Simultaneous Detection and Discrimination of Virulent and Benign *Dichelobacter nodosus* in Sheep of Flocks Affected by Foot Rot and in Clinically Healthy Flocks by Competitive Real-Time PCR

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Ovine foot rot caused by *Dichelobacter nodosus* is affecting sheep worldwide. The current diagnostic methods are difficult and cumbersome. Here, we present a competitive real-time PCR based on allelic discrimination of the protease genes *aprV2* and *aprB2*. This method allows direct detection and differentiation of virulent and benign *D. nodosus* from interdigital skin swabs in a single test. Clinically affected sheep harbored high loads of only virulent strains, whereas healthy sheep had lower loads of predominantly benign strains.

*Dichelobacter nodosus* is the essential pathogen involved in the multifactorial disease of ovine foot rot. The Gram-negative bacterium causes painful inflammation and necrotizing lesions of the interdigital skin, a characteristic odor, and undermining of the hoof wall resulting in severe lameness in more advanced cases (1, 2). The clinical presentation depends on the virulence of the *D. nodosus* strain involved and on environmental factors. Diagnosis by cultivation and subsequent typing of this fastidious anaerobe is difficult, laborious, and not routinely done in diagnostic laboratories, and it is often not fast enough to implement the necessary measures to segregate infected animals and prevent the disease from spreading (3). Moreover, the gelatin-gel and elastase assays to test for protease activity, traditionally carried out to detect and differentiate virulent and benign *D. nodosus* strains, is difficult to perform and is strongly dependent on the quality of the growth medium and hence may yield inconsistent results (4). PCR-based approaches have markedly improved sensitivity and speed of detection of *D. nodosus* (3, 5–9). However, a method of fast, reliable and, ideally, simultaneous detection and virulotyping does to date not exist.

The acidic protease 2 (AprV2) has been identified as a key virulence factor of *D. nodosus* (10). In virulent strains, the aprV2 gene encodes a thermostable protease involved in foot rot tissue damage, whereas benign strains contain the homologous gene *aprB2* encoding a thermolabile protease. The *aprV2* and *aprB2* alleles differ by a 2-bp substitution, TA/CG, at position 661/662 (11). These single nucleotide polymorphisms (SNPs) result in a distinct amino acid change (Tyr92Arg), defining elastase activity in the mature protein (10). We have recently shown by sequencing that these SNPs in *aprV2/B2* fully correlated with the clinical status of the individual sheep or the foot rot history of the herd, and the TA and CG nucleotides were consistent with the virulent and the benign *D. nodosus* strains, respectively (12). In contrast, other SNPs in the *aprV2/B2* and in the protease genes *aprV5/B5* and *bprV/B8* showed no consistent relation to strain virulence (12).

To rapidly assess infections by virulent or benign *D. nodosus*, we developed a competitive real-time PCR method permitting simultaneous detection and allelic discrimination of *aprV2* and *aprB2* directly from clinical samples. One primer pair and two 3′-minor groove binder (MGB) probes allowing allelic discrimination were designed using Primer Express software v 3.0 (Table 1). The two probes DnAprTM-vMGB (FAM) and DnAprTM-bMGB (VIC) cover the SNPs and are specific for *aprV2* and *aprB2*, respectively. This kind of approach is rarely applied to bacteria but has several advantages, especially in the case of *D. nodosus*. First, in the absence of the specific target but in the presence of a highly similar target, PCR detection and discrimination based on mismatches could lead to false-positive results. This happens when either benign or virulent *D. nodosus* (or even both simultaneously) is present in sheep populations and even in individual animals (13). With the use of two probes competitively, the specific probe will prevent the nonspecific one from binding, thereby raising the overall specificity of the assay. Second, this PCR method allows detection of both the virulent and the benign allele in a single reaction, indicating the presence of either one or both, including their relative amounts. Optimized assay conditions consisted of a 25-μl reaction mixture containing 1 X TaqMan Genotyping MasterMix (Applied Biosystems, Foster City, CA), 300 nM primers, 100 nM DnAprTM-vMGB and 250 nM DnAprTM-bMGB, pyrogen-free water, and 2.5 μl of DNA template (Table 1). Amplification was done in a 7500 Real-Time PCR-System instrument (Applied Biosystems), using cycles of 2 min at 50°C and 10 min at 95°C, followed by 40 cycles with 15 s at 95°C and 1 min at 60°C. Results were analyzed using the Sequence Detector 7500 software (v 2.0.5.) with the threshold set at 0.015. Samples showing no probe-specific fluorescent signal were considered as negative (*C*<sub>T</sub> = 40), and samples resulting in probe-specific fluorescent signals were defined as being positive (*C*<sub>T</sub> < 40). Purified genomic DNA samples from the *D. nodosus* type...
strain ATCC 25549T for the virulent genotype aprV2 and from the Norwegian field strain Nor11B for the benign genotype aprB2 (14) were used as reference strains for assay optimization and as controls. Pyrogen-free water was applied to DNA and clinical sample preparation and also used as a nontemplate control.

The approximate detection limit and reproducibility of the aprV2/B2 real-time PCR assay were determined using 10-fold serial dilutions of DNA from reference strains ATCC 25549T and Nor11B. Mean CT values were plotted against DNA concentrations on a log scale and the efficiency (E) was calculated based on the slope of the resulting regression curve using the formula $E = (10^{-1/slope} - 1) \times 100$.

For the virulent strain ATCC 25549T, positive signals from the aprV2-specific probe but not from the aprB2-specific probe were observed. The opposite was true for the benign isolate Nor11B. The assay therefore allows discrimination of $D. nodosus$ virulotypes. Linearity over a tested range of six 10-fold dilutions was high, with $R^2$ values of 0.992 and 0.971, as were the calculated efficiencies of 100% and 92% with ATCC 25549T (aprV2) and Nor11B (aprB2), respectively. The detection limit, as calculated based on the DNA concentration of the type strain and the known genome size, was around 10 genome equivalents per reaction.

Using sequence data from the study of Stäuble et al. (12) as a gold standard to further test the performance of the competitive real-time PCR, the latter correctly identified all 45 samples containing the aprV2, and all 19 field samples containing the aprB2 allele were properly recognized (see Table S1 in the supplemental material). No false positives or false negatives were detected, and thus the assay proved to be 100% specific and 100% sensitive, and it correctly identified virulent and benign $D. nodosus$.

One hundred samples from flocks affected by foot rot, 92 samples from flocks not affected, and 4 samples from a farm with flocks of unclear status were collected from 16 farms in Switzerland, 2 farms in Germany, and 8 farms in France (see Table S1 in the supplemental material). They originated from affected flocks with a spectrum of disease severity (indicated by foot rot scores from 1 to 5) and from nonaffected flocks with healthy sheep (score 0), based on the Australian scoring system of Stewart and Claxton (15), whereby flock diagnosis is based on the most severe lesions present. Analogously, scores per sheep were determined by the highest-rated foot, and a sample from this foot was taken for subsequent analysis. Specimens were taken from the interdigital skin and, if present, from the margin of a lesion by a cotton swab. This turned out to be better than sampling by biopsy punch or by ring curette (data not shown). Cotton swabs were directly transferred into 1 ml SV lysis buffer (4 M guanidine thiocyanate, 0.01 M Tris-HCl [pH 7.5], and 1% β-mercaptoethanol), soaked for 30 to 60 s, and then removed. Samples in this buffer can be stored for several days without cooling, thus permitting easy transport to the laboratory for further processing using a quick DNA extraction.

**FIG 1** Comparison of CT values and the distributions of on clinical sample results from the aprV2/B2 and the pnpA real-time PCR assays. Box-whisker plots of CT values of field samples from clinically affected ($n = 100$; panel A) and nonaffected flocks ($n = 92$; panel B) are shown (pnpA assay detecting the presence of $D. nodosus$ without distinction of virulence, aprV2 assay detecting virulent, and aprB2 detecting benign $D. nodosus$ strains). The median and the upper and the lower quartiles are given in the box. The other two quartiles are indicated by lines and the outliers by dots (defined as values 1.5 times below or above the interquartile range). Based on the Kruskal-Wallis test, there were no significant differences ($P < 0.05$) between CT values from pnpA and aprV2 or aprB2 within the groups of affected or nonaffected flocks, respectively. However, CT values are significantly lower in the group of affected than in the group of nonaffected flocks.
The 196 samples were tested for the presence of virulent and benign _D. nodosus_ with the competitive real-time PCR, and the results were compared to results from the nondiscriminatory _pnpA_-based real-time PCR assay, which was used to estimate the load of _D. nodosus_ in the samples (12).

All of the samples from affected flocks tested positive for the virulent genotype _aprV2_ but were negative for _aprB2_. Two samples from a French flock with foot abscesses but unclear foot rot status tested positive for the virulent genotype, and this result was confirmed by sequencing. The assay detected the virulent genotype in animals of affected flocks without clinical symptoms at the time of sampling. Therefore, a simple swabbing of the interdigital skin in clinically healthy sheep may contain high concentrations of virulent _D. nodosus_ readily detectable at this early stage by the new assay. This is consistent with histological studies of bacterial invasion revealing the highest _D. nodosus_ cell load in early onset cases, which might not be clinically evident at this point (16, 17). These findings underline the fact that scoring systems and clinical assessments do not necessarily correlate with bacterial load and _D. nodosus_ virulotype.

In nonaffected flocks, over 80% of the samples tested positive for the benign genotype _aprV2_, as they also did in the _pnpA_ assay. Three samples were negative, as in the _pnpA_ assay. Nine others were negative for _aprV2_ and _aprB2_, although they were weakly positive in the _pnpA_ assay. Seven samples were positive for _aprV2_, however, with high _C_ \textsubscript{T} values indicating small amounts of virulent _D. nodosus_. Four of these showed positive results only for _aprV2_. The three others were positive for both _aprV2_ and _aprB2_, indicating the presence of both virulent and benign _D. nodosus_. Such mixed infections were observed only in animals from two flocks out of the 8 designated “nonaffected” (farms 9 and 15). In these flocks, other samples with only benign and three with only virulent _D. nodosus_ were also found. These two flocks had recurrent problems with foot rot during the grazing period following sampling.

There were good correlations of _C_ \textsubscript{T} values based on _pnpA_ and those of the allele-specific _aprV2/aprB2_ assay (Fig. 1 and Table 2). Generally, _C_ \textsubscript{T} values of animals from affected farms were clearly below 30, whereas those from nonaffected flocks were above 30, indicating that nonaffected animals had a much smaller quantity of _D. nodosus_. An exception was flock 11, which had low _C_ \textsubscript{T} values of around 25 for _aprB2_ only, indicating a high bacterial load of benign _D. nodosus_. The owner bandaged the feet of the sampled sheep due to slight lameness and very mild interdigital redness and exudates. We assume that this created favorable conditions for the growth of _D. nodosus_. This case shows that pure cultures of benign _D. nodosus_ at high loads may lead to a milder form of disease that is clearly detectable by the competitive real-time PCR. There were no significant differences in _C_ \textsubscript{T} values of the samples with scores of 1 to 5 (Table 2), indicating that once the disease is clinically evident loads of _D. nodosus_ are independent of the severity of the disease.

In conclusion, we present a rapid and sensitive diagnostic tool for early detection and virulotyping of _D. nodosus_ directly from simple, noninvasive interdigital swabs of sheep. This assay will help to elucidate the epidemiology of _D. nodosus_ and support efforts to combat the disease.

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### REFERENCES


### TABLE 2 Mean and median _C_ \textsubscript{T} values of real-time PCR results at the flock and animal levels

<table>
<thead>
<tr>
<th>Category (n)</th>
<th><em>C</em> \textsubscript{T} values for:</th>
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<tbody>
<tr>
<td></td>
<td><em>aprV2</em></td>
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<tr>
<td></td>
<td>Mean (SD) Median</td>
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<tr>
<td>Flocks affected (100)</td>
<td>26.1 (4.8) 24.5</td>
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<tr>
<td>Flocks healthy (92)</td>
<td>39.7 (1.2) 40.0</td>
</tr>
<tr>
<td>Animal score 0 (105)</td>
<td>37.2 (5.5) 40.0</td>
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<td>Animal score 1 (9)</td>
<td>25.0 (5.4) 22.7</td>
</tr>
<tr>
<td>Animal score 2 (16)</td>
<td>25.8 (5.2) 22.4</td>
</tr>
<tr>
<td>Animal score 3 (10)</td>
<td>23.2 (2.6) 21.9</td>
</tr>
<tr>
<td>Animal score 4 (17)</td>
<td>27.4 (4.0) 27.4</td>
</tr>
<tr>
<td>Animal score 5 (12)</td>
<td>28.0 (5.5) 26.5</td>
</tr>
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Mean and median values of real-time PCR results at the flock and animal levels.


