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1 **Diagnostic performance of direct and indirect methods for assessing failure of transfer of**  
2 **passive immunity in dairy calves using latent class analysis**

3

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25

## 26 **Abstract**

27       Accurate diagnosis of failure of transfer of passive immunity (FTPI) in newborn calves is an  
28 essential component of dairy farm management plan. Several methods (direct and indirect) are  
29 available for diagnosis of FTPI in dairy calves. However, the indirect methods offer an advantage  
30 over the direct methods in not requiring an experienced veterinarian, rapid, cost efficient and can be  
31 performed under field-setting. The objective of this study was to estimate the diagnostic performance  
32 of radial immunodiffusion (RID) assay, transmission infrared (TIR) spectroscopy and digital Brix  
33 refractometer for diagnosis of FTPI in dairy calves using latent class models at four cut-off values of  
34 digital Brix refractometer. Holstein calves ( $n = 691$ ) from 40 commercial dairy farms in the four  
35 Atlantic Canada provinces were blood-sampled and tested for detection of FTPI. Results showed that  
36 the number of calves with FTPI was 253 (36.6%) by RID, 194 (28.1%) by TIR and 204 (29.5%) by  
37 Brix refractometer at cut-off value of 8.2%. Estimates of  $Se_{RID}$  was higher than  $Se_{TIR}$  and  $Se_{Brix}$ , at all  
38 Brix refractometer cut-offs, but with increase of Brix refractometer cut-off from 8.2 to 8.5%,  $Se_{RID}$   
39 and  $Se_{TIR}$  were decreased from 96.0% (95% PCI: 88.0-99.0) and 79.0% (95% PCI: 70.0-85.0), to  
40 92.0% (95% PCI: 77.0-99.0) and 74.0% (95% PCI: 61.0-82.0), respectively.  $Sp_{RID}$  and  $Sp_{TIR}$  were  
41 always higher than  $Sp_{Brix}$  at all tested cut-offs and were above 92.0%, and 96.0%, respectively. With  
42 increasing the cut-off of Brix refractometer from 8.2 to 8.5%,  $Se_{Brix}$  estimate has remarkably  
43 increased from 79.0% (95% PCI: 70.0-96.0) to 95.0% (95% PCI: 87.0-100.0), respectively. Whilst,  
44  $Sp_{Brix}$  was decreased from 95.0% (95% PCI: 91.0-98.0) at cut-off 8.2% to 84.0% (95% PCI: 78.0-  
45 94.0) at cut-off 8.5%. In conclusion, RID has a higher Se than TIR and Brix, if the latter is used with  
46 cut-offs of 8.2% or 8.3%. However, the higher the cut-off, the more comparable sensitivities of RID  
47 and digital Brix refractometer. The median estimate of  $Sp_{TIR}$  were always higher than  $Sp_{RID}$  and  
48  $Sp_{Brix}$  at all tested cut-offs. However, the 95% confidence intervals estimates of the three tests were  
49 overlapping across the tested cut-offs of digital Brix refractometer reflecting the inability to prefer a  
50 test over the other based on the Sp estimate.

51 **Keywords:** Calves, FTPI, RID, Infrared spectroscopy, Refractometer, Latent class analysis

52

## 53 **1. Introduction**

54 Newborn calves are born hypogammaglobulinemic, without circulating immunoglobulin G  
55 (IgG), due to the diffuse epitheliochorial structure of their placentation that does not allow for the  
56 passage of IgG from the dam to the fetus (Smith, et al., 1964). Therefore, newborn calves rely upon  
57 the acquisition of passive immunity via transfer of maternal IgG through colostrum intake (Butler,  
58 1983; Godden, 2008). Inadequate transfer of colostral IgG (threshold <1000 mg/dl) to newborn  
59 calves within 48h of birth is defined as failure of transfer of passive immunity (FTPI) (Godden,  
60 2008). There is a recognized association between FTPI and reduced calf growth rate as well as  
61 increased risk of neonatal infectious diseases (Tyler, et al., 1999). Effects of FTPI might extend  
62 beyond the neonatal period, affecting long-term productivity and resulting in decreased milk yields  
63 and increased culling rates during the first lactation period (DeNise, et al., 1989; Heinrichs and  
64 Heinrichs, 2011). The reported prevalence of FTPI in Canada is relatively high, estimated at 25 to  
65 37% (Wallace, et al., 2006; Trotz-Williams, et al., 2008), 12% in the United States (Dairy, 2007),  
66 and 38% in Australia (Vogels, et al., 2013). Although early diagnosis of FTPI is an important part of  
67 the dairy herd management practices to ensure its timely detection and thus implementation of  
68 interventional measures, only 6% of dairy farms are routinely screened for FTPI (USDA, 2016).

69 Several methods have been developed to assess FTPI in dairy calves by measuring circulating  
70 IgG concentration either directly or indirectly. Direct methods include radial immunodiffusion (RID)  
71 assay (McBeath, et al., 1971), transmission infrared (TIR) spectroscopy (Elsohaby, et al., 2014),  
72 enzyme-linked immunosorbent assay (ELISA) (Filteau, et al., 2003) and an automated turbidimetric  
73 immunoassay (Alley, et al., 2012). The indirect methods include the sodium sulfate turbidity test  
74 (Pfeiffer and McGuire, 1977), zinc sulfate (ZnSO<sub>4</sub>) turbidity test (McEwan, et al., 1970),  
75 glutaraldehyde coagulation test (Tyler et al., 1996) and refractometry (Naylor and Kronfeld, 1977).

76 The RID assay is the classical direct and quantitative reference method for measuring IgG  
77 concentrations (McBeath, et al., 1971). The RID assay is expensive and utilizes reagents with a  
78 limited shelf life. The RID procedure takes 18 to 24h to obtain the results and requires advanced  
79 technical skill to not only perform the assay but also measure the zones of precipitation accurately  
80 (Riley, et al., 2007; Biemann, et al., 2010). Further, imprecision in RID assay replicates from the  
81 same sample have been noted and are attributed to inconsistencies in the assay standards (Ameri and  
82 Wilkerson, 2008). Recently, TIR spectroscopy has been touted as a suitable alternative for measuring  
83 bovine serum IgG and, as such, for assessing FTPI in dairy calves (Elsohaby, et al., 2014) owing to  
84 its rapidity, low cost and its minimal requirement in sample preparation (Shaw, et al., 1998).  
85 Refractometers are an effective indirect tool for assessing FTPI in dairy calves under field settings,  
86 because immunoglobulins are the major constituents of total protein in neonatal calf blood, besides  
87 albumin; and albumin is relatively stable in healthy individuals (Deelen, et al., 2014; Cuttance, et al.,  
88 2017). The correlation between RID-determined IgG concentrations and serum total protein has been  
89 determined in previous studies (Deelen, et al., 2014; Elsohaby, et al., 2015; Cuttance, et al., 2017).  
90 However, the results of refractometry are affected by instrument quality, ambient temperature, calf  
91 age and health status (Wallace, et al., 2006; Thornhill, et al., 2015).

92 The diagnostic test characteristics of TIR spectroscopy and digital Brix refractometer have  
93 formerly been evaluated using an imperfect RID assay as the reference standard (Deelen, et al., 2014;  
94 Elsohaby, et al., 2016). Owing to the imperfection of reference tests, Bayesian latent class analysis  
95 models (BLCMs) present a suitable option for the simultaneous estimation of Se and Sp of two or  
96 more tests without any assumption about the underlying true disease status of each subject (Hui and  
97 Walter, 1980). Basically, these models are premised on three key assumptions: (1) the target  
98 population should consist of two or more subpopulations with different prevalences, (2) the  
99 sensitivity and specificity of the index tests should be constant across the subpopulations and (3) the  
100 tests should be conditionally independent (CID) given the disease status (Hui and Walter, 1980). To

101 the best of our knowledge, there are no published studies that apply a BLCM framework to quantify  
102 the accuracy of RID, TIR-spectroscopy and digital Brix refractometer for the assessment of FTPI in  
103 dairy calves. Therefore, the objective of this study was to estimate the diagnostic performance of  
104 RID, TIR spectroscopy and digital Brix refractometer for diagnosis of FTPI in dairy calves within a  
105 Bayesian framework.

106

## 107 **2. Materials and methods**

### 108 **2.1. Study population**

109 Forty commercial Holstein dairy herds were selected to participate in a study to investigate  
110 colostrum and calf health management practices in Atlantic Canada dairy herds (Prince Edward  
111 Island (PE; n = 5), Nova Scotia (NS; n = 21), New Brunswick (NB; n = 8) and Newfoundland (NL; n  
112 = 6)). The herds were selected by the veterinary clinics in the study area. To be eligible for inclusion  
113 in the study, herds had to provide at least 10 blood samples.

114

### 115 **2.2. Sample collection**

116 A total of 691 holstein calves from PE (n = 203), NS (n = 218), NB (n = 210) and NL (n = 60)  
117 were blood-sampled between June 2013 and September 2015. Sampling was conducted in  
118 accordance with the Canadian Council on Animal Care guidelines (Care, Canadian Council On  
119 Animal, 2009) under a protocol approved by the Animal Care Committee at the University of Prince  
120 Edward Island (UPEI; protocol #6006206). Specifically, within each farm, whole blood was  
121 collected from 1 to 14 day-old calves by jugular venipuncture, using a 20-gauge, 1-inch hypodermic  
122 needle (BD Vacutainer Precision Glide, Becton Dickinson Co., Franklin Lakes, NJ), into a sterile,  
123 plastic vacutainer tube (BD Vacutainer, Becton Dickinson Co.) without anticoagulant. Samples were  
124 labeled with a calf identification number, dated and then stored on the farm at 20°C refrigeration  
125 until transported to the Maritime Quality Milk Laboratory, UPEI. Serum was separated by

126 centrifugation at  $1500 \times g$  for 10 min at  $\sim 20^{\circ}\text{C}$ . Serum samples were divided into 3 aliquots and  
127 stored at  $-80^{\circ}\text{C}$ .

128

## 129 **2.3. Direct diagnostic tests**

### 130 **2.3.1. RID assay**

131 Serum samples were allowed to thaw at room temperature ( $20$  to  $24^{\circ}\text{C}$ ) and vortexed at a  
132 maximum of  $2700$  rpm for  $10$  s. Subsequently, IgG was measured by a commercial RID assay  
133 (Bovine IgG RID Kit, Triple J Farms, Bellingham, WA). The RID assay was performed according to  
134 the manufacturer's instructions, using  $5 \mu\text{l}$  of undiluted serum sample in each well. The diameter of  
135 precipitated rings was measured using a hand-held caliper after  $18$  to  $24$  h of incubation at room  
136 temperature. Each sample and assay standard was tested in replicates of two. The averages of the 2  
137 replicates of the assay standards were used to build a calibration curve that was subsequently used to  
138 determine IgG concentrations for the serum samples. The final IgG concentration for each sample  
139 was determined by calculating the average of the 2 replicates. Serum samples with IgG  
140 concentrations greater than the manufacturer's stated performance range for the assay ( $>3000$  mg/dl)  
141 were diluted (1:1) with deionized sterile water and retested. The IgG concentration of  $1000$  mg/dl  
142 was used as a cut-point to differentiate calves with and without FTPI (Weaver, et al., 2000; Godden,  
143 2008).

144

### 145 **2.3.2. TIR spectroscopy**

146 Thawed serum samples were diluted (1:1) with deionized sterile water and vortexed at a  
147 maximum of  $2700$  rpm for  $10$  s. Each diluted serum sample was tested in replicates of 6 by evenly  
148 spreading  $10\text{-}\mu\text{l}$  aliquots into  $5\text{-mm}$  diameter wells within an adhesive-masked, 96-well silicon  
149 microplate (Riley et al., 2007). An empty well served as the background reference for each

150 microplate. The loaded microplates were allowed to dry at room temperature (20–24°C) for 2 h, to  
151 produce dried, thin films.

152 For collection of the spectra, the microplates were inserted into a multisampler (HTS-XT  
153 Autosampler, Bruker Optics, Milton, ON, Canada) interfaced with an infrared (IR) spectrometer  
154 (Tensor 37, Bruker Optics) equipped with a deuterium tryglycine sulfate detector and controlled by  
155 proprietary software (OPUS ver. 6.5, Bruker Optics). A total of 4146 (691 samples × 6 replicates)  
156 spectra were collected over the wavenumber range between 4000 and 400 cm<sup>-1</sup> with a nominal  
157 resolution of 4 cm<sup>-1</sup>, with 512 scans collected for data acquisition. Collected spectra were converted  
158 into a printable format using manufacturer's software (GRAMS/AI ver.7.02, Thermo Fisher  
159 Scientific Inc., Waltham, MA). The printable format spectral data were imported into MATLAB  
160 (MathWorks R2016a, Natick, MA), and then preprocessed using the techniques previously described  
161 for developing the partial least squares (PLS) regression model (Elsohaby et al., 2014).

162 A previously developed PLS model built for prediction of serum IgG concentration from IR  
163 spectra (Elsohaby et al., 2014) was used to predict serum IgG concentrations. The IgG concentration  
164 was predicted from each spectrum; and, subsequently, the IgG concentration for each serum sample  
165 was calculated as the average of the 6 replicate IgG values. The IgG concentration of 1000 mg/dl  
166 was used as a cut-point to differentiate calves with and without FTPI (Godden, 2008; Weaver et al.,  
167 2000).

168

## 169 **2.4. Indirect diagnostic test**

### 170 **2.4.1. Digital Brix refractometer**

171 Thawed serum samples were vortexed at a maximum of 2700 rpm for 10 s and then tested  
172 using a digital Brix refractometer (PAL-1, Atago Co. Ltd., Bellevue, WA), with a scale from 0 to  
173 52% Brix. Approximately, 250 µl of serum were used, with the Brix score of the liquid determined  
174 by shining a light through the sample in the prism followed by measuring the index of refraction and

175 reading off the percentage Brix on a digital scale. The refractometer was cleaned and re-calibrated  
176 with distilled water at room temperature before each analysis. Previous studies have reported that  
177 Brix scores of 8.2% (Morrill, et al., 2013), 8.3% (Elsohaby, et al., 2015), 8.4% (Deelen, et al., 2014)  
178 and 8.5% (Hernandez, et al., 2016), may be used to identify FTPI in dairy calves.

179

## 180 **2.5. Population classification**

181 Dairy calf data derived from the four Canadian provinces (PE, NB, NS, and NL) constituted  
182 four calf populations that were presumed to have different FTPI prevalences. These populations  
183 formed the basis for the estimation of the Se and Sp of the three diagnostic tests.

184

## 185 **2.6. Statistical analysis**

186 A Bayesian latent class model fitted in OpenBUGS v3.2.2 (Thomas et al., 2006) was used to  
187 infer the Se and Sp of the three tests (RID, TIR and digital Brix refractometer), as well as the four  
188 population prevalences as per the standards for reporting diagnostic accuracy studies that use  
189 BLCMs (Kostoulas et al., 2017). The Bayesian model was implemented in R version 3.5.1 using  
190 (BRugs) package. In particular, the accuracy of the diagnostic tests was assumed to be similar across  
191 the study populations, i.e. Se and Sp constancy. However, granted that the two direct tests (RID and  
192 TIR) are based on related measurement mechanisms for FTPI but independent of the indirect digital  
193 Brix test i.e. are conditionally correlated, we allowed for dependence between the two tests by  
194 adding two conditional covariance parameters,  $\sigma_{Se}$  and  $\sigma_{Sp}$ , between pairs of the Se and Sp of the  
195 tests respectively as specified by (Gardner, et al., 2000). Notably, the performance of the digital Brix  
196 test was evaluated based on four pre-identified cut-off values: 8.2% (Morrill, et al., 2013), 8.3%  
197 (Elsohaby, et al., 2015), 8.4% (Deelen, et al., 2014) and 8.5% (Hernandez, et al., 2016), thus  
198 resulting in four cut-off-specific models.

199 Counts ( $O_k$ ) of the different test combinations (e.g. +,+,+) were assumed to follow a multinomial  
 200 distribution of the form:

201

$$202 \quad O_k | Se_i Sp_i P_k \sim \text{multinomial}(\text{prob}_k, n_k)$$

203

204 Where  $Se_i$  and  $Sp_i$  represent the respective test characteristics for test  $i$  ( $i = 1,2,3$ ) and  $P_k$  is the  
 205 specific prevalence for the  $k^{\text{th}}$  ( $k = 1,2,3,4$ ) population.  $\text{Prob}_k$  is a vector of probabilities of  
 206 observing the different combinations of test results, whereas  $n_k$  reflects the total number of calves  
 207 tested for the  $k^{\text{th}}$  population. For instance, in the 1<sup>st</sup> population for an individual testing positive to  
 208 each of the three tests,  $\text{prob}_1$  is given by:

209

$$210 \quad \text{prob}_1 = (Pr(T_1^+ T_2^+ T_3^+ | D^+) + Pr(T_1^+ T_2^+ T_3^+ | D^-)) \\
 = (Se_1 Se_2 + \sigma_{se}) Se_3 P_1 + ([1 - Sp_1][1 - Sp_2] + \sigma_{sp}) [1 - Sp_3] [1 - P_1]$$

211

212 Given four populations, the available data furnished 28 degrees of freedom sufficient to estimate 12  
 213 parameters (Se and Sp of the three tests, four prevalences and two conditional covariances),  
 214 essentially yielding an identifiable model. Non-informative priors ( $\text{beta}(1,1)$ ) were used to fit the  
 215 Bayesian model since no reliable prior information was available for any of the aforementioned  
 216 parameters. Notably, the hypothesis:  $H_0: \sigma_{se}, \sigma_{sp} = 0$ , was evaluated using a Bayesian  $P$ -value.

217 The model was initialised with two Markov Chain Monte Carlo chains with different values.  
 218 Each chain comprised 70000 samples, with the first 20000 being discarded as the burn-in  
 219 (supplementary file). Convergence of the chains was evaluated by visual appraisal of the time series  
 220 plots of selected variables and the Gelman-Rubin diagnostic plots. The posterior distribution of the  
 221 population prevalences, the Se and Sp of the three tests, as well as the conditional covariances were  
 222 reported as the median and the corresponding 95% posterior credibility intervals (PCI).

### 223 3. Results

224 The cross-classified counts of the three tests outcomes at each of the digital Brix cut-off levels  
225 and specific calf populations are displayed in Table 1. Based on these tabulated data, the Se and Sp  
226 for RID, TIR and digital Brix refractometer, together with the conditional covariance parameters  
227 between the RID and TIR test characteristics were derived. The true prevalences of FTPI in dairy  
228 calves in the four Canadian provinces are presented in Table 2.

229 RID showed the best Se and Sp estimates at all the tested cut-offs of digital Brix refractometer,  
230 but the higher the cut-off, the more comparable sensitivities of RID and digital Brix refractometer  
231 became until a cut-off of 8.5%. With increasing digital Brix refractometer cut-off, Se of RID assay  
232 and TIR spectroscopy decreased from 96.0% (95% PCI: 88.0-99.0) and 79.0% (95% PCI: 70.0-85.0),  
233 (at lower cut-off 8.2%) to 92.0% (95% PCI: 77.0-99.0) and 74.0% (95% PCI: 61.0-82.0), (at higher  
234 cut-off 8.5%), respectively. With increasing the cut-off of digital Brix refractometer from cut-off  
235 8.2% to 8.5%, the Se estimate remarkably increased from 79.0% (95% PCI: 70.0-96.0) to 95.0%  
236 (95% PCI: 87.0-100.0), which is a good improvement. However, Sp estimate of digital Brix  
237 refractometer sharply decreased from 95.0% (95% PCI: 91.0-98.0), (at cut-off 8.2%) to 84.0% (95%  
238 PCI: 78.0-94.0), (at cut-off 8.5%). Sp of RID assay and TIR spectroscopy were always higher than  
239 Sp of digital Brix refractometer at all the tested cut-offs and were above 92.0%, and 96.0%,  
240 respectively (Table 2). In the model, since the parameter,  $\sigma_{sp}$  was significant (Bayesian P-value=),  
241 the dependence model was retained for subsequent analyses.

242

### 243 4. Discussion

#### 244 Characteristics of tests estimates

245 Using a Bayesian framework, we estimated the Se and Sp of RID, TIR spectroscopy and digital  
246 Brix refractometer to determine presence or absence of calf FTPI at different cut-off values of the  
247 digital Brix refractometer without the assumption of a reference standard. Previous studies have

248 compared TIR spectroscopy and digital Brix refractometer with the assumption of RID as gold  
249 standard for measuring serum IgG concentration and diagnosis of FTPI in calves (Deelen, et al.,  
250 2014; Elsohaby, et al., 2016). The analysis showed that RID has a higher Se than TIR and Brix, if the  
251 latter is used with cut-offs of 8.2% or 8.3%. However, the higher the cut-off, the more comparable  
252 sensitivities of RID and digital Brix refractometer. The possible explanation for high  $Se_{RID}$  is that  
253 RID assay measures IgG concentration through antigen-antibody precipitation (McBeath, et al.,  
254 1971). However, the TIR spectroscopy and Brix refractometer measure serum proteins and then  
255 either use mathematical models to directly extract the IgG concentration for TIR spectroscopy  
256 (Elsohaby, et al., 2016) or relate the Brix scores to IgG concentration for refractometry (Deelen, et  
257 al., 2014). The TIR spectroscopy demonstrated lower Se (79%) and similar Sp (97%) at cut-off 8.2%  
258 than that previously reported by (Elsohaby, et al., 2016) [ $Se = 0.87\%$  (0.76–0.95) and  $Sp = 0.97\%$   
259 (0.92–0.99)], which could be argued by the using of imperfect reference standard. However, the Se  
260 and Sp of the digital Brix refractometer fall within the range of those reported previously by (Deelen,  
261 et al., 2014) [ $Se = 88.9\%$  and  $Sp = 88.9\%$ ], (Elsohaby, et al., 2015) [ $Se = 85.5\%$  and  $SP = 83.5\%$ ],  
262 and (Hernandez, et al., 2016) [ $Se = 100\%$  and  $Sp = 89.2\%$ ].

263 Various cut-off values have been recommended as an appropriate cut-off for diagnosis of  
264 calves with FTPI using digital Brix refractometer (Deelen, et al., 2014; Elsohaby, et al., 2015). In  
265 this study, our findings showed that the test estimates are changed at the different cut-offs of BRIX  
266 test, especially the Se estimates, meanwhile the 95% CI of the Sp estimates of the three tests at the  
267 different cut-offs were overlapping. Previous studies recommended different cut-offs for diagnosis of  
268 FTPI in newborn calves, for example, Morrill, et al. (2013) recommended cut-off value of 8.2%. In  
269 contrast, other studies recommended other cut-offs 8.2% (Elsohaby, et al., 2015), 8.4% (Deelen, et  
270 al., 2014), 8.5% (Hernandez, et al., 2016) and 8.8% (Cuttance et al., 2017). The possible reasons for  
271 this difference could be related to the use of refractometers from different manufacturers, as well as  
272 age, breed and health status of calves involved in these studies (Wallace, et al., 2006; Thornhill, et

273 al., 2015). In addition, previous studies used traditional diagnostic evaluation method, which may  
274 biased the findings due to the imperfect gold standard tests (Toft et al., 2005). The Se and Sp of the  
275 RID and TIR spectroscopy for diagnosis of calves with FTPI have been shown to be consistent (RID:  
276 Se estimates centered around 95% and Sp estimates centered around 93%, while, TIR: Se estimates  
277 centered around 76% and Sp estimates centered around 96%), regardless of the digital Brix  
278 refractometer cut-off values. However, the  $Se_{Brix}$  increased from 79% to 95% and  $Sp_{Brix}$  decreased  
279 from 95% to 84% with increasing the cut-off value from 8.2 to 8.5%, which is in accordance with  
280 previous studies (Deelen, et al., 2014; Elsohaby, et al., 2015; Hernandez, et al., 2016). In those  
281 studies, estimation of digital Brix refractometer diagnostic characteristics was based on the  
282 assumption of an existing perfect reference standard. It was notable that the median values of the Sp  
283 estimate of TIR were always higher than Sp estimates of RID and Brix at all tested cut-offs.  
284 However, the 95% confidence intervals estimate of the RID, TIR and Brix tests was overlapping  
285 across the tested cut-offs of digital Brix refractometer reflecting the inability to prefer a test over the  
286 other based on the Sp estimate.

287 The uncertainty associated with the Se estimates of those assays is a reflection of the varying  
288 number of truly infected herds for each assay at different cut-off values that are used in the tests' Se  
289 estimation. At the highest cut-off value of the digital Brix refractometer (8.5%), the RID and TIR  
290 spectroscopy have the largest uncertainty around its Se estimate, whereas digital Brix refractometer  
291 had the smallest. At the lowest cut-off (8.2%), the reverse was true. The uncertainty associated with  
292 the changes in Se estimates of those tests at different cut-offs was probably attributed to the changing  
293 of target condition, number of true positive and negative values at those cut-offs for the different  
294 tests, and to the greater difference in the prevalences amongst the populations studied (Mweu et al.,  
295 2012).

296

## 297 **Model assumptions**

298 Test characteristics (Se and Sp) for RID, TIR spectroscopy and digital Brix refractometer were  
299 estimated at four different cut-offs using Bayesian LCA. The LCA analysis was based on a modified  
300 version of the LCA introduced by Hui and Walter (1980) for evaluation of diagnostic tests in the  
301 absence of a gold standard. We evaluated the Hui-Walter model assumptions and it has been  
302 fulfilled. Different prevalences in populations are fundamental to LCA models (Kostoulas et al.,  
303 2017). In this study, location of the study participants was regarded as a variable for study population  
304 stratifier to classify them into four provinces. The apparent prevalence of FTPI in dairy calves from  
305 the different provinces (PE, NB, NS, and NL) showed a wide variation. Subsequently, it was  
306 assumed that the test characteristics could be considered constant across the populations to fulfill the  
307 first model assumption. For RID and TIR spectroscopy, serum samples with IgG concentration  
308 greater than 1000 mg/dl was considered “negative” and those with IgG concentration less than 1000  
309 mg/dl was considered “positive” (Godden, 2008; Weaver et al., 2000; Elsohaby et al., 2014).

310 As for the second model assumption, the RID and TIR were considered conditionally  
311 dependent (COC) given the same disease status because both of them are direct test measuring the  
312 same target (IgG) in the serum samples while, digital Brix refractometer measuring the IgG in the  
313 serum samples indirectly through the index score of refraction. To confirm our assumption about  
314 COC between RID and TIR, therefore, we ran different models such as CID between the three tests  
315 and COC models (digital Brix refractometer and RID) and (digital Brix refractometer and TIR).  
316 Based on the DIC, we found the COC (RID and TIR) model is giving the smallest DIC value hence;  
317 it has been considered the best fitting model and was presented in this study. The third model  
318 assumption was achieved by repeating the model analysis with exclusion of each of the  
319 subpopulation, one at a time. The test estimate results showed unsubstantial changes, which supports  
320 that the assumption was not violated.

321

## 322 **Conclusions**

323 We have estimated the Se and Sp of RID, TIR spectroscopy and digital Brix refractometer for  
324 diagnosis of FTPI without the assumption of an existing reference standard. RID has a higher Se than  
325 TIR and Brix, if the latter is used with cut-offs of 8.2% or 8.3%. However, the higher the cut-off, the  
326 more comparable sensitivities of RID and digital Brix refractometer. The median estimate of  $Sp_{TIR}$   
327 were always higher than  $Sp_{RID}$  and  $Sp_{Brix}$  at all tested cut-offs. However, the 95% confidence  
328 intervals estimates of the three tests were overlapping across the tested cut-offs of digital Brix  
329 refractometer reflecting the inability to prefer a test over the other based on the Sp estimate.

330

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339

### 340 **Conflict of interests**

341 None of the authors have financial or personal relationships with other people or organizations  
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343

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476 **Table 1:** Cross-tabulated results for combinations of three diagnostic tests for diagnosis of failure of transfer of passive immunity (FTPI) in  
 477 dairy calves (n = 691) from four different provinces in Atlantic Canada.

Cut-offs of Brix refractometer	Population based on location	Tests combinations (RID T <sub>1</sub> ; TIR T <sub>2</sub> ; Brix T <sub>3</sub> ) <sup>a</sup>								Total (n)
		+++	++-	+ - +	+ - -	- + +	- + -	- - +	---	
Cut-off 8.2%	NB	35	10	15	9	0	1	6	134	210
	NL	20	4	6	5	0	0	2	23	60
	NS	51	20	10	13	0	0	6	118	218
	PE	36	12	2	5	3	2	12	131	203
Total (n)		142	46	33	32	3	3	26	406	691
Cut-off 8.3%	NB	38	7	18	6	0	1	11	129	210
	NL	22	2	7	4	0	0	3	22	60
	NS	53	18	10	13	0	0	10	114	218
	PE	40	8	2	5	5	0	17	126	203
Total (n)		153	35	37	28	5	1	41	391	691
Cut-off 8.4%	NB	41	4	21	3	0	1	12	128	210
	NL	23	1	8	3	0	0	5	20	60
	NS	58	13	10	13	0	0	19	105	218
	PE	44	4	3	4	5	0	21	122	203
Total (n)		166	22	42	23	5	1	57	375	691
Cut-off 8.5%	NB	41	4	22	2	0	1	18	122	210
	NL	23	1	10	1	0	0	8	17	60
	NS	61	10	11	12	0	0	23	101	218
	PE	45	3	4	3	5	0	30	113	203
Total (n)		170	18	47	18	5	1	79	353	691

478 <sup>a</sup> T<sub>1</sub> = radial immunodiffusion (RID) assay; T<sub>2</sub> = transmission infrared (TIR) spectroscopy; T<sub>3</sub> = digital Brix refractometer.

479 **Table 2:** Posterior median and 95% posterior credibility interval (PCI) of tests sensitivity (Se) and specificity (Sp) estimates and true  
 480 prevalence of FTPI at four cut-offs for digital Brix refractometer (8.2%, 8.3%, 8.4%, and 8.5%) in dairy calves (n = 691) from four  
 481 different Canadian provinces.

Parameters	Cut-offs for digital Brix refractometer											
	Cut-off 8.2%			Cut-off 8.3%			Cut-off 8.4%			Cut-off 8.5%		
	Median	95% PCI <sup>a</sup>		Median	95% PCI		Median	95% PCI		Median	95% PCI	
Se <sub>RID</sub>	0.96	0.88	0.99	0.95	0.85	0.99	0.93	0.79	0.99	0.92	0.77	0.99
Se <sub>TIR</sub>	0.79	0.70	0.85	0.79	0.69	0.85	0.76	0.64	0.84	0.74	0.61	0.82
Se <sub>Brix</sub>	0.79	0.70	0.96	0.87	0.77	0.99	0.91	0.84	0.99	0.95	0.87	1.00
Sp <sub>RID</sub>	0.93	0.84	0.97	0.91	0.84	0.97	0.93	0.87	0.97	0.93	0.88	0.98
Sp <sub>TIR</sub>	0.97	0.90	1.00	0.96	0.90	1.00	0.98	0.93	1.00	0.96	0.92	1.00
Sp <sub>Brix</sub>	0.95	0.91	0.98	0.91	0.87	0.96	0.89	0.84	0.97	0.84	0.78	0.94
Prevalence in NS	0.29	0.21	0.37	0.30	0.22	0.38	0.32	0.25	0.40	0.32	0.24	0.41
Prevalence in NL	0.54	0.39	0.68	0.54	0.40	0.68	0.57	0.43	0.72	0.61	0.46	0.76
Prevalence in NB	0.38	0.27	0.47	0.36	0.26	0.46	0.38	0.29	0.49	0.38	0.29	0.50
Prevalence in PE	0.26	0.18	0.34	0.27	0.19	0.35	0.29	0.21	0.39	0.29	0.21	0.41
$\sigma_{SeRID\_TIR}$	0.01	-0.003	0.069	0.013	-0.005	0.08	0.03	-0.004	0.11	0.03	-0.003	0.13
$\sigma_{SpRID\_TIR}$	0.02	0.0003	0.079	0.03	0.0002	0.08	0.02	0.0001	0.06	0.03	0.0004	0.064

482 <sup>a</sup> 95 % Posterior credibility interval (PCI).