A Randomized Trial of a Transglutaminase 2 Inhibitor for Celiac Disease


BACKGROUND
In celiac disease, small intestinal transglutaminase 2 causes deamidation of glutamine residues in gluten peptides, which enhances stimulation of T cells and leads to mucosal injury. Inhibition of transglutaminase 2 is a potential treatment for celiac disease.

METHODS
In a proof-of-concept trial, we assessed the efficacy and safety of a 6-week treatment with ZED1227, a selective oral transglutaminase 2 inhibitor, at three dose levels as compared with placebo, in adults with well-controlled celiac disease who underwent a daily gluten challenge. The primary end point was the attenuation of gluten-induced mucosal damage, as measured by the ratio of villus height to crypt depth. Secondary end points included intraepithelial lymphocyte density, the Celiac Symptom Index score, and the Celiac Disease Questionnaire score (for assessment of health-related quality of life).

RESULTS
Of the 41 patients assigned to the 10-mg ZED1227 group, the 41 assigned to the 50-mg group, the 41 assigned to the 100-mg group, and the 40 assigned to the placebo group, 35, 39, 38, and 30 patients, respectively, had adequate duodenal-biopsy samples for the assessment of the primary end point. Treatment with ZED1227 at all three dose levels attenuated gluten-induced duodenal mucosal injury. The estimated difference from placebo in the mean ratio of villus height to crypt depth from baseline to week 6 was 0.44 (95% confidence interval [CI], 0.15 to 0.73) in the 10-mg group (P = 0.001), 0.49 (95% CI, 0.20 to 0.77) in the 50-mg group (P = 0.001), and 0.48 (95% CI, 0.20 to 0.77) in the 100-mg group (P = 0.001). The estimated differences from placebo in the change in intraepithelial lymphocyte density were −2.7 cells per 100 epithelial cells (95% CI, −7.6 to 2.2) in the 10-mg group, −4.2 cells per 100 epithelial cells (95% CI, −8.9 to 0.6) in the 50-mg group, and −9.6 cells per 100 epithelial cells (95% CI, −14.4 to −4.8) in the 100-mg group. Use of the 100-mg dose may have improved symptom and quality-of-life scores. The most common adverse events, the incidences of which were similar across all groups, were headache, nausea, diarrhea, vomiting, and abdominal pain. Rash developed in 3 of 40 patients (8%) in the 100-mg group.

CONCLUSIONS
In this preliminary trial, treatment with ZED1227 attenuated gluten-induced duodenal mucosal damage in patients with celiac disease. (Funded by Dr. Falk Pharma; CEC-3 EudraCT number, 2017-002241-30.)

* A complete list of the investigators and contributors in the CEC-3 Trial Group is provided in the Supplementary Appendix, available at NEJM.org.

Drs. Schuppan and Mäki contributed equally to this article.

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Celiac disease is characterized by inflammation of the small intestine, is frequently associated with autoimmunity, and affects 0.2 to 2.0% of the population in most countries. The identification of cases has increased in the past decades owing to improved serologic diagnosis, as has the true prevalence of celiac disease. Celiac disease is driven by the ingestion of gluten in wheat and related grains in genetically predisposed persons who have HLA-DQ2 and HLA-DQ8 genotypes, which are necessary but not sufficient for the manifestation of celiac disease. The classic symptoms of celiac disease are diarrhea, weight loss, and malnutrition, but celiac disease frequently manifests with nonspecific or atypical symptoms, including fatigue, altered bowel habits, anemia, osteoporosis, or autoimmune diseases such as autoimmune thyroiditis and type 1 diabetes.

Active celiac disease is diagnosed on the basis of elevated levels of serum autoantibodies to transglutaminase 2 and is confirmed by histologic villus atrophy and crypt hyperplasia in the proximal small intestine, accompanied by intraepithelial lymphocyte infiltration in duodenal mucosa. The only available treatment for celiac disease is lifelong adherence to a strict gluten-free diet, a diet that is difficult to maintain, and only 50% of patients have mucosal recovery and often do not have negative serum autoantibodies 1 year or later after diagnosis. Moreover, many patients with celiac disease report having persistent symptoms despite adherence to the gluten-free diet. Thus, there is an unmet medical need for an effective treatment adjunct to a strict gluten-free diet. Currently, no drug therapy reliably prevents the effects of dietary gluten or has been approved by regulators to treat celiac disease.

Transglutaminase 2, the celiac autoantigen, is expressed in the intestinal mucosa, where it modifies immunogenic gluten peptides by means of deamidation of certain charge-neutral glutamine residues, yielding negatively charged glutamic acid residues. This modification promotes gluten-peptide presentation by HLA-DQ2 or HLA-DQ8 molecules on mucosal antigen–presenting cells and enables the activation and expansion of gluten peptide–specific CD4+ type 1 helper T cells and the secretion of proinflammatory cytokines. This process leads to villus atrophy and crypt hyperplasia and to B-cell differentiation and the production of transglutaminase 2 IgA.

ZED1227 inhibits transglutaminase 2 with high specificity and prevents the formation of deamidated gluten and, putatively, the initial steps of gluten-induced T-cell activation. ZED1227 is formulated as an oral capsule for duodenal targeting and has been tested for clinical safety in earlier studies (EudraCT numbers, 2014-003044-13 and 2015-005283-42 [data on file]). Our phase 1 clinical studies, which involved 106 healthy persons who were exposed to doses of up to 500 mg of ZED1227 for up to 8 days, did not show drug-related adverse effects or signs of drug toxicity, and systemic drug levels after oral ingestion were low. Here, we report the results of a phase 2, randomized, double-blind, placebo-controlled, dose-finding trial of ZED1227 capsules to evaluate efficacy and safety in adult patients with celiac disease in histologic and serologic (transglutaminase 2 IgA) remission owing to a gluten-free diet who were challenged with daily gluten intake for 6 weeks.

### Methods

**Trial Oversight**

We conducted this trial at 20 sites in seven countries (Estonia, Finland, Germany, Ireland, Lithuania, Norway, and Switzerland). The trial was approved by an independent ethics committee at each site. Written informed consent was obtained from each patient before screening. The sponsor, Dr. Falk Pharma, contributed to the trial design, data analysis, and the writing and editing of the manuscript. Data were collected by the investigators with the use of electronic case-report forms. All the authors vouch for the accuracy and completeness of the data and for the fidelity of the trial to the protocol, which is available with the full text of this article at NEJM.org.

**Trial Patients**

Adults 18 to 65 years of age who had received a biopsy-confirmed diagnosis of celiac disease at least 12 months before screening and who were positive for HLA-DQ2 or HLA-DQ8 genotypes were considered for inclusion in the trial. Patients had to have successfully adhered to a gluten-free diet for at least 12 months, to present with negative serologic testing for transglutaminase 2 IgA, to be 1 year or later after diagnosis, and to have a transglutaminase 2 IgA concentration of at least 10 times the upper limit of normal. Patients were excluded if they had had Coeliac disease that resulted in small-intestinal surgery. Patients were required to adhere to a gluten-free diet for at least 12 months before screening, to have a negative serologic response to gluten at screening, and to not have any other gastrointestinal disease or serious acute medical illness.

**Randomization and Allocation**

Patients were randomized to fixed doses of ZED1227 or placebo using a stratified sequential block randomization scheme. The sequence was generated by the statistical department at Dr. Falk Pharma. We used randomization by phone or computer to assign 40 patients to each active dose and 20 patients to placebo. The randomization scheme was stratified by celiac disease duration (at least 1 year or later after diagnosis) and by celiac disease histologic score (Marsh 1 or Marsh 2).

**Study Drug**

ZED1227 is formulated as an oral capsule for duodenal targeting and has been tested for clinical safety in earlier studies (EudraCT numbers, 2014-003044-13 and 2015-005283-42 [data on file]). Our phase 1 clinical studies, which involved 106 healthy persons who were exposed to doses of up to 500 mg of ZED1227 for up to 8 days, did not show drug-related adverse effects or signs of drug toxicity, and systemic drug levels after oral ingestion were low. Here, we report the results of a phase 2, randomized, double-blind, placebo-controlled, dose-finding trial of ZED1227 capsules to evaluate efficacy and safety in adult patients with celiac disease in histologic and serologic (transglutaminase 2 IgA) remission owing to a gluten-free diet who were challenged with daily gluten intake for 6 weeks.

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IgA and a mean ratio of villus height to crypt depth of 1.5 or higher, and to agree to tolerate a challenge of ingesting 3 g of gluten daily for 6 weeks. Full inclusion and exclusion criteria are provided in the Supplementary Appendix, available at NEJM.org.

**TRIAL DESIGN AND TREATMENT**

In this double-blind, placebo-controlled, dose-ranging trial, eligible patients were randomly assigned, in a 1:1:1:1 ratio, to one of four parallel groups to receive 10 mg of ZED1227, 50 mg of ZED1227, 100 mg of ZED1227, or placebo, all with matched appearance, concurrent with the gluten challenge (Fig. S1 in the Supplementary Appendix). Each morning after at least 6 hours of fasting, patients took ZED1227 or placebo orally and, 30 minutes later, ate one sponsor-provided biscuit containing 3 g of gluten before breakfast. Throughout the 6-week trial, patients were required to continue their strict gluten-free diet, aside from eating the sponsor-provided gluten-containing biscuit.

Duodenal mucosal damage as an objective marker of gluten-induced celiac disease activity can be measured quantitatively by means of standardized histopathological morphometry. The gluten challenge, in which a moderate amount of gluten is ingested daily for a limited duration, produces a statistically and clinically significant but reversible deterioration of duodenal mucosa and allows for the assessment of efficacy of the active treatment.

**END POINTS**

The primary end point was the attenuation of gluten-induced deterioration of intestinal mucosal morphologic features, as measured by the ratio of villus height to crypt depth in duodenal-biopsy samples obtained starting at the baseline (screening) visit to the end of the 6-week gluten challenge and treatment period. Secondary end points included changes from baseline to week 6 in the density of CD3+ intraepithelial lymphocytes, the modified Marsh–Oberhuber classification, patient-reported outcomes as measured by the Celiac Symptom Index and the Celiac Disease Questionnaire, blood markers of malabsorption (e.g., ferritin, transferrin saturation, and albumin), plasma concentrations of ZED1227, and serologic markers of celiac disease. On the modified Marsh–Oberhuber classification, a score of 0 indicates normal duodenal morphology without increased intraepithelial lymphocytes; a score of 1, normal duodenal morphology with increased intraepithelial lymphocytes; a score of 2, normal villi but crypt hyperplasia; and scores of 3a through 3c, increasing severity of villus atrophy and crypt hyperplasia, with a score of 3c indicating complete villus atrophy. The Celiac Symptom Index is a 16-item questionnaire, with each item rated on a scale of 1 (no symptoms) to 5 (symptoms all the time); overall scores range from 16 to 80, with higher scores indicating worse celiac disease-related symptoms. The Celiac Disease Questionnaire is a 28-item questionnaire, with each item rated from 1 (reduced health-related quality of life) to 7 (high health-related quality of life); overall scores range from 28 to 196, with higher scores indicating better quality of life.

Safety was evaluated by the monitoring of adverse events, vital signs, body weight, clinical laboratory tests, and side-effect profile as assessed by the investigator and the patient. For the assessment of change in the ratio of villus height to crypt depth, patients were excluded from the analysis if they did not have adequate follow-up duodenal-biopsy samples that allowed for the measurement of at least three separate villus–crypt units. A sensitivity analysis included all the patients who underwent randomization and received at least one dose of ZED1227 or placebo. All the other efficacy analyses involved patients who underwent randomization and received at least one dose of ZED1227 or placebo, without imputation of missing values at follow-up; modeling was performed with the use of complete cases only.

**TRIAL PROCEDURES AND ASSESSMENTS**

Enrollment required a screening period of no more than 8 weeks, including upper gastrointestinal endoscopy with duodenal biopsies performed within 4 weeks before the administration of the first dose in order to provide baseline histologic data. At the week 0 visit, the trial drug (ZED1227 or placebo) and gluten biscuits were dispensed to patients according to assigned group. Patients returned to the trial sites at weeks 2, 4, and 6 for assessments and at week 10 for a follow-up visit. A second endoscopy with biopsies was performed at the week 6 or withdrawal visit. Both endoscopies were conducted by experienced gastroenterologists.
ologists. Four forceps biopsy samples (one biopsy sample per pass) were obtained from the second and third parts of the duodenum, put in a PAXgene fixative, and sent to the central histopathology laboratory (Jilab, Tampere, Finland) for processing and reading. Validated, standardized morphometric procedures separately evaluated mucosal morphology and inflammation. The categorical Marsh–Oberhuber classification was used for the standard classification of the mucosal lesions (see the Supplementary Appendix).

Patients kept a diary (on paper or electronically) to record their daily use of the assigned trial drug as well as their gluten biscuit and food intake, concomitant medications, and stool frequency and characteristics. Scores on the Celiac Symptom Index and Celiac Disease Questionnaire were determined at all visits. At the end of the treatment period (week 6), investigators and patients independently rated the trial treatment as being “very good,” “good,” “satisfactory,” or “poor” with regard to both efficacy and the side-effect profile.

Adverse events were recorded and evaluated by the investigators. Blood samples were obtained to determine hematologic, coagulation, and serum markers.

**Statistical Analysis**

We estimated that a sample of 136 patients, or 34 patients per group, would provide the trial with 80% power for the primary analysis, assuming an alpha error of 0.05, an effect size of 0.6, and standard deviation of 0.8. On the basis of an estimated 15% of patients either withdrawing or having insufficient samples for evaluation, we planned for the enrollment of 160 patients (40 per group).

The primary end point, the mean change in the ratio of villus height to crypt depth from baseline to week 6, was analyzed with the use of a generalized linear model with the identity link, in which trial group and the baseline ratio of villus height to crypt depth were fixed effects, because assumptions for the parametric model were met. Each ZED1227 dose group was compared with the placebo group. The same statistical method was used for the analyses of the change from baseline to week 6 in the intraepithelial lymphocyte density, Celiac Symptom Index scores, and Celiac Disease Questionnaire scores, which were key secondary end points.

The statistical analysis of other end points (the change of Marsh–Oberhuber classification, transglutaminase 2 IgA and IgA antiendomysial antibodies, and blood malabsorption markers) is described in the Supplementary Appendix. The analysis to assess sensitivity to missing data is described in the Supplementary Appendix.

Plasma concentrations of ZED1227 and metabolites were measured and analyzed for pharmacokinetic profiles. The results are not reported here.

All statistical comparisons between each ZED1227 dose and placebo were two-sided, with a familywise alpha error of 0.05. For the analysis of the primary end point, 95% confidence intervals and P values were adjusted for multiple comparisons with the use of Bonferroni correction to account for the three comparisons with placebo. An adjusted P value of 0.0167 was considered to indicate statistical significance for the primary end point, and individual confidence intervals were constructed with the use of 98.3% levels. For secondary end points, 95% confidence intervals are reported without P values; the 95% confidence intervals have not been adjusted for multiple comparisons and cannot be used to infer definitive treatment effects. One interim analysis was conducted for the primary efficacy variable (see the Supplementary Appendix).

**Results**

**Characteristics of the Patients and Regimen Adherence**

The trial was conducted from May 16, 2018, to February 27, 2020. Of the 163 patients who underwent randomization (with 41 patients assigned to the 10-mg ZED1227 group, 41 to the 50-mg group, 41 to the 100-mg group, and 40 to the placebo group), 3 did not receive ZED1227 or placebo because of the development of other clinical conditions, and 1 patient received ZED1227 but was lost to follow-up (Fig. S2). Analyses of efficacy excluded these 4 patients and thus included 41 patients in the 10-mg group, 41 in the 50-mg group, 39 in the 100-mg group, and 38 in the placebo group.

The demographic characteristics of these 159 patients were similar across the groups, except for a higher percentage of women in the 10-mg group (Table 1). According to the investigators’ assessment and patients’ diaries, adherence was...
Transglutaminase 2 Inhibitor for Celiac Disease

high and similar in all four groups, ranging from 96 to 100% both for the trial regimen and for gluten intake.

**Efficacy Results**

Histology-related efficacy end points could be evaluated in 142 patients who had sufficient biopsy samples at both baseline and week 6; a total of 35 patients in the 10-mg group, 39 in the 50-mg group, 38 in the 100-mg group, and 30 in the placebo group were included in the analysis. Four of these patients stopped treatment before week 6 but qualified for inclusion in the primary end-point analysis with a treatment duration of 23 to 32 days.

As expected, in the placebo group, the gluten challenge decreased the ratio of villus height to crypt depth from baseline to week 6 (estimated change, −0.61; 95% confidence interval [CI], −0.78 to −0.44). Treatment with daily doses of 50 mg and 100 mg of ZED1227 prevented this deterioration (estimated change, −0.12 [95% CI, −0.27 to 0.03] and −0.13 [95% CI, −0.28 to 0.03], respectively); efficacy in the 10-mg group was slightly less (estimated change, −0.17; 95% CI, −0.33 to −0.01). As compared with placebo, all three dose levels of ZED1227 significantly prevented a decrease in the ratio of villus height to crypt depth (P≤0.001 for all comparisons) (Table 2 and Figs. 1 and S3A). Results of the sensitivity analysis were similar to those of the primary end-point analysis (Table S1).

Gluten ingestion caused an increase from baseline in intraepithelial lymphocyte density, a
key variable of mucosal inflammation, in the placebo group, the 10-mg group, and the 50-mg group but not in the 100-mg group; the increase was attenuated by ZED1227 dose-dependently (Table 3 and Figs. S3B and S4). According to the modified Marsh–Oberhuber classification, a histologic score in which class 2 describes deepened crypts and class 3a to 3c categorically describes increasing severity of villus atrophy and increasing crypt depth, the odds and risk ratios favored all three doses of ZED1227 over placebo (Tables S2 and S3).

The Celiac Symptom Index score increased from baseline to week 6 in all groups and returned to baseline at the follow-up visit. Comparison with placebo favored all dose levels of ZED1227. The Celiac Disease Questionnaire overall score increased from baseline to week 6 in all ZED1227 dose groups but decreased with placebo. The changes in the Celiac Disease Questionnaire gastrointestinal subscore from baseline to week 6 and comparison with placebo favored ZED1227. At the week 6 visit, 10% of the patients in the 10-mg group, 7% of those in the 50-mg group, 8% of those in the 100-mg group, and 26% of those in the placebo group assessed the efficacy as “poor.” Data are shown in Tables 3 and S4 and Figure S5.

At screening (baseline), all the patients had normal levels of transglutaminase 2 IgA. At the week 6 assessment, 1 patient (2%) who received the 10-mg dose, 1 (2%) who received the 50-mg dose, and no patient who received the 100-mg dose, as compared with 6 patients (16%) who received placebo, had a conversion to a positive result. The titer of transglutaminase 2 IgA increased by a mean of 2.4 kU per liter in the placebo group, by 1.7 kU per liter in the 10-mg group, and by 0.3 kU per liter in the 50-mg group and decreased by 0.1 kU per liter in the 100-mg group. Similar results were obtained regarding IgA antiendomysial antibodies (Tables S5 and S6).

**SAFETY**

Adverse events occurred in 125 of the 160 patients (78%) who received at least one dose of ZED1227 or placebo (Table 4). In addition to the 159 patients in the efficacy analysis, 1 patient was added to the 100-mg group for the safety

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**Figure 1. Paired Data Plots of the Mean Ratio of Villus Height to Crypt Depth (Primary End Point).**
The primary end point was the attenuation of gluten-induced mucosal damage, as measured by the ratio of villus height to crypt depth. The prespecified population for this analysis included the 142 patients who had villus height and crypt depth measurements from at least three villus–crypt units in total from the duodenum biopsies available at both the screening (baseline) visit and the final or withdrawal visit. Horizontal bars indicate mean values in each group at each time point.
transferrin saturation, zinc, vitamin B12, and folic functions, surrogates of resorption (albumin, blood, including cell counts, liver and kidney liac disease pathogenesis. 8,9 As compared with the small intestinal mucosa, a key driver of ce- tentiation of gluten-peptide immunogenicity in specifically block transglutaminase 2–mediated po- gluten intake. ZED1227 was developed to spe - langed with a moderate amount (3 g) of daily in patients with celiac disease who were chal - transglutaminase 2 inhibitor ZED1227 was shown of transglutaminase 2 inhibition with the oral placebo-controlled, 6-week trial, the effectiveness In this preliminary, randomized, double-blind, ZED1227 or placebo and recovered. These 2 patients discontinued ZED1227 or placebo and recovered. A broad range of variables were measured in blood, including cell counts, liver and kidney functions, surrogates of resorption (albumin, transferrin saturation, zinc, vitamin B12, and folic acid), and factor XIII, another common transglu-aminase. Results were similar across all the trial groups. During the gluten challenge, the levels of alanine aminotransferase and alkaline phosphatase increased from baseline to week 6 in the placebo group and then normalized at week 10. Such changes were not observed in any of the ZED1227 groups (Table S7).

**DISCUSSION**

In this preliminary, randomized, double-blind, placebo-controlled, 6-week trial, the effectiveness of transglutaminase 2 inhibition with the oral transglutaminase 2 inhibitor ZED1227 was shown in patients with celiac disease who were challenged with a moderate amount (3 g) of daily gluten intake. ZED1227 was developed to specifi- cally block transglutaminase 2–mediated po- tentiation of gluten-peptide immunogenicity in the small intestinal mucosa, a key driver of ce- liac disease pathogenesis.8,9 As compared with placebo, all doses of ZED1227 attenuated the gluten-induced small intestinal damage. This trial showed that treatment with the high- ly specific transglutaminase 2 inhibitor ZED1227 attenuated the gluten-induced damage in the duodenal mucosa. The ratio of villus height to crypt depth is widely considered to be the most objective and valid primary end point in clinical studies for therapies for celiac disease,24,28–30 and the end point was achieved at all three dose levels of ZED1227. The benefits across multiple end points were most pronounced for the 50-mg and 100-mg doses. Improved patient-reported outcomes across the dose groups need to be con- firmed in a larger study, since they may reflect the rather small size of each group for the evalua- tion of symptoms or the scales capturing some symptoms that may overlap with, but are unre- lated to, celiac disease. Overall, the incidence and severity of adverse events were similar in the ZED1227 groups and the placebo group.

Since the discovery of transglutaminase 2 as the autoantigen in celiac disease,15 extensive research has confirmed it to be a crucial mecha- nistic driver of gluten-induced inflammation and clinical manifestations in patients with celiac disease.8,10,16,17 This trial supports the role of transglutaminase 2 in the pathogenesis of celiac disease, given that its inhibition prevents the deamidation of gluten peptides in the small intestinal mucosa and thus abolishes the immuno- genic process. ZED1227 targets the intestinal mucosa predominantly and thereby mediates protec- tion; thus, it is unaffected by the complexity of the food matrix and is less dependent on the timing of ingestion of gluten-containing food.

The Food and Drug Administration recently reinforced its recommendation that, in pharmaco- logic trials of celiac disease, the prevention of histologic damage should be a major end point in phase 2 clinical studies, and the improvement of celiac disease–related patient-reported outcomes and quality of life should both be primary end points in phase 3 trials.10 This recommendation is justified, since only 40% of adult patients with newly diagnosed celiac disease have gastrointes- tinal symptoms, whereas a gluten challenge in- duces a manifest duodenal mucosal lesion, often before any symptoms occur.22,31 Furthermore, mucosal healing is considered to be the key cri- terion of successful treatment and a prerequisite for patients’ long-term well-being and the pre- vention of severe complications.32–34 Therefore, we selected the gluten challenge and used vali-
Table 3. Effect of ZED1227 Treatment on Intraepithelial Lymphocyte Density and Scores on the Celiac Symptom Index and Celiac Disease Questionnaire.*

<table>
<thead>
<tr>
<th>Variable</th>
<th>ZED1227, 10 mg</th>
<th>ZED1227, 50 mg</th>
<th>ZED1227, 100 mg</th>
<th>Placebo</th>
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</thead>
<tbody>
<tr>
<td><strong>Intraepithelial lymphocyte density</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Baseline</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>No. of patients</td>
<td>41</td>
<td>41</td>
<td>39</td>
<td>38</td>
</tr>
<tr>
<td>No. of cells per 100 epithelial cells</td>
<td>26.5±6.8</td>
<td>29.3±9.0</td>
<td>26.4±8.4</td>
<td>27.9±10.2</td>
</tr>
<tr>
<td>After gluten challenge at wk 6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. of patients</td>
<td>35</td>
<td>39</td>
<td>38</td>
<td>31</td>
</tr>
<tr>
<td>No. of cells per 100 epithelial cells</td>
<td>34.6±12.0</td>
<td>35.7±12.0</td>
<td>27.9±7.8</td>
<td>38.6±15.7</td>
</tr>
<tr>
<td>Change from baseline (95% CI) — no. of cells per 100 epithelial cells†</td>
<td>8.3 (5.0 to 11.7)</td>
<td>6.9 (3.7 to 10.1)</td>
<td>1.5 (-1.8 to 4.7)</td>
<td>11.0 (7.4 to 14.6)</td>
</tr>
<tr>
<td>Estimated difference vs. placebo (95% CI)</td>
<td>-2.7 (-7.6 to 2.2)</td>
<td>-4.2 (-8.9 to 0.6)</td>
<td>-9.6 (-14.4 to -4.8)</td>
<td>—</td>
</tr>
<tr>
<td><strong>Celiac Symptom Index‡</strong></td>
<td></td>
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<td>38</td>
<td>39</td>
<td>38</td>
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<tr>
<td>Score</td>
<td>24.4±5.6</td>
<td>27.0±7.8</td>
<td>24.2±5.1</td>
<td>26.0±5.8</td>
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<tr>
<td>After gluten challenge at wk 6</td>
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<tr>
<td>No. of patients</td>
<td>38</td>
<td>38</td>
<td>37</td>
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<tr>
<td>Score</td>
<td>25.9±6.1</td>
<td>29.0±8.0</td>
<td>25.2±5.8</td>
<td>29.8±9.4</td>
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<tr>
<td>Change from baseline (95% CI)‡</td>
<td>0.9 (-1.0 to 2.8)</td>
<td>2.0 (0.0 to 3.9)</td>
<td>0.1 (-1.8 to 2.1)</td>
<td>4.0 (1.8 to 6.1)</td>
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<tr>
<td>Estimated difference vs. placebo (95% CI)</td>
<td>-3.0 (-5.9 to -0.2)</td>
<td>-2.0 (-4.9 to 0.9)</td>
<td>-3.8 (-6.7 to -1.0)</td>
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<tr>
<td><strong>Celiac Disease Questionnaire, overall§</strong></td>
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<tr>
<td>No. of patients</td>
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<td>40</td>
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<td>Score</td>
<td>172.5±13.0</td>
<td>164.5±17.5</td>
<td>170.3±12.9</td>
<td>168.4±16.9</td>
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<tr>
<td>Score</td>
<td>174.5±12.6</td>
<td>166.3±16.6</td>
<td>174.2±13.6</td>
<td>166.4±18.6</td>
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<tr>
<td>Change from baseline (95% CI)§</td>
<td>3.2 (-0.6 to 7.0)</td>
<td>0.9 (-3.0 to 4.7)</td>
<td>3.7 (-0.2 to 7.7)</td>
<td>-2.1 (-6.2 to 2.1)</td>
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<tr>
<td>Estimated difference vs. placebo (95% CI)</td>
<td>5.3 (-0.4 to 10.9)</td>
<td>2.9 (-2.7 to 8.6)</td>
<td>5.8 (0.1 to 11.5)</td>
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<tr>
<td><strong>Celiac Disease Questionnaire, gastrointestinal subscore§</strong></td>
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<td>Baseline</td>
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<td>No. of patients</td>
<td>41</td>
<td>40</td>
<td>38</td>
<td>36</td>
</tr>
<tr>
<td>Score</td>
<td>42.6±5.6</td>
<td>41.7±4.5</td>
<td>42.0±4.2</td>
<td>41.9±5.3</td>
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<td>After gluten challenge at wk 6</td>
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<tr>
<td>No. of patients</td>
<td>40</td>
<td>41</td>
<td>39</td>
<td>34</td>
</tr>
<tr>
<td>Score</td>
<td>42.1±6.5</td>
<td>40.5±5.8</td>
<td>42.3±4.6</td>
<td>38.3±7.0</td>
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<tr>
<td>Change from baseline (95% CI)§</td>
<td>-0.5 (-2.1 to 1.2)</td>
<td>-1.2 (-2.9 to 0.4)</td>
<td>0.1 (-1.6 to 1.8)</td>
<td>-3.6 (-5.4 to -1.8)</td>
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</table>
Transglutaminase 2 Inhibitor for Celiac Disease

Quantitative histopathological testing as the primary end point in our proof-of-concept trial.20,21,24,27,29,35-38

Celiac disease is highly prevalent in White, Middle Eastern, and Indian populations and is prevalent among Native Americans and Northeast Asians. The prevalence is low among Black Africans and Southeast Asians, but the prevalence in these populations can be high if European ancestry is also involved. Therefore, the patients in our trial represented the ancestral cross-section of the European countries participating in the trial; there was no intention to include or exclude certain racial or ethnic groups from the trial.

Strengths of this trial were the high levels of patient adherence to the regimen and to the gluten challenge, which maximized the data that...
could be evaluated. Limitations include a substantial amount of missing data and the loss of several patients to follow-up, the short duration of the trial, and the controlled gluten ingestion. Future studies of ZED1227 in more patients are needed to provide additional evidence of the safety and efficacy of the drug, potentially in real-life conditions with minor gluten ingestion.

In this phase 2 trial, we found that the oral transglutaminase 2 inhibitor ZED1227 effectively attenuated intestinal mucosal injury in patients with celiac disease challenged with a moderate dose of daily gluten.

Supported by Dr. Falk Pharma.

Disclosure forms provided by the authors are available with the full text of this article at NEJM.org.

A data sharing statement provided by the authors is available with the full text of this article at NEJM.org.

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**REFERENCES**