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► **To cite this version:**

Sarah H. Binns, Laura E. Green, Mick Bailey. Development and validation of an ELISA to detect antibodies to *Corynebacterium pseudotuberculosis* in ovine sera. *Veterinary Microbiology*, 2007, 123 (1-3), pp.169. 10.1016/j.vetmic.2007.02.015 . hal-00532211

HAL Id: hal-00532211

<https://hal.science/hal-00532211>

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Accepted Manuscript

Title: Development and validation of an ELISA to detect antibodies to *Corynebacterium pseudotuberculosis* in ovine sera

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PII: S0378-1135(07)00075-2
DOI: doi:10.1016/j.vetmic.2007.02.015
Reference: VETMIC 3592

To appear in: *VETMIC*

Received date: 11-8-2004
Revised date: 15-1-2007
Accepted date: 9-2-2007



Please cite this article as: Binns, S.H., Green, L.E., Bailey, M., Development and validation of an ELISA to detect antibodies to *Corynebacterium pseudotuberculosis* in ovine sera, *Veterinary Microbiology* (2007), doi:10.1016/j.vetmic.2007.02.015

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1 **Development and validation of an ELISA to detect antibodies to**
2 **Corynebacterium pseudotuberculosis in ovine sera**

3

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12

13 **Abstract**

14 Several enzyme-linked immunosorbent assays (ELISAs) have been developed for
15 the detection of antibodies to Corynebacterium pseudotuberculosis, the causative
16 agent of caseous lymphadenitis (CLA). However, none are commercially available in
17 the UK. It was therefore necessary to develop a new, economic ELISA for use in a
18 research project studying the epidemiology of CLA in UK sheep.

19 The ELISA with its diagnostic qualities is presented. The ELISA was developed using
20 sonicated C. pseudotuberculosis and optimised to detect total antibody or IgG class
21 antibody in serum. Receiver Operating Characteristic (ROC) curves were obtained
22 and the area under the ROC curve was used to compare the sensitivity and specificity
23 of the two ELISAs.

24 Both versions of the ELISA were evaluated on a panel of 150 positive reference sera
25 and 103 negative reference sera. Using the test at 100% specificity, the sensitivity of
26 detection of total antibody was 71% (95% confidence interval 63-78%), and the

27 sensitivity of detection of IgG antibody to C. pseudotuberculosis was 83% (76-89%),
28 which compares favourably with other reported ELISA tests for CLA in sheep. The
29 sensitivity of the IgG antibody assay may be higher because of the greater affinity of
30 IgG class antibodies compared with the IgM antibodies also detected by the total
31 antibody ELISA.

32 The results of ROC analysis indicated that the IgG isotype ELISA was more
33 accurate than the total antibody ELISA. The efficiency of the test was greatest when
34 serum samples were run in a dilution series than when any single serum dilution was
35 used. The ELISA is considered to be suitable for application in field studies of CLA
36 in UK sheep.

37

38 Keywords:

39 Corynebacterium pseudotuberculosis; Sheep-bacteria; ELISA; Diagnosis; Sensitivity;
40 Specificity

41

42 **1. Introduction**

43 Corynebacterium pseudotuberculosis (formerly C. ovis) is the causative agent of
44 caseous lymphadenitis (CLA) in sheep and goats. The disease is characterised by
45 abscess formation in lymph nodes and/or viscera. In the UK, affected sheep typically
46 have abscesses in the parotid or retropharyngeal lymph nodes, and the disease can be
47 diagnosed by bacteriological culture of pus from such abscesses. However, a
48 proportion of infected sheep may have only internal abscesses, often in the lungs or
49 mediastinal lymph nodes, and show no overt clinical signs of infection. Identification
50 of sheep with internal abscesses requires alternative diagnostic methods, and therefore
51 researchers have developed serological tests for the diagnosis of CLA.

52 CLA was first diagnosed in the UK in 1990, in imported Boer goats, and was first
53 reported in sheep in this country in 1991. It has since spread widely within the UK
54 sheep flock (Binns et al. 2002). CLA can cause economic losses for pedigree sheep
55 breeders and concern has been raised that the disease may spread to commercial
56 flocks and lead to an increased condemnation of lambs at slaughter. The true
57 prevalence of infection in UK sheep has not been estimated, partly due to the lack of
58 an adequate and available diagnostic test for infection in live sheep.

59 Although there are currently several serodiagnostic tests for the detection of
60 antibodies to C. pseudotuberculosis in sheep, including haemolysis inhibition (Burrell
61 1980), indirect haemagglutination, anti-haemolysin inhibition, complement fixation
62 tests (Shigidi 1979), immunodiffusion (Burrell 1980) and enzyme-linked
63 immunosorbent assays (ELISA), none are without problems (Sutherland et al. 1987).
64 Various antigen preparations have been used in the ELISA tests, including cell wall
65 antigens (Sutherland et al. 1987), crude exotoxin (phospholipase D) (ter Laak et al.
66 1992; Dercksen et al. 2000), cell supernatant (Maki et al. 1985), and recombinant
67 exotoxin (Menzies et al. 1994).

68 Typically the tests perform adequately in goats (Dercksen et al. 2000; Kaba et al.
69 2001), but with reduced sensitivity in sheep, especially in subclinically infected sheep
70 with only internal abscesses. Tests may also have differing specificity when compared
71 with bacteriological culture, possibly due to cross-reactions with related bacterial
72 species or infected but recovered sheep (culture negative) or because of presence of
73 maternal antibodies. Finally, the rate of seropositivity in culture-positive sheep varies
74 with age and immune status and with the route and extent of exposure to C.
75 pseudotuberculosis and the interval between exposure and diagnosis (Sutherland et al.
76 1987).

77 The most specific diagnostic test reported for C. pseudotuberculosis is an ELISA
78 based on recombinant phospholipase D (PLD) expressed in E. coli (Menzies et al.
79 1994). Perhaps the best current ELISA test is that developed for use in the Dutch CLA
80 elimination and control programme (Dercksen et al. 2000). This modified double
81 antibody sandwich ELISA has a sensitivity of $79 \pm 5\%$ and specificity of $99 \pm 1\%$ for
82 sheep. Neither of these ELISA tests are commercially available in the UK at present,
83 and all those developed to date are relatively expensive. This paper describes the
84 development of an alternative test used to for epidemiological research studies of
85 ovine CLA in the UK.

86

87 **2. Materials and Methods**

88 2.1 Sample collection and management

89 Blood samples were collected from sheep by jugular venepuncture into 10 ml
90 vacutainer tubes without anticoagulant (Becton-Dickinson). Serum was separated
91 from clotted blood in vacutainers by centrifugation and decanting. Serum samples
92 were aliquoted and stored at 4°C until processed; long-term storage was undertaken at
93 -20°C .

94 To ascertain the true infection status of abscessed sheep in the positive reference
95 sample, pus samples were taken from superficial abscesses of live sheep, or at post
96 mortem examination from dead sheep, and transported in charcoal Amies' transport
97 medium to the laboratory. Bacteriological culture was carried out on blood agar under
98 conditions of $5\% \text{CO}_2$ for approximately 48 hours. Colonies morphologically
99 resembling those of C. pseudotuberculosis were Gram-stained, and Gram-positive
100 rods were tested for urease and catalase. Isolates that were urease and catalase
101 positive were identified as C. pseudotuberculosis. A representative selection of

102 isolates was confirmed as C. pseudotuberculosis using the API-Coryne biochemical
103 test system (Bio-Mérieux).

104

105 2.2 Reference serum samples

106 The ELISA was evaluated on a panel of 150 positive reference sera from sheep in
107 22 flocks, each sheep had at least one abscess positive for C. pseudotuberculosis at
108 bacteriological culture at the time of sampling and 103 negative reference sera from
109 sheep in four flocks which had never had a case of CLA. Many of the negative
110 reference sera were obtained by one of the authors (LG) in 1993, before CLA had
111 reached a high prevalence in the UK.

112 A pooled positive control standard serum was prepared from all test sera with a
113 relative antibody concentration higher than 0.8 times the highest positive serum
114 sample in the positive reference collection ($\underline{n} = 28$). Negative control standard sera (\underline{n}
115 = 3) were obtained from three one-year-old, barn-reared experimental Dorset sheep,
116 which were determined to be free from lesions suggestive of CLA at post mortem
117 examination. Bacteriological cultures of parotid and mediastinal lymph nodes from
118 these sheep were also negative.

119

120 2.3 Antigen preparation

121 The antigen used to coat the ELISA plates was obtained by growing up one bead
122 from frozen stocks of an isolate of C. pseudotuberculosis obtained from an infected
123 sheep (isolate 1620) in brain-heart infusion broth at 37°C with agitation for 48 hours.
124 The culture was then centrifuged for 10 minutes at 2000 rpm; the cells were washed
125 twice in 10 ml phosphate-buffered saline (PBS), and resuspended in 1.5 ml PBS. The
126 cells were pulse sonicated (Soniprobe Type 1130A, Dawe Instrumental Ltd., London)

127 for six 30-second pulses to disrupt the cell walls. The antigen preparation was
128 quantified using the Coomassie Blue method (Bradford 1976). Prepared antigen was
129 stored in 1.5 ml aliquots at -20°C . Alternative antigen preparations that were initially
130 tested included culture supernatant and non-sonicated cells, all antigens in either of
131 these preparations were present in the sonicated cell preparation in preliminary
132 experiments (unpublished data) and so the cell sonicate was used for further analysis.

133

134 2.4 ELISA procedure and development

135 Ninety-six well PVC microtitration plates (Greiner Bio-One Ltd., Stonehouse,
136 Glos.) were coated with the sonicated bacteria at $4\ \mu\text{g/ml}$ in $100\ \mu\text{l}$
137 carbonate/bicarbonate buffer (15mM sodium carbonate, 35mM sodium bicarbonate)
138 at a pH of 9.6, and incubated overnight at 4°C . The plates were washed between each
139 incubation step three times in PBS-Tween (phosphate-buffered saline plus $0.1\% \text{ v/v}$
140 Tween-20) using a commercial plate washer (Titertek M384 Atlas Microplate
141 Washer, Biological Instrumentation Services, Ltd.). Serum was added to the wells and
142 the plates were again incubated overnight at 4°C .

143 Both versions of the ELISA used a two-step detection system; the primary detection
144 antibody (mouse anti-sheep monoclonal) varied between the tests (see below), but the
145 secondary detection was carried out using $100\ \mu\text{l}$ of alkaline-phosphatase conjugated
146 donkey anti-mouse IgG monoclonal antibody (Jackson ImmunoResearch Ltd.) diluted
147 to $1/1000$ in PBS-Tween in all cases. Both detection antibodies were incubated on the
148 plates at 37°C for one hour and then $50\ \mu\text{l}$ per well alkaline phosphatase substrate p-
149 nitrophenol phosphate, disodium (1mg/ml) (Sigma) in carbonate/bicarbonate buffer
150 was added. The plates were then left at room temperature to develop. The plates were
151 read at 405nm against 492nm (non-specific absorption) when the highest standard

152 optical density (OD) reached 1.5-2.0 units on a Multiscan EX (Thermo LabSystems,
153 Vantaa, Finland). The ELISA was optimised with respect to incubation times, and the
154 concentrations of coating antigen and detection antibodies were optimised using
155 chequerboard titrations.

156

157 2.5 Pan-light-chain ELISA

158 For this version of the ELISA, test sera were assayed using serial dilutions in 100 μ l
159 PBS-T against the positive standard, which was also run in serial dilutions. For each
160 plate, 12 wells were filled with 100 μ l PBS-T only, to serve as a background control.
161 The primary detection antibody was the cell culture supernatant from cell line
162 K67.3G2 supplied by Karin Haverson, School of Clinical Veterinary Science,
163 University of Bristol. This monoclonal antibody detects ovine light chains, and
164 therefore all antibody classes, and was diluted in PBS-Tween to 1/100 and added at
165 100 μ l per well.

166

167 2.6 Anti-IgG ELISA

168 For this version of the ELISA, test sera were tested at serial dilutions in 100 μ l PBS-T
169 starting at 1/100 against the positive standard. On each plate, 12 wells were filled with
170 PBS only, to serve as a background control. The primary detection antibody used in
171 this test was a monoclonal anti-ovine IgG (IgG1 plus IgG2) (clone VPM6, Serotec),
172 diluted in PBS-Tween to 1/1000 (100 μ l per well).

173

174 2.7 ELISA analysis

175

176 Each of the sera were tested at a range of one in three dilutions; two negative standard
177 control sera and the pooled positive standard (in duplicate) were also run in serial
178 dilutions on each plate to provide positive and negative reference curves (serum
179 dilution against OD). The process for calculating antibody concentrations relative to a
180 standard has been previously described in several species (Finerty et al, 2000; Bailey
181 et al, 2004;). Briefly, the mean background OD for completely negative wells was
182 first subtracted from each OD reading. The concentration of antibody in the reference
183 serum was arbitrarily assigned as 1. A graph was plotted of log[reference serum]
184 against a transformed function for the OD. In this case, a square-root transformation
185 of the OD produced the best straight line region within the curve. The intercept and
186 gradient of this straight line region was calculated for each plate, and the values
187 obtained used to calculate the amount of antibody in each well relative to the standard
188 (equation 1).

189

190 [1] Concentration of antibody = gradient * OD^{0.5} + intercept

191

192 Since each sample well contained a dilution of the original sample, the calculated
193 relative[Ab] for each well was multiplied by the dilution to obtain a value for rel[Ab]
194 in the original sample. Where rel[Ab] was calculated from multiple dilutions of a
195 particular sample, only those dilutions whose OD values were within the linear part of
196 the curve were used to obtain the mean and standard deviation (SD) of the rel[Ab].
197 This method required the assumption that the gradients of the line of log(dilution)
198 against OD^{0.5} (usually a reflection of affinity) were the same for all samples: in fact,
199 the gradients of some of the samples in the negative reference population were
200 shallower, indicating low affinity

201

202 2.8 Statistical analysis

203

204 Statistical analysis was carried out using Stata version v.7 (Statacorp). The variables
205 analysed were the antibody concentration relative to the positive standard over the
206 linear portion of the dilution series (rel[Ab]) at each individual dilution for the anti-
207 IgG ELISA. Within- and between-assay repeatability was assessed by calculating the
208 coefficient of variation for rel[Ab]. The agreement between test results was assessed
209 by the calculation of the kappa statistic for the dichotomous value (positive or
210 negative) using an appropriate cut-off, and Spearman rank correlation coefficients for
211 the continuous variable (rel[Ab]) (Altman, 1991). The analysis of agreement was
212 carried out for pairs of results using the same assay on different occasions, and using
213 the two different ELISA tests.

214 Receiver Operating Characteristic (ROC) curves (plots of sensitivity against [1-
215 specificity]) were plotted and used to estimate the optimal cut-off for various values
216 of sensitivity (Se) and specificity (Sp); the area under the ROC curve (AUC) was
217 estimated by non-parametric integration (Greiner et al. 1995). Exact binomial 95%
218 confidence intervals (or one-sided 97.5% CI for an estimate of 100% Se or Sp) for
219 sensitivity and specificity were calculated. The mean and geometric mean relative
220 antibody concentration were obtained for the positive and negative reference
221 populations and tested using t-tests. Further measures of diagnostic test accuracy
222 (Greiner et al. 1995) were estimated in an Excel spreadsheet. Odds ratios were
223 corrected by adding 0.5 to each cell when Se or Sp was estimated to be 100%. The
224 above analysis was carried out for each variable at cut-offs of 100% sensitivity, 100%

225 specificity, the maximum specificity with a sensitivity of $\geq 80\%$, the maximum
226 sensitivity with a specificity of $\geq 96\%$, and roughly equal sensitivity and specificity.

227

228 **3. Results**

229

230 3.1 Distributions of the ELISA responses of reference sera

231

232 The geometric mean relative antibody concentrations, calculated for each dilution of
233 sample independently, were significantly different between the positive and negative
234 reference populations except for the two highest single dilutions using the anti-IgG
235 ELISA system (Table 1). This reflects the fact that at high dilutions, OD readings for
236 positive and negative samples fall below the linear part of the curve and become
237 unreliable, demonstrated by the increasing 95% confidence intervals relative to the
238 mean.

239 The distributions of the relative antibody concentrations in each sample were
240 negatively skewed, so logarithmic transformations were used in the analysis.
241 Histograms of the logarithm of Rel[Ab] for both versions of the ELISA overlapped
242 (boxed in Fig. 1 and 2) where the results of the positive and negative reference
243 populations overlapped. This area was substantially narrower and involved fewer
244 sheep for the anti-IgG ELISA (Fig. 1) than for the K67 ELISA (Fig. 2), indicating the
245 greater efficiency of the former in discriminating between the two reference
246 populations.

247

248 3.2 Assessment of repeatability and inter-test and within-test agreement

249

250 The within-assay (duplicate samples run at the same time, although rarely on the same
251 plate) coefficient of variation (CV) was slightly lower than the between-assay
252 (duplicate samples run on different occasions) CV (Table 2). The agreement for
253 repeated assays within each version of the ELISA was acceptable (Table 3). However,
254 the agreement between the K67 and anti-IgG versions of the test was lower,
255 particularly in the positive reference population, indicating that the latter had
256 increased sensitivity at 100% specificity compared with the former.

257

258 3.3 Cut-off determination and determination of sensitivity and specificity

259

260 The sensitivity of the K67 test to detect total antibody and the anti-IgG test to detect
261 IgG antibody to C. pseudotuberculosis was 71% (95% confidence interval 63-78%)
262 and 83% (76-89%) respectively when the specificity was set at 100% (Table 4). The
263 specificity of the K67 test was 23% (95% confidence interval 14-34%), and that of the
264 anti-IgG test was 64% (53-74%) when the sensitivity was set at 100% (Table 4).

265

266 3.4 ROC analysis

267 The results of ROC analysis indicated that the IgG isotype ELISA (AUC 0.9887)
268 was more accurate than the total antibody ELISA (AUC 0.9494), $P = 0.003$. Using a
269 1/100 dilution in the anti-IgG ELISA, the overall accuracy was not significantly
270 different from that obtained using the whole series (AUC 0.9741, $P = 0.2$), but it was
271 impossible to obtain 100% specificity using this dilution or the 1/900 dilution; the
272 maximum specificity obtained in both cases was 98.9% (95%CI: 94.2-99.9%).

273

274 **4. Discussion**

275 The sensitivity and specificity of the anti-IgG ELISA compared favourably with
276 other reported ELISA tests for CLA in sheep (Dercksen et al. 2000). The current
277 ELISA was simpler and cheaper to run than the Dutch test which is an indirect
278 double-sandwich antibody ELISA.

279 For a disease such as CLA, deciding a gold standard with high discriminatory
280 efficacy is challenging. In the current study the gold standard used to define the
281 positive reference population was culture of C. pseudotuberculosis from typical
282 lesions. This is a reasonable positive standard. However, the assumption that negative
283 culture is a negative control may not be valid. Many C. pseudotuberculosis-infected
284 sheep do not display clinical signs, and lesions may be non-culturable rather than
285 negative for C. pseudotuberculosis. It is impossible to be certain that the negative
286 reference population is truly uninfected and has never been in contact with the
287 bacterium (Menzies et al. 1994). We aimed to maximise our confidence of the status
288 of our negative reference population by using a combination of sheep from clinically-
289 negative flocks, specific-pathogen-free sheep and experimental sheep that had never
290 been in contact with CLA. If any of the negative reference population were infected,
291 this would have resulted in misclassification, which in turn would bias the estimates
292 of sensitivity and specificity (Staquet et al. 1981).

293 The representativeness of the negative reference population used for establishing the
294 cut-off value is of major importance (Greiner and Böhning 1994). Negative samples
295 ideally need to come from the same population as positive samples so that other
296 biological factors within the target population can be ignored. In our case, the
297 negative reference population were younger than the target population, and many of
298 the samples were obtained in 1993, several years earlier than the current study field
299 samples for which the ELISA was developed. This was done to ensure that the

300 negative control sheep were truly uninfected, but these factors are a potential
301 limitation to the ELISA qualities.

302 The ELISA presented in this paper was based on crude bacterial antigen, containing
303 all the antigens in the cell supernatant and cell wall, to detect antibodies to as many
304 antigens of C. pseudotuberculosis as possible, thus combining both cell-wall and
305 toxin-based assays (Sutherland et al. 1987). Other authors have reported that a cell
306 supernatant antigen performed better than sonicated cells (Maki et al. 1985) but this
307 was not our experience. Muckle et al. (1992) reported that the specificity of crude
308 antigen preparations was low, we addressed this by using a double antibody detection
309 system and the specificity of our ELISA was reasonable. However, as demonstrated
310 here the specificity of an IgG antibody test is higher than that of the total antibody
311 ELISA for a given sensitivity, because the latter also detects IgM which may result in
312 much greater cross-reactivity than with IgG alone.

313 The ROC analysis was used to detect the best trade-off between sensitivity and
314 specificity, to compare the accuracy of the two ELISAs and to investigate the use of
315 single dilutions of test sera in the anti-IgG assay. The use of a series of dilutions of
316 test sera was necessary initially to establish a cut-off point for the ELISA, to detect
317 any prozone effect, and to identify a single serum dilution that could be routinely
318 employed for test samples. The dilution series in fact proved more accurate than any
319 single dilution of test sera in the anti-IgG assay. Most other reported ELISA tests for
320 CLA use only a single serum dilution for each sample (Sutherland et al. 1987;
321 Sutherland et al. 1987; ter Laak et al. 1992; Dercksen et al. 2000). The validation of a
322 choice of one dilution against a series of dilutions is not described in these papers.
323 However, such assays may have serious inaccuracies due to prozone effects at low
324 dilutions and increasing errors at high dilutions (Figure 4). For the IgG ELISA

325 presented here the 1/100 dilution gave a similar AUC ROC to the dilution series, but
326 it was not possible to obtain 100% specificity with this dilution. If this were not an
327 important consideration, the test could be run using single 1/100 dilutions of test sera,
328 resulting in a decrease in the cost of running the assay.

329 A proportion of C. pseudotuberculosis culture-positive sheep were negative to our
330 ELISA. This has been reported for all ELISAs developed to date. This is unlikely to
331 be due to the particular infecting strain of C. pseudotuberculosis, because sheep
332 experimentally infected with either sheep or goat strains of the bacterium showed
333 similar responses on Western Blot analysis, and differed from the responses of
334 identically-treated goats (Kamp et al. 2001). It is possible that some ‘false negative’
335 sheep did not produce antibody to the particular antigen(s) used, but this is less likely
336 with crude antigen. It is also unlikely that infected sheep tested negative to the
337 antibody-ELISA because they have lost antibodies because, although the half-life of
338 experimentally-transferred antibody is only about three weeks, antibody can usually
339 be detected for at least a year in natural infections. Even in sheep without gross
340 lesions, it is likely that small quantities of antigen are sequestered by the follicular
341 dendritic cells in lymph nodes, and that these periodically stimulate memory cells
342 (Kosco-Vilbois and Scheidegger, 1995).

343 Although the immune response to CLA in most sheep has a strong humoral
344 component (Pépin et al. 1993), it is possible that the low sensitivity of ELISA tests
345 designed to detect antibodies to C. pseudotuberculosis may result from some sheep, or
346 sheep during certain stages of infection, expressing a predominately cell-mediated
347 immune response to the pathogen. In general, T_H1 cells promote cell-mediated
348 immunity (CMI) while T_H2 cells stimulate a humoral immune response (Infante-
349 Duarte and Kamradt, 1999). Genetic predisposition to express Th1 or Th2 responses

350 does occur in sheep and contributes to differences in the ability to control infectious
351 agents (Gill et al, 2000). Some pathogens, such as Mycobacterium avium subsp.
352 paratuberculosis stimulate different arms of the immune response at different stages of
353 pathogenesis (Burrells et al. 1998). Alternative techniques to identify diseased but Ab
354 negative sheep include an ELISA to IFN- γ produced by stimulated leucocytes
355 (Prescott et al. 2002) and polymerase chain reaction (Çetinka et al. 2002), but the
356 feasibility of these techniques in diagnosing infection in live sheep on farms has not
357 yet been demonstrated.

358 The anti-IgG ELISA test reported here has since been used in epidemiology studies
359 in the UK. The lack of sensitivity in individual sheep was overcome by increasing the
360 sample size per flock, to ensure that if infection was present then it would be detected.
361 An alternative would have been to reduce the cut-off value, resulting in an increased
362 sensitivity at the expense of reduced specificity.

363

364 **Acknowledgements**

365 SHB was in receipt of a Wellcome Trust Training Fellowship in Clinical
366 Epidemiology. Thanks to the staff of the Bacteriology Diagnostic Laboratory at the
367 Department of Clinical Veterinary Science, University of Bristol for carrying out
368 bacteriological culture and identification of the organism, Karin Haverson for
369 supplying the anti-sheep pan-light-chain monoclonal antibody, Frank Malone
370 (DARDNI) for provision of 100 reference positive sera and the vets and farmers who
371 supplied the other serum samples.

372

373 **References**

- 374 Altman, D.G. 1991. Practical statistics for medical research. Chapman & Hall, Boca
375 Raton.
- 376 Bailey, M., Haverson K, Miller B, Jones P, Sola I, Enjuanes L, Stokes CR (2004)
377 Effects of infection with transmissible gastroenteritis virus on concomitant
378 immune responses to dietary and injected antigens. Clinical and Diagnostic
379 Laboratory Immunology 11: 337-343.
- 380 Binns, S. H., Bailey, M., Green L.E. 2002. Postal survey of ovine caseous
381 lymphadenitis in the United Kingdom between 1990 and 1999. Vet. Rec. 150,
382 263-268.
- 383 Bradford, M. M. 1976. Coomassie Blue method of quantitating proteins. Anal.
384 Biochem. 72, 248.
- 385 Burrell, D. H. 1980. A simplified double immunodiffusion technique for detection of
386 Corynebacterium ovis antigen. Res. Vet. Sci. 28, 234-237.
- 387 Burrells, C., Clarke, C. J., Colston, A., Kay J. M., Porter, J., Little, D., Sharp, J. M.
388 1998. A study of immunological responses of sheep clinically-affected with
389 paratuberculosis (Johne's disease). The relationship of blood, mesenteric
390 lymph node and intestinal lymphocyte responses to gross and microscopic
391 pathology. Vet. Immunol. Immunopathol. 66, 343-358.
- 392 Çetinka, B., Karahan, M., Atil, E., Kalin, R., De Baere, T., Vaneechoutte, M. 2002.
393 Identification of Corynebacterium pseudotuberculosis isolates from sheep and
394 goats by PCR. Vet. Microbiol. 88, 75-83.
- 395 Dercksen, D. P., Brinkhof, J. M. A., Dekker-Nooren, T. van Maanen, K., Bode, C.F.,
396 Baird, G., Kamp, E.M. 2000. A comparison of four serological tests for the

- 397 diagnosis of caseous lymphadenitis in sheep and goats. *Vet. Microbiol.* 75,
398 167-175.
- 399 Finerty, S., Stokes, C.R., Gruffydd-Jones, T.J., Hillman, T.J., Reeves, N.A., Whiting,
400 C.V., Schaaper, W.M.M., Dalsgaard, K., Harbour, D.A. (2000) Mucosal
401 immunization with experimental feline immunodeficiency virus (FIV)
402 vaccines induces both antibody and T cell responses but does not protect
403 against rectal FIV challenge. *Vaccine* 18: 3254-3265.
- 404 Greiner, M., Böhnig, D. 1994. Notes about determining the cut-off value in enzyme-
405 linked immunosorbent assay (ELISA) - Reply. *Prev. Vet. Med.* 20, 307-310.
- 406 Greiner, M., Sohr, D., Gobel, P. 1995. A modified ROC analysis for the selection of
407 cut-off values and the definition of intermediate results of serodiagnostic tests.
408 *J. Immunol. Meth.* 185, 123-132.
- 409 Kaba, J., Kutschke, L., Gerlach, G.-F. 2001. Development of an ELISA for the
410 diagnosis of Corynebacterium pseudotuberculosis infections in goats. *Vet.*
411 *Microbiol.* 78, 155-163.
- 412 Kamp, E. M., Antonis, A., Derksen, D. 2001. Western Blot analysis of the serological
413 responses of goats and sheep experimentally infected with two different strains
414 of Corynebacterium pseudotuberculosis of ovine and caprine origin. 5th
415 International Sheep Veterinary Congress, Stellenbosch, South Africa.
- 416 KoscoVilbois, M. H., Scheidegger, D. 1995. Follicular dendritic cells: Antigen
417 retention, B cell activation, and cytokine production. *Curr. Topics Microbiol.*
418 *Immunol.* 201, 69-82.
- 419 Maki, L. R., Shen, S.-H., Bergstrom, R.C., Stetzenbach, L.D. (1985). "Diagnosis of
420 Corynebacterium pseudotuberculosis infections in sheep, using an enzyme-
421 linked immunosorbent assay. *Am. J. Vet. Res.* 46(1), 212-214.

- 422 Menzies, P. I., Muckle, C. A., Hwang, Y. T., Songer, J. G. 1994. Evaluation of an
423 enzyme-linked immunosorbent assay using an Escherichia coli recombinant
424 phospholipase D antigen for the diagnosis of Corynebacterium
425 pseudotuberculosis infection. Small Rum. Res. 13, 193-198.
- 426 Muckle, C. A., Menzies, P. I., Li, Y., Hwang, Y. T., van Wesenbeeck, M. 1992.
427 "Analysis of the immunodominant antigens of Corynebacterium
428 pseudotuberculosis. Vet.Microbiol. 30, 47-58.
- 429 Pépin, M., Pardon, P., Marly, J., Lantier, F., Arrigo, J. L. 1993. Acquired immunity
430 after primary caseous lymphadenitis in sheep. Am. J. Vet. Res. 54(6), 873-
431 877.
- 432 Prescott, J. F., Menzies, P. I., Hwang, Y. T. 2002. An interferon-gamma assay for
433 diagnosis of Corynebacterium pseudotuberculosis infection in adult sheep
434 from a research flock. Vet. Microbiol. 88, 287-297.
- 435 Shigidi, M. T. A. 1979. A comparison of five serological tests for the diagnosis of
436 experimental Corynebacterium ovis infection in sheep. Brit. Vet. J. 135, 172-
437 177.
- 438 Staquet, M., Rozenzweig, M., Lee, Y. J., Muggia, F. M. 1981. Methodology for the
439 assessment of new dichotomous diagnostic tests. J. Chron. Dis. 34, 599-610.
- 440 Sutherland, S. S., Ellis, T. M., Mercy, A. R., Paton, M. W., Middleton, H. 1987.
441 Evaluation of an enzyme-linked immunosorbent assay for the detection of
442 Corynebacterium pseudotuberculosis infection in sheep. Aust. Vet. J. 64(9),
443 263-266.
- 444 Sutherland, S. S., Paton, M. W., Mercy, A. R., Ellis, T. M. 1987. A reliable method
445 for establishing caseous lymphadenitis infection in sheep. Aust. Vet. J. 64(10),
446 323-324.

447 ter Laak, E. A., Bosch, J., Bijl, G. C., Screuder, B. E. C. 1992. Double-antibody
448 sandwich enzyme-linked immunosorbent assay and immunoblot analysis used
449 for control of caseous lymphadenitis in goats and sheep. *Am. J. Vet. Res.*
450 53(7), 1125-1132.

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Table 1: Mean and geometric mean relative [Ab] (rel[Ab]) in positive and negative reference populations

Relative [Ab] calculated using:	Positive reference population	Negative reference population	P-value (t-test)
	geometric mean rel[Ab] (95% CI)	geometric mean rel[Ab] (95% CI)	
Total Ab*, all dilutions	0.19 (0.16-0.23)	0.022 (0.017-0.027)	<0.001
IgG [#] , all dilutions	0.14 (0.11-0.18)	0.007 (0.006-0.008)	<0.001
IgG, serum diluted 1/100	0.025 (0.024-0.027)	0.006 (0.005-0.006)	<0.001
IgG, serum diluted 1/300	0.057 (0.051-0.064)	0.009 (0.008-0.01)	<0.001
IgG, serum diluted 1/900	0.102 (0.087-0.12)	0.020 (0.019-0.022)	<0.001
IgG, serum diluted 1/2700	0.16 (0.13-0.19)	0.051 (0.048-0.054)	<0.001
IgG, serum diluted 1/8100	0.26 (0.22-0.30)	0.14 (0.14-0.15)	<0.001
IgG, serum diluted 1/24300	0.49 (0.43-0.56)	0.43 (0.40-0.45)	0.11
IgG, serum diluted 1/72900	1.12 (1.03-1.21)	1.27 (1.17-1.38)	0.03

*Total Ab: Total Antibody ELISA (K67)

[#] IgG: anti-IgG ELISA

Table 2. Within- and between-assay coefficients of variation (CV):

Sample:	K67 ELISA		Anti-IgG ELISA	
	Median within-assay	Median between-assay	Median within-assay	Median between-assay
	CV [#] (%)	CV (%)	CV (%)	CV (%)
Whole reference population	25.2	27.6	19.6	30.2
	IQ*: 12.7-34.3	IQ: 10.7-55.0	6.7-39.0	IQ:15.2-47.8
Positive reference samples	19.9	22.1	Insufficient data	31.5
	IQ: 8.5-34.3	IQ: 9.2-42.9		IQ:15.2-49.3
Negative reference samples	17.1	50.4	19.6	30.1
	IQ: 13.3-25.5	IQ: 26.8-95.6	6.7-39.0	IQ: 11.1-47.8

[#]CV: Coefficient of variation

*IQ: inter-quartile range

Table 3: Agreement between results of repeated applications of the same ELISA, and between results obtained with K67 and IgG ELISAs

Sample:	K67		Anti-IgG		Between K67 & IgG	
	Kappa (P-Value)	*Spearman (P-value)	Kappa (P-Value)	Spearman (P-value)	Kappa (P-Value)	Spearman (P-value)
Reference population (100% specificity)	0.78 (<0.001)	0.91 (<0.001)	0.87 (<0.001)	0.93 (<0.001)	0.41 (<0.001)	0.77 (<0.001)
Reference population (100% sensitivity)	0.60 (<0.001)		0.62 (<0.001)		0.49 (<0.001)	
Positive reference (100% specificity)	0.76 (0.001)	0.86 (0.001)	0.67 (<0.001)	0.88 (<0.001)	0.22 (<0.001)	0.64 (<0.001)
Negative reference (100% sensitivity)	0.49 (0.002)	0.38 (0.006)	0.46 (<0.001)	0.78 (<0.001)	0.15 (0.14)	0.05 (0.79)

*Spearman rank correlation coefficient

Table 4: Accuracy at Specificity = 1 (97.5% lower confidence limit for specificity = 0.96; Positive predictive value = 1; Likelihood ratio of a positive test = 0)

Rel[Ab] calculated using:	Sensitivity	95% CI (sensitivity)	Efficiency ^c	NPV ^d	Youden's Index ^e	LR ^{-f}	Odds ratio (corrected)
Total Ab ^a , all dilutions	0.708	0.627-0.781	0.804	0.625	0.708	0.292	340.06
IgG ^b , all dilutions	0.833	0.764-0.889	0.897	0.790	0.833	0.167	930.18
IgG, serum diluted 1/100				Not obtained			
IgG, serum diluted 1/300	0.020	0.004-0.057	0.398	0.390	0.020	0.98	4.48
IgG, serum diluted 1/900				Not obtained			
IgG, serum diluted 1/2700	0.587	0.503-0.666	0.749	0.607	0.587	0.413	267.62
IgG, serum diluted 1/8100	0.207	0.145-0.280	0.512	0.441	0.207	0.793	49.82
IgG, serum diluted 1/24300	0.193	0.133-0.266	0.504	0.437	0.193	0.807	45.89
IgG, serum diluted 1/72900	0	0-0.024	0.385	0.385	-1	1	0.628

^aTotal Ab: Total Antibody ELISA (K67)^bIgG: anti-IgG ELISA^cEfficiency: (true positives + true negatives) / total^dNPV: Negative predictive value^eYouden's Index: Se + Sp - 1^fLR-: Negative likelihood ratio: [Probability of no disease/Probability of disease] given test result, divided by the odds [prevalence]^gOdds ratio: Positive likelihood ratio / Negative likelihood ratio

Table 5: Accuracy at Sensitivity = 1 (97.5% lower confidence limit for sensitivity = 0.98; Negative predictive value = 1; Likelihood ratio of a negative test = 0)

Rel[Ab] calculated using:	Specificity	95% CI (Specificity)	Efficiency ^c	PPV ^d	Youden's Index ^e	LR ⁺¹	Odds ratio (corrected) ^g
Total Ab ^a , all dilutions	0.229	0.137-0.344	0.748	0.727	0.727	1.296	87.50
IgG ^b , all dilutions	0.638	0.533-0.735	0.861	0.815	0.815	2.765	527.84
IgG, serum diluted 1/100	0.734	0.633-0.820	0.898	0.857	0.857	3.759	820.37
IgG, serum diluted 1/300	0.511	0.405-0.615	0.812	0.765	0.765	2.043	313.95
IgG, serum diluted 1/900	0.021	0.003-0.075	0.623	0.620	0.620	1.022	8.14
IgG, serum diluted 1/2700	0	0-0.038	0.614	0.614	0.614	1	1.59
IgG, serum diluted 1/8100	0	0-0.038	0.614	0.614	0.614	1	1.59
IgG, serum diluted 1/24300	0	0-0.038	0.614	0.614	0.614	1	1.59
IgG, serum diluted 1/72900	0.0106	0.0003-0.058	0.619	0.617	0.617	1.010	4.83

^aTotal Ab: Total Antibody ELISA (K67)

^bIgG: anti-IgG ELISA

^cEfficiency: (true positives + true negatives) / total

^dPPV: Positive predictive value

^eYouden's Index: Se + Sp - 1

^fLR+: Positive likelihood ratio: [Probability of disease/Probability of no disease] given test result, divided by the odds [prevalence]

^gOdds ratio: Positive likelihood ratio / Negative likelihood ratio

Table 6: Results of ROC analysis

Rel[Ab] calculated using:	AUC ROC	Max Se at ≥0.96 Sp (95% CI)	PPV	NPV	Max Sp at ≥80% Se (95% CI)	PPV	NPV	Equal Se/Sp (95% CI Se)	PPV	NPV
Total Ab ^a , all dilutions	0.9494**	0.771 (.69-.84)	0.98	0.67	0.943 (.86-.98)	0.97	0.70	0.861 (.79-.91)	0.93	0.75
IgG ^b , all dilutions	0.9887	0.933 (.88-.97)	0.98	0.90	1.0 (.96-1.0)	1	0.79	0.947 (.90-.95)	0.97	0.92
IgG, serum diluted 1/100	0.9741	0.860 (.79-.91)	0.98	0.81	.968 (.91-.99)	0.98	0.81	0.940 (.89-.97)	0.97	0.91
IgG, serum diluted 1/300	0.9677	0.887 (.83-.93)	0.98	0.84	0.98 (.93-.99)	0.98	0.75	0.920 (.86-.96)	0.95	0.88
IgG, serum diluted 1/900	0.9372**	0.827 (.76-.88)	0.98	0.78	.989 (.94-.99)	0.93	0.41	0.887 (.82-.93)	0.92	0.83
IgG, serum diluted 1/2700	0.8351**	0.673 (.59-.75)	0.97	0.66	0.585 (.48-.69)	0.76	0.68	0.747 (.67-.81)	0.83	0.66
IgG, serum diluted 1/8100	0.6408**	0.387 (.31-.47)	0.95	0.50	0.287 (.20-.39)	0.65	0.49	0.573 (.49-.65)	0.69	0.47
IgG, serum diluted 1/24300	0.4532**	0.193 (.13-.27)	0.94	0.43	0.850 (.037-.16)	0.59	0.22	0.400 (.30-.51)	0.52	0.30
IgG, serum diluted 1/72900	0.3429**	0.093 (.052-.15)	0.82	0.40	0.351 (.26-.46)	0.67	0.53	0.633 (.55-.71)	0.74	0.52

**Significantly different (P < 0.05) from AUC ROC for αIgG series.

^aTotal Ab: Total Antibody ELISA (K67)

^bIgG: anti-IgG ELISA

Figure captions:

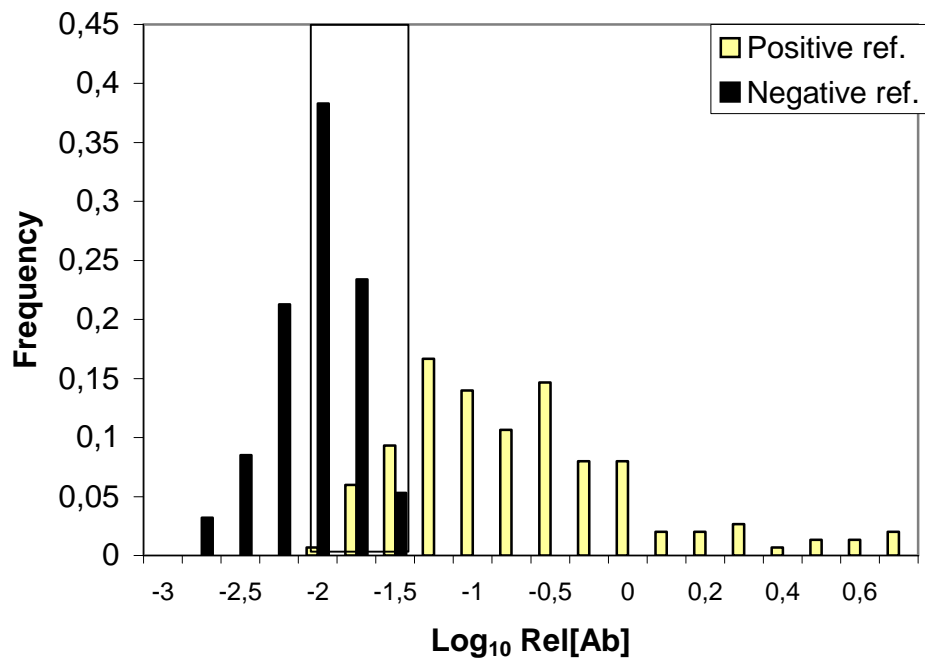
Fig. 1: Histogram of Relative [Ab] for positive and negative reference serum samples: Anti-IgG ELISA. Box represents overlap between positive and negative reference populations

Fig. 2: Histogram of Relative [Ab] for positive and negative reference serum samples: K67 ELISA. Box represents overlap between positive and negative reference populations

Fig. 3: Receiver Operating Characteristic (ROC) curves for α IgG and K67 ELISAs

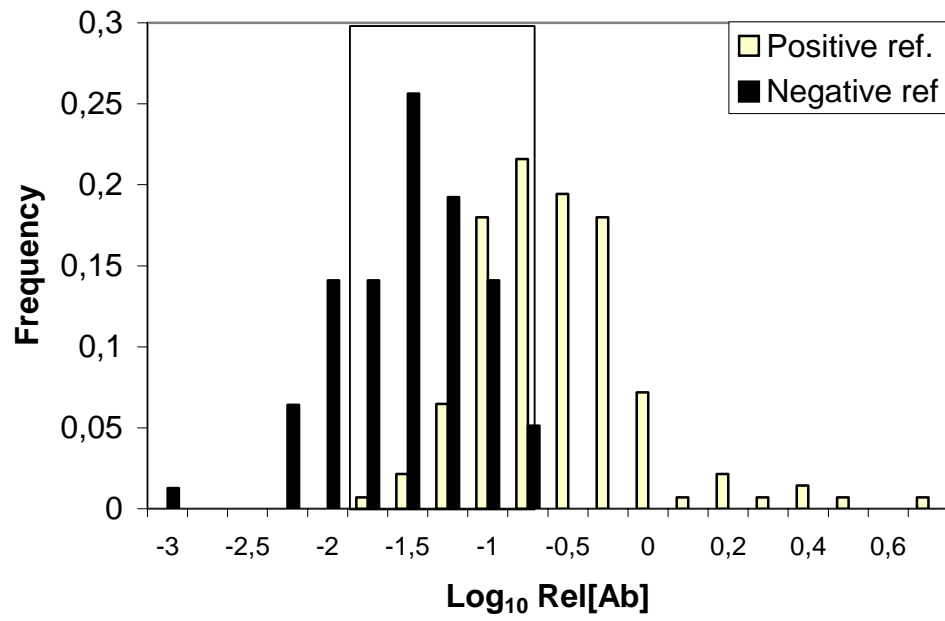
Fig. 4: Sample data comparing $\sqrt{\text{OD}}$ against $\log(\text{dilution})$ for standard (plus regression line) and two samples. Estimation of the concentration of sample 1 would be inaccurate from a single dilution of 1/100, while estimation of sample 2 would be inaccurate at a dilution of 1/1000.

Figure 1



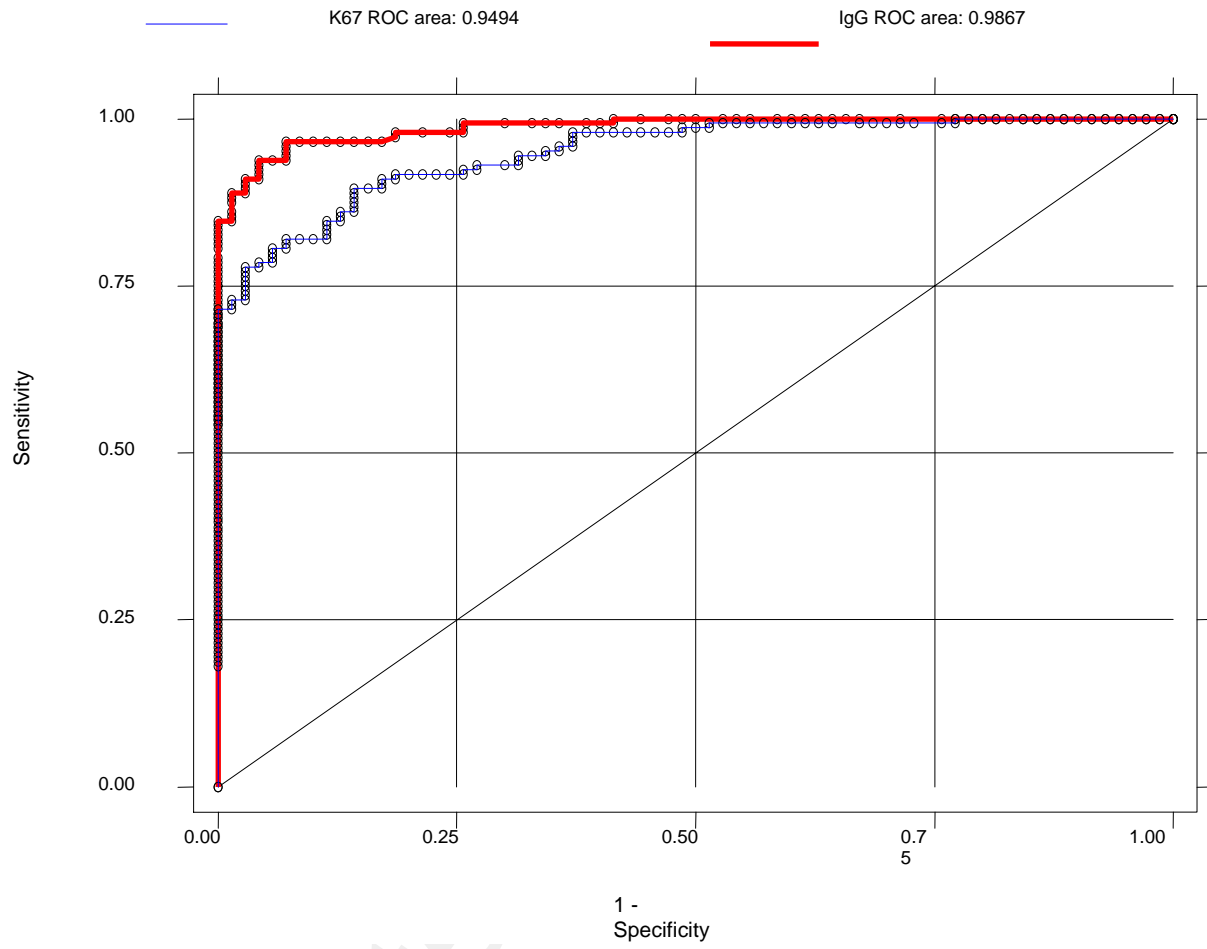
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Figure 2



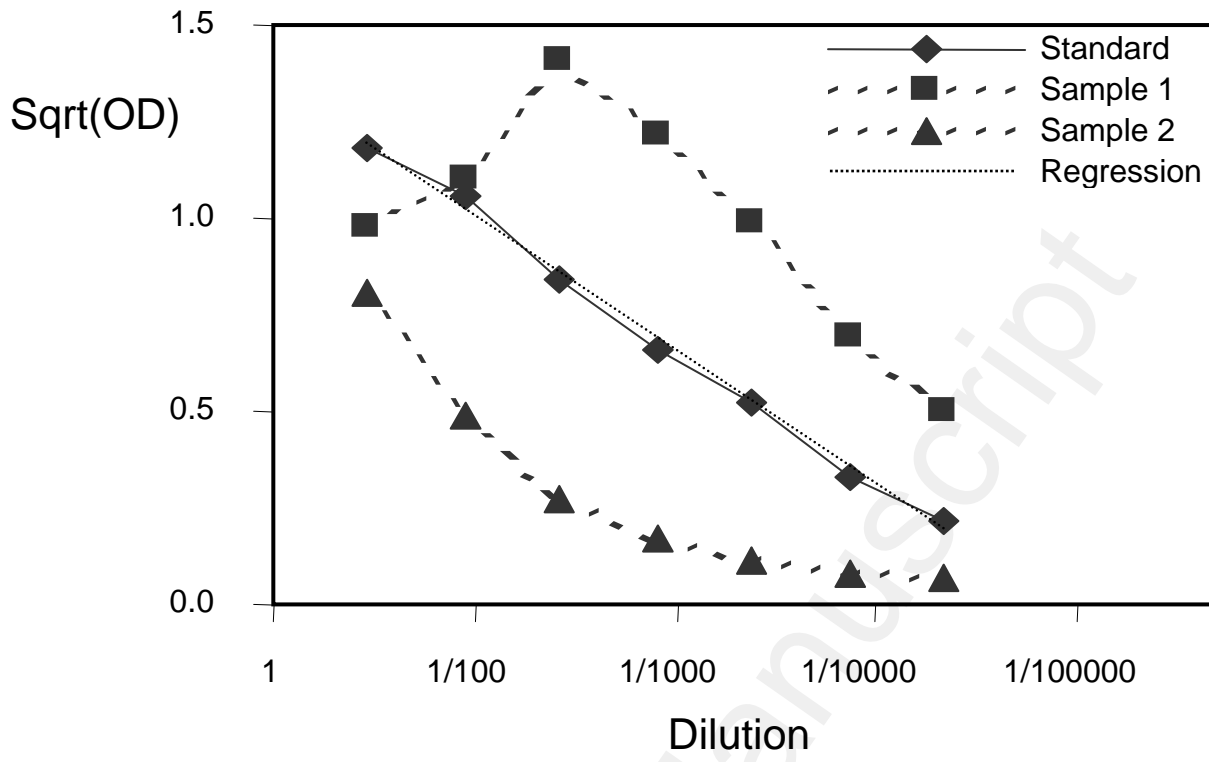
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Figure 3



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Figure 4



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