SERODIAGNOSIS OF NEUROCYSTICERCOSIS USING SYNTHETIC 8-KD PROTEINS: COMPARISON OF ASSAY FORMATS

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Abstract. The assay of choice for serological detection of cysticercosis in humans and pigs is the enzyme-linked immunoelectrotransfer blot (EITB), a Western blot assay that relies on the use of seven lentil-lectin–purified glycoproteins (LLGPs) derived from Taenia solium metacestodes. The EITB is has a sensitivity of 98% and a specificity of 100% in detecting cysticercosis, yet scarcity of native source material and the labor-intensive process of metacestode purification hinder its practicality. These limitations have necessitated the reproduction of the EITB antigens in synthetic forms. Four chemically synthesized LLGP antigens, TS14, TS18var1, TSRS1, and TSRS2var1, were assayed individually by enzyme-linked immunosorbent assay (ELISA) and Western blot for immunoreactivity against a large cohort of sera from clinically defined neurocysticercosis patients. The sensitivity and specificity of all four of these antigens using the ELISA format were well below the standards set by the LLGP EITB, whereas results of the Western blot format closely mirrored those of the LLGP EITB.

INTRODUCTION

The World Health Organization has recently classified neurocysticercosis (NCC) as the most important neurologic disease of parasitic origin in humans.1 Neurocysticercosis is a major cause of adult-onset epilepsy in areas where the pork tapeworm Taenia solium is endemic.2–5 The disease develops after ingestion of tapeworm eggs and the subsequent encystment of the larval metacestode in the tissues of the brain and central nervous system. The cysts can remain viable for many years, but eventually degenerate into inactive granulomas, and finally calcified lesions. Neurocysticercosis can be asymptomatic, but may produce a broad range of clinical manifestations, including headaches, seizures, hydrocephaly, and death. Unfortunately, T. solium-endemic areas are often rural and impoverished, lacking in basic sanitation and adequate medical care. The disease is first detected when infected persons exhibit neurologic symptoms and seek medical treatment in city clinics. Diagnosis of NCC in these cases is performed by computed tomography (CT) or magnetic resonance imaging (MRI) scans of the brain, followed by a confirmatory serologic assay. The enzyme-linked immunoelectrotransfer blot (EITB), a Western blot assay developed in 1989 that has a sensitivity of 98% and a specificity of 100% in detecting pathologically confirmed cases of NCC, was recognized as the serologic assay of choice for the detection of cysticercosis in humans and pigs by the World Health Organization/Pan American Health Organization in 1995.7–10 To produce the assay, cysts are excised from porcine tissue, homogenized, and partially purified on a lentil-lectin column. The resulting lentil-lectin glycoproteins (LLGPs) are then separated by electrophoresis and blotted onto a nitrocellulose matrix for detection with NCC-specific patient antibody. Separation of LLGP results in seven distinct antigenic bands of 13, 14, 18, 21, 24, 39–42, and 50 kD (Figure 1A).11–14 Antibody reactivity with any one of these bands indicates exposure to cysticercosis.

Although the EITB has been instrumental in detecting NCC where brain imaging equipment and expertise is unavailable, its dependence on the acquisition and purification of native cyst antigen make it impractical and costly. Furthermore, the EITB is not quantitative. A quantitative assay that detects antibodies to cysticercosis may provide a means to monitor patient disease status and efficacy of chemotherapy. One quantitative assay format, the enzyme-linked immunosorbent assay (ELISA), performed in polystyrene plates, is particularly desirable, because it lends itself to high-throughput diagnostic applications. Previous attempts to use LLGP in an ELISA format have failed because LLGP contains irrelevant proteins that bind to polystyrene with a higher affinity than any of the seven T. solium-specific antigens. To build a new assay format that maintained the sensitivity and specificity of the EITB without its reliance on native antigen, we isolated the seven diagnostic proteins in LLGP, cloned and sequenced them, then reproduced them either synthetically or recombinantly.11–14 The LLGP antigens of 13, 14, 18 and 21-kD (Figure 1A) have been identified as belonging to a large, closely related group of proteins representing four distinct phylogenetic clades, the 8-kD antigen family.12,13 Previous results showed that 48–82% of patients tested reacted in the EITB with these antigens.14 Four chemically synthesized representative T. solium (TS) antigens from each of the four clades, TS14, TS18var1, TSRS1, and TSRS2var1, were assayed individually by ELISA and Western blot for immunoreactivity against large cohorts of sera from clinically defined neurocysticercosis patients, healthy individuals who had not traveled outside the United States, and persons infected with other parasitic diseases from areas without cysticercosis.
MATERIALS AND METHODS

**Defined serum collections.** Defined cysticercosis serum samples \((n = 377)\) were collected at the Nacional de Ciencias Neurologicas (Lima, Peru) from patients presenting with clinical symptoms of NCC. Patients were confirmed as having NCC by both EITB serology and CT or MRI brain imaging as outlined by del Brutto and others.\(^{15}\) Patient samples were collected in compliance with protocols reviewed and approved by the ethical review boards of all institutions concerned (Centers for Disease Control and Prevention and Universidad Peruana Cayetano Heredia). All patients involved in this study provided written informed consent. Patients were assorted according to the presence and number of viable, racemose (malignant), degenerating, and calcified cysts shown by brain images. Serum from patients diagnosed as having either \(\geq 2\) viable cysts or a racemose cyst \((n = 107)\) in this collection were used to determine the overall antigen sensitivity in both assay formats because single lesions are not clear indicators of NCC.\(^{2,15,16}\) Antigen-specific sensitivity for serum antibodies from patients diagnosed as having only single, viable cysts \((n = 20)\), degenerating (dying) cysts \((n = 66)\), and inactive, calcified cysts \((n = 114)\) was also evaluated. Brain scans of many patients \((n = 70)\) showed cysts in several stages of viability, and were evaluated separately. To define the specificity of the 8-kD antigens for cysticercosis, serum samples from healthy individuals who had not traveled outside the United States (normal human sera [NHS]) \((n = 146)\), and sera from persons infected with other parasitic diseases from countries where NCC is not endemic \((n = 162)\) were tested. The infected serum used to test for specificity were from confirmed cases of infection with *Ascaris lumbricoides* (6), *Cryptosporidium parvum* (10), *Echinococcus granulosus* (20), *Echinococcus multilocularis* (1), *Fasciola hepatica* (4), *Leishmania donovani* (1), *Leishmania tropica* (1) *Plasmodium falciparum* (16), *Schistosoma haematobium* (17), *Schistosoma mansoni* (36), *Trichinella spp.* (16), and *Taenia saginata* (14). Normal human sera \((20)\) from an area in Egypt that is socioeconomically similar to Peru, as well as highly endemic for exposure to schistosomiasis and other parasitic diseases, were also included for their potential cross-reactivity.

**8-kD antigens.** The full-length, 8-kD proteins were chemically synthesized without their signal sequences by commercial manufacturers at a purity of \(\geq 95\%\) as follows: TS14 (AF082829), (Gryphon Sciences, San Francisco, CA and AnaSpec Inc., San Jose, CA); TS18var1 (AF098073), (AnaSpec); TSRS1 (AF082830) (AnaSpec); and TSRS2var1 (AF356343), (SynPep Corp., Dublin, CA and AnaSpec). All of the synthetic 8-kD mature protein sequences are 66 amino acids in length, with the exception of TS18var1, which is 67 amino acids long (Table 1). In cases where individual proteins were acquired by more than one manufacturer, intra-assay comparisons of specific activity showed that there was no difference in protein performance between manufacturers.

**Enzyme-linked immunosorbent assay.** The quantitative determination of patient seroreactivity to the 8-kD proteins was determined by the Falcon* assay screening test (FAST)–ELISA method described previously.\(^{17}\) Briefly, lyophilized 8-kD antigens were solubilized in 0.05 M N-2-hydroxyethylpiperazine-N’-2-ethane sulfonic acid (HEPES), pH 7.0, 0.1 M NaCl, 2 mM dithiothreitol (DTT) and quantitated by 280 nM ultraviolet (UV) spectrophotometry, using the extinction coefficients of each. To prevent freezing at the storage temperature of \(\sim 80^\circ\)C, glycerol was added to a final concentration of 43.5%. All antigens were assayed separately in excess. Each was diluted in phosphate-buffered saline (PBS), pH 7.2, to a concentration of 0.01 mg/mL, then sensitized to the polystyrene sticks of NUNC-TSP transferable solid-phase screening system lids (catalog no. 445497; Nalge Nunc International, Roskilde, Denmark) from the corresponding 96-well flat bottom incubation plates (catalog no. 269620; Nalge Nunc International).
Mature protein sequences of the full-length, *Taenia solium* 8-kD antigens chemically synthesized for evaluation in enzyme-linked immunosorbent and enzyme-linked immunoelectrotransfer blot serodetection assays.\(^\text{12,13}\)

<table>
<thead>
<tr>
<th>Protein name</th>
<th>GenBank accession no.</th>
<th>Sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>TS14</td>
<td>AF08289</td>
<td>EKNKPKDVANSTKKGIEYHVEFHEDPEGKQIAQLKEKWEAMELEDKGKIRSLVEHCKGPKKTA</td>
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<tr>
<td>TS18var1</td>
<td>AF098073</td>
<td>EKTIPKCDTINSTKKEIEYHVNWFFHDPDGQKIAQLKNEWTEVQGAKGEIRSLAEYCRGLKNKTA</td>
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<td>TSR1</td>
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<tr>
<td>TSR2var1</td>
<td>AF356343</td>
<td>EKNKTDVGBKSKKWEVFHHRFEDPEGKQIAQLKDWNETAPECKVRALLAENRRLGKNTA</td>
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**RESULTS**

**Enzyme-linked immunosorbent assay.** All protein antigens were directly coated to polystyrene at an excess concentration.

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<table>
<thead>
<tr>
<th>Table 1</th>
<th>Comparative serodiagnosis of neurocysticercosis</th>
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<tbody>
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<td>Protein name</td>
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<td>TS14</td>
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<tr>
<td>TSR2var1</td>
<td>AF356343</td>
<td>EKNKTDVGBKSKKWEVFHHRFEDPEGKQIAQLKDWNETAPECKVRALLAENRRLGKNTA</td>
</tr>
</tbody>
</table>
of 0.01 mg/mL. The initial evaluation study was performed using representative subsets of the Peruvian clinically defined sera (n = 206), NHS (n = 97), and the sera from patients infected with other parasitic diseases from non-endemic countries (n = 79). Sensitivity of each antigen for patient sera in various clinical stages was calculated, as well as the specificity of NCC serum antibody against cysticercosis antigens (Table 2). Overall assay efficacy, as measured by Youden’s J index ([Sensitivity + Specificity] – 1) was calculated using patients showing either ≥ 2 viable cysts or racemose cases of NCC by brain imaging techniques.20 Antigen sensitivity in detecting seroreactivity of patients with viable single cysts, degenerating cysts, and inactive calcifications is also shown. Patients with mixed infections (n = 41) were excluded from the analyses shown.

Each of the four 8-kD antigens had distinctly different reactivities with all serum samples tested. The cutoff points for each antigen were selected based on the best value obtained using Youden’s J index as a measure of efficiency. Plots showing the performance of all four 8-kD antigens and their respective cutoff values are shown in Figure 2. Since this evaluation study was repeated with highly similar results, we discontinued testing in this assay format.

Enzyme-linked immunoelectrotransfer blot. With the exception of TS14, all protein antigens performed better in the EITB format than in the ELISA, as shown by increases in Youden’s J index, which was again calculated using only those serum samples from patients with multiple and racemose cysts (n = 107) against the serum from persons with other parasitic diseases from countries not endemic for NCC (n = 162) and NHS samples (n = 146) (Tables 2 and 3). Since the J index values for all four antigens were similar to those shown in Table 3 when calculated using only those NCC and control serum used for evaluation of the 8-kD ELISA (n = 382) (Table 2), the results of the larger cohorts are described. TSRS1 showed the greatest increase in sensitivity to multiple viable and racemose cysts (from 77% to 96%), whereas all other proteins showed lesser change in this disease category (≥ 5%). Likewise, TSRS1 showed the greatest improvement overall in detecting all other disease states, increasing in sensitivity by 35% for single cysts, 28% for degenerating cysts, and 27% for calcified cysts. TS14 also showed an increase in detecting various disease states, but was found to be highly cross-reactive with non-NCC sera, with a specificity of only 76%, which was lower than that of the ELISA format (85%). Except for TS14, all protein antigens showed improvement in specificity. Only TSRS1 improved in specificity for all disease categories, as well as showing increased specificity over the ELISA format.

Both TSRS1 and TS18var1 had Youden’s J index values greater than 0.9 in the EITB format, which is indicative of an efficient assay.20 Visual comparison of the two antigens on blot run against the same set of NCC serum samples shows that TSRS1 is superior in definition and clarity (Figure 1B). Weak positive NCC patient samples are harder to distinguish on the TS18var1 blot (Figure 1C), and often appear as faint, shadowy bands.

DISCUSSION

The principal objective of this study was to develop a cysticercosis detection assay that was not reliant on native cyst material, yet equaled the sensitivity and specificity shown by the current seroassay of choice, the native EITB.10 The development of synthetic and recombinant LLGP antigens has afforded the opportunity to assess the feasibility of supplanting the native EITB as the standard serologic assay for cysticercosis confirmation. The results of the TSRS1 EITB indicate that native antigen is not superior to synthetic antigen for detection of antibodies to NCC in this assay format, showing a sensitivity of 96% and a specificity of 98%, which are comparable to that of LLGP EITB (Table 3). A distinct advantage of the TSRS1 EITB is that only one antigenic band will appear in a positive NCC assay, as opposed to detection of any one of seven antigenic bands for a positive result in the native LLGP EITB.

Although TS18var1 EITB also performed with a high degree of sensitivity (97%) and specificity (100%) against NCC cases of multiple or racemose cysts, it is not a suitable substitute for native antigen in this assay format (Table 3). The TS18var1 EITB only detected 35% of single-cyst cases, whereas TSRS1 and native antigen both detected 85% of those patients. Furthermore, TS18var1 was tested at an ideal gel-loading concentration of 0.001 mg/mL/mm; higher concentrations of TS18var1 were cross-reactive with both NHS and other parasitic disease sera. The ultra-low concentration of this antigen in the EITB is problematic in two ways. First, the positive cases are not as clearly defined, often resulting in very faint bands (Figure 1C). Second, the consistent reproducibility of this assay is not ensured at such a low concentration. Conversely, TSRS1 exhibited no problems of cross-reactivity when tested at higher concentrations, and slight variations of the loading concentration of 0.02 mg/mL/mm did not skew assay results affecting sensitivity and specificity.

The secondary objective of this study was to develop a quantitative confirmatory assay for cysticercosis that may im-

### Table 2: Performance of four Taenia solium 8-kD antigens in an enzyme-linked immunosorbent assay format when tested against sera from clinically defined neurocysticercosis patients showing various stages of disease progression (n = 206)*

<table>
<thead>
<tr>
<th>% sensitivity</th>
<th>≥ 2 viable and racemose cysts (n = 73)</th>
<th>Single viable cyst (n = 16)</th>
<th>Degenerating cysts (n = 43)</th>
<th>Calcified cysts (n = 74)</th>
<th>% specificity (n = 176)</th>
<th>Youden’s J index</th>
</tr>
</thead>
<tbody>
<tr>
<td>TS14 (0.01)</td>
<td>90</td>
<td>50</td>
<td>42</td>
<td>30</td>
<td>85</td>
<td>0.756</td>
</tr>
<tr>
<td>TS18var1 (0.01)</td>
<td>95</td>
<td>44</td>
<td>56</td>
<td>49</td>
<td>85</td>
<td>0.791</td>
</tr>
<tr>
<td>TSRS1 (0.01)</td>
<td>77</td>
<td>50</td>
<td>33</td>
<td>20</td>
<td>93</td>
<td>0.699</td>
</tr>
<tr>
<td>TSRS2var1 (0.01)</td>
<td>86</td>
<td>44</td>
<td>35</td>
<td>31</td>
<td>86</td>
<td>0.721</td>
</tr>
</tbody>
</table>

* Serum samples from persons infected with other parasitic diseases from countries where cysticercosis is not endemic (n = 79) and healthy individuals who have not traveled outside the United States (n = 97) were used to determine antigen specificity.
part information regarding patient disease status, as well as lend itself to a high-throughput assay format. Unfortunately, direct coating of the 8-kD synthetic peptides to polystyrene for serodetection of NCC was unsuccessful. The antigens tested were either insensitive to some infected serum, as in the case of TSRS1, or highly cross-reactive with uninfected serum. Although the TS18var1 ELISA had the highest Youden’s J index (0.791), its specificity for NCC cases is too low (85%) for accurate interpretation in clinical settings.

Initial ELISA evaluation studies using biotinylated 8-kD antigens sensitized to streptavidin-coated polystyrene yielded promising results. When biotinylated-TS18var1 was further tested in an ELISA against a larger cohort of sera (202 samples), it performed similarly to the direct-coating TS18var1 ELISA in this study (Bueno E, unpublished data). The clinically defined Peruvian patient test serum used here has afforded the most comprehensive analyses of the synthesized 8-kD antigens in the ELISA format to date.

**TABLE 3**
Performance of four *Taenia solium* 8-kD antigens in an enzyme-linked immunoelectrotransfer blot format when tested against sera from clinically defined neurocysticercosis (NCC) patients showing various stages of disease progression (n = 307)*

<table>
<thead>
<tr>
<th>Antigen (mg/mL/mm)</th>
<th>2 viable and racemose cysts (n = 107)</th>
<th>Single viable cysts (n = 20)</th>
<th>Degenerating cysts (n = 66)</th>
<th>Calcified cysts (n = 114)</th>
<th>% specificity (n = 146)</th>
<th>Youden’s J index</th>
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<tr>
<td>TS14 (0.005)</td>
<td>94</td>
<td>70</td>
<td>55</td>
<td>63</td>
<td>76</td>
<td>0.703</td>
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<tr>
<td>TS18var1 (0.001)</td>
<td>97</td>
<td>35</td>
<td>44</td>
<td>33</td>
<td>100</td>
<td>0.972</td>
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<tr>
<td>TSRS1 (0.020)</td>
<td>96</td>
<td>85</td>
<td>61</td>
<td>47</td>
<td>98</td>
<td>0.943</td>
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<tr>
<td>TSRS2var1 (0.005)</td>
<td>82</td>
<td>40</td>
<td>38</td>
<td>29</td>
<td>98</td>
<td>0.800</td>
</tr>
</tbody>
</table>

* Serum samples from persons infected with other parasitic diseases from countries where cysticercosis is not endemic (n = 162), and healthy individuals who have not traveled outside the United States (n = 146) were used to determine antigen specificity. The Youden's J Index values for all four antigens were similar when calculated using the same NCC patient and control serum samples used in an 8-kD enzyme-linked immunosorbent assay (n = 382), so results of the larger serum cohorts are shown.

![Figure 2](image-url) Performance of the four *Taenia solium* 8-kD antigens in an enzyme-linked immunosorbent assay (ELISA) format as determined by serum antibody reactivity of neurocysticercosis (NCC) patients having either ≥ 2 viable or racemose cysts (n = 73), patients with other parasitic diseases (Others) (n = 79) and normal human sera (NHS) (n = 97). Cutoff points for **A**, TS14, **B**, TS18var1, **C**, TSRS1, and **D**, TSRS2var1, were determined using Youden’s J index ([Sensitivity + Specificity] − 1), and are shown by the horizontal line with the corresponding unit value at the right. Units of activity in all plots are based on the standard curve and are shown in log_{10}-scale format.
Synthetic protein antigens provide a simplified, low-cost alternative to native antigens in diagnostic applications. As cysticercosis eradication efforts progress, native cyst material will become increasingly more difficult to obtain. There are a few examples of attempts to use synthetic peptides to detect cysticercosis.\textsuperscript{13,15,17,21} Although all of these published trials used their respective peptide antigens in an ELISA format, only one, the biotinylated 8-kD antigen trial, was a serodetection assay.\textsuperscript{13} The others relied on extraction of patient cerebrospinal fluid as the test sample, which is a highly invasive procedure, as well as impractical in most clinical settings where cysticercosis is endemic.

As indicated by this study, assay format has a great bearing on the value of the 8-kD synthetic proteins as cysticercosis detection antigens. TSSR1 performed well in the EITB format in which it was discovered, yet failed to perform with the desired sensitivity and specificity in the ELISA format. The TSSR1 EITB has effectively shown that synthetic antigens can closely match the sensitivity and specificity of native antigen when tested in the appropriate format. Due to the small size of synthetic proteins, and their lack of native structure, both solid- and liquid-phase diagnostic applications merit exploration.\textsuperscript{21} Future seroassay development with 8-kD peptides will include direct application of 8-kD synthetic antigens to nitrocellulose, and an ELISA in which the antigen-antibody binding occurs in solution.

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