concentrations [36]. Biosensors typically consist of a biological recognition element — such as an antibody or nucleic acid probe — coupled with a physicochemical detector [36]. In celiac disease diagnostics, biosensors may be designed to detect anti-tTG antibodies or gluten peptides.

Nanomaterials such as gold nanoparticles, graphene, and quantum dots are increasingly used to enhance signal detection and improve assay sensitivity [36]. Electrochemical biosensors incorporating gold nanoparticles have demonstrated the ability to detect anti-tTG antibodies with sensitivity comparable or superior to conventional ELISA assays [36]. These technologies may eventually enable rapid point-of-care diagnostic tests for celiac disease.

Table 1. Major diagnostic biomarkers of celiac disease, including their biological targets, detection methods, and clinical significance.

Biomarker	Biological Target	Diagnostic Method	Clinical Significance
Anti-tissue transglutaminase antibodies (anti-tTG IgA)	Tissue transglutaminase enzyme	ELISA	Primary screening test; high sensitivity and specificity for celiac disease
Anti-endomysial antibodies (EMA)	Endomysial connective tissue (tTG antigen)	Indirect immunofluorescence	Very high specificity; commonly used as a confirmatory test
Deamidated gliadin peptide antibodies (DGP IgA/IgG)	Deamidated gliadin peptides	ELISA	Useful in early disease and in patients with IgA deficiency

Biomarker	Biological Target	Diagnostic Method	Clinical Significance
HLA-DQ2 HLA-DQ8	/ MHC class II molecules	Genetic (PCR) testing	Presence indicates genetic susceptibility; absence almost excludes disease
Zonulin	Tight junction regulatory protein	ELISA / experimental assays	Marker of increased intestinal permeability

Source: authors' own compilation based on published data [3,5,7,10,11,15,21,37].

5. CONCLUSION

Modern diagnostics of celiac disease rely on a combination of serological, genetic, and histopathological methods. Advances in molecular biology and immunology have enabled the identification of highly specific biomarkers such as anti-tTG antibodies and deamidated gliadin peptide antibodies.

Understanding the biochemical mechanisms underlying celiac disease — particularly the role of tissue transglutaminase and gluten peptide modification — has been crucial for the development of modern diagnostic tests.

Emerging technologies including proteomic analysis, microRNA profiling, and nanotechnology-based biosensors represent promising tools for improving early detection and monitoring of the disease.

Further research into molecular biomarkers may enable the development of non-invasive diagnostic methods that will enhance clinical management of patients with celiac disease.

DISCLOSURES

Authors' Contributions

Conceptualization:	K.S.
Methodology:	A.S.
Software:	A.S.
Formal Analysis:	K.S.

Investigation:	K.S.
Resources:	A.S., K.S.
Writing — Original Draft:	A.S.
Writing — Review & Editing:	K.S.
Visualization:	K.S.
Supervision:	A.S.
Project Administration:	K.S.

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