Use of the rSpaA415 antigen for detection of IgG anti-Erysipelothrix rhusiopathiae in farmed cattle indicates a low prevalence in dairy and feedlot cattle in the United States of America and Great Britain

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Abstract

Background Clinical cases of Erysipelothrix rhusiopathiae, a zoonotic gram-positive bacterium, have been reported in many ruminant species, including in cattle, deer, moose and muskoxen. Fatal cases have been repeatedly reported in cattle over the years but to date there is only one Japanese study investigating the seroprevalence of this bacterium in bovine using the growth agglutination test (GAT). This technique is subjective, time-consuming, expensive and hazardous compared to modern serological tests such as enzyme-linked immunosorbent assays (ELISA) or the newly developed fluorescent microbead-based immunoassays (FMIA). Results A FMIA based on the surface protein SpaA (rSpaA415) antigen of E. rhusiopathiae developed in this study had an almost perfect agreement with the GAT (k=0.83) and showed a sensitivity of 89.7% and a specificity of 92.9% when compared to the GAT. Overall, detection rates of E. rhusiopathiae antibody positive samples were 13.8% (51/370) in British herds and 6% (12/200) in US herds. Positive cattle were present in 34.3% (24/70) of the investigated British farms and in 34.7% (8/23) of the US farms with an on-farm prevalence of 7.1% to 100% for the British and 8.3-30% for the US. Conclusions FMIA is a fast, safe and economic alternative to the GAT for the diagnosis of E. rhusiopathiae in cattle. This work is the first seroprevalence study of E. rhusiopathiae in healthy farmed cattle in the Great Britain and the US and revealed that infection occurs at a low level. Further investigations to evaluate risks of zoonotic transmission when handling cattle are needed.

Background

Erysipelothrix is a gram-positive bacterium. The genus Erysipelothrix contains four species associated with 28 different serotypes; Erysipelothrix rhusiopathiae (serotypes 1a, 1b, 2, 4, 5, 6, 8, 9, 11, 12, 15, 16, 17, 19, 21, 23 and N), Erysipelothrix tonsilarum (serotypes 3,
7, 10, 14, 20, 22, 24, 25 and 26), *Erysipelothrix sp.* strain 1 serotype 13) and *Erysipelothrix sp.* strain 2 (serotype 18) [1]. *Erysipelothrix rhusiopathiae* is considered to be the pathogenic species of the genus and known as the etiologic agent of swine erysipelas which can be associated with sporadic cases or larger outbreaks of major economic importance [2]. Besides pigs, *E. rhusiopathiae* can cause a wide range of diseases in other species such as sheep, fish, poultry, cattle and humans [3–6]. Infections in humans are primarily a result of contact with infected animals and are presented either as a localised cutaneous lesion called erysipeloid, as a generalised cutaneous lesion, or as a septicaemic form which is often associated with endocarditis [7].

Recently, *E. rhusiopathiae* has been isolated in increasing frequency from ruminants, especially from farmed cattle (*Bos taurus*) [4, 5]. Most of the clinical cases in cattle are observed in young calves presenting septicaemia [8] with abscesses in the liver and lungs [9], encephalomeningitis [10], or polyserositis and arthritis [11].

*Erysipelothrix rhusiopathiae* has been associated with multiple unusual mortality events in muskoxen (*Ovibos moschatus wardi*) in the Canadian Arctic Archipelago [12]. During the years 2009–2011, a total of 22 muskoxen were found dead during multiple expeditions in the Canadian Arctic Archipelago and in 2012 approximately 150 muskoxen were found dead; *E. rhusiopathiae* serotype 5 was confirmed by serotyping, PCR and/or histopathology on tissues from these animals [12]. Interestingly, *E. rhusiopathiae* serotype 5 was also isolated from a fatal case of metritis in a Norwegian heifer [13] and from a fatal case of acute multifocal necrotic hepatitis in a white tailored reindeer in Iowa, USA [14]. In Canada, the death of three elks (*Alces Alces*) was linked to a septicaemia caused by *Erysipelothrix* of serotype 17 [15]. The bacterium was isolated from liver, kidney, lungs and lymph nodes from the three animals [15].

During studies in Japanese abattoirs, *Erysipelothrix* was isolated from 6.4% of 1236
healthy, slaughtered cattle [16] which demonstrates that cattle may be subclinically infected with the bacterium. An epidemiological follow-up study using the growth agglutination test (GAT) to detect antibodies anti-\textit{Erysipelothrix} in Japanese cattle found that 76% of 854 healthy cattle had detectable antibodies [3]. The same study also found a higher rate of seropositive cattle in areas with concurrent swine industry [3]. This data could indicate that \textit{Erysipelothrix} is mainly transmitted by pigs although cattle may also act as a vehicle for its distribution [5, 16]. In support of this, \textit{Erysipelothrix} was isolated from cattle slurry [3] which could enhance the bacterium’s ability to spread as \textit{Erysipelothrix} can survive in soil contaminated with faecal material [4]. Current methods of antibody detection in cattle have been carried out using solely GAT. GAT has been extensively used in pigs and chickens and it has shown a good correlation between the antibody titres and immune status in vaccinated pigs [17] and challenged chickens [18] but this correlation has not yet been studied in cattle. The use of GAT in pigs and chickens was replaced by recently developed enzyme-linked immunosorbent assays (ELISAs) and fluorescent microbead-based immunoassays (FMIs) [6, 19–22] due to their ability to permit the testing of large numbers of samples in a short time, while giving objective results.

Although \textit{Erysipelothrix} and antibodies against it have been detected in healthy cattle in Japan [3–5], data is lacking for the distribution of \textit{Erysipelothrix} in cattle across Europe and North America where its epidemiological importance is not known.

Surface protective antigens (Spa) of \textit{Erysipelothrix} have been shown to be highly immunogenic. Four Spa types (SpaA, SpaB1, SpaB2 and SpaC) have been identified. Based on testing reference strains, SpaA can be associated with \textit{E. rhusiopathiae} serotypes 1a, 1b, 2, 5, 9, 12, 15, 16, 17, 23 and N, SpaB1 can be associated with \textit{E. rhusiopathiae} serotypes 4, 6, 8, 19 and 21, SpB2 can be associated with \textit{E. rhusiopathiae} serotype 11 and
SpaC can be associated with *E. sp.* strain 2 serotype 18. No Spa types were detected in any of the serotypes of *E. tonsillarum* and *E. sp.* strain 1 [23].

A highly sensitive (96.5%) and specific (100%) ELISA was recently developed for the detection of *Erysipelothrix* in swine using a recombinant SpaA (rSpaA415) [6]. This was then enhanced by adapting it into an FMIA [21]. This study aimed to investigate the antibody distribution against *Erysipelothrix* in cattle in Great Britain and the USA to increase the knowledge of its epidemiological significance and to develop an ELISA and FMIA test using rSpaA415 antigen for the detection of antibodies against *Erysipelothrix* in cattle to overcome the disadvantages of GAT.

Results

*Development and optimisation of rSpaA415 FMIA and ELISA and cut-off evaluation using the GAT as the reference assay.*

A first subset of 300 samples were tested with the ELISA and FMIA to evaluate the performance of both tests. The FMIA had superior performance compared to the ELISA. Specifically, the FMIA had an area under the curve (AUC) of 94.8% (95%CI 91%–98%) indicating a high accuracy of the test. The optimal cut-off was determined to be 1073.5 MFI giving a diagnostic sensitivity and specificity of 89.7% and 92.9% respectively. The ELISA had an AUC of 64.7% (95%CI 55%–74%) and a sensitivity and specificity of 61% and 53% for the optimal cut-off which had an S/P value of 22%.

ELISA and FMIA had an agreement of 79% and a kappa value of 0.31 showing a fair agreement. FMIA was preferred because it was more accurate, sensitive, specific, and easy to operate than the ELISA and was selected to test the remaining field samples. The percentage of agreement of the FMIA and GAT was 93% (95%CI, 88%–96%) which was almost perfect (κ = 0.83). McNemar’s test showed that the paired discordances occurred randomly and that therefore, both tests were comparable (McNemar’s p value = 1). The
CVs obtained for the FMIA test for the positive (13.1%) and negative (14%) reference sera were considered good suggesting a high level of assay reproducibility.

*Antibody titres on field and experimental samples*

Experimentally vaccinated cattle developed antibodies against *E. rhusiopathiae* as demonstrated by the FMIA, ELISA and GAT (Fig. 1, Table 1). Both cows had detectable antibodies on 14 dpv and antibody levels remained detectable until the 42 dpv. MFI and GAT titres were higher in experimentally vaccinated cattle compared to non-vaccinated field cattle with natural exposure. The distribution of GAT titres against *E. rhusiopathiae* for the studied bovine samples is summarized in Table 1. The majority of positive field samples had GAT titres of 32 (22%, 36/162), followed by 64 (13%, 21/162) and 128 (13%, 5/16). The majority of the samples tested showed agglutination below the cut-off (50%, 81/162). High antibody titres were detected more frequently in British cattle compared to US cattle (Table 1).

MFI and GAT titres were plotted and showed a good correlation (Fig. 2) which was supported by Pearson coefficient (*r* = 0.93).

*Prevalence of Erysipelothrix antibodies in US and British cattle herds by FMIA*

Antibodies against *E. rhusiopathiae* were present in both populations of farmed cattle at a low level. Overall, the prevalence in the studied British cattle population was 13.8% (51/370). Positive cattle were identified in 34.3% (24/70) of the farms tested with an on-farm prevalence of 7.1% to 100%. The number of seropositive cows among the sampled US population was 6% (12/200), positive cattle were identified in 34.7% (8/23) of the investigated farms, and the on-farm prevalence ranged from 8.3–30%. The difference in the prevalence between the USA and Great Britain was statistically significant by Chi-square test (*p* = 0.0047, $\chi^2 = 7.99$) and the difference in prevalence between farms was statistically significant for British farms (*p* = 0.002, Fisher value = 86.5) but not for US
farms (p = 0.23, Fisher value = 18.9).

Discussion

The growth agglutination test was used as the reference test as it is the only methodology used so far to evaluate the *Erysipelothix* antibody responses in cattle. The FMIA developed in this study is an improved tool for the detection of *Erysipelothix* antibodies in cattle and had almost perfect agreement with the GAT, with a high sensitivity and high specificity. There are three main disadvantages of the GAT. First, the assay is time consuming as only 8 samples can be included in a plate with two overnight incubations, one to prepare the inoculum and a second one to read the results. Second, the GAT is hazardous since live pathogenic bacteria have to be used. Finally, and third, the results are read by naked eye which may be subjective and variable between operators. In contrast, the FMIA permits the testing of large numbers of samples in less than 4 hours and gives precise and objective results. For these reasons, we propose in here the use of MFI as an alternative to GAT.

The specificity of the GAT in cross-reaction with antibodies against organisms other than *E. rhusiopathiae* has not been studied in detail. The cross-reactivity of rSpaA415 has been validated with pig pathogens but it remains unknown for pathogens infecting bovine. Higher specificity is predicted by using FMIA than GAT as the GAT involves an extent of non-specific agglutination since a titre of less of 32 indicates a negative reaction. Differences in sensitivity and specificity between GAT and MFI could be due to the *Erysipelothrix* serotypes infecting cattle. The serotype used in GAT is serotype 1a but it is uncertain to what extent the GAT agglutinates across different *E. rhusiopathiae* strains or other *Erysipelothrix* species. Antibody responses against rSpaA415 were detected in sera from rabbits inoculated with *E. rhusiopathiae* serotypes containing Spa A (1a, 1b, 2, 5, 9, 12, 15, 16, 17 and 23), Spa B1 (4, 6, 8, 19 and 21), Spa B2 (11) and *E. sp.* strain
2 containing Spa Cserotype 18). In contrast, low antibody responses were observed in sera from rabbits inoculated with *E. tonsillarum* serotype 20 (no Spa type) and no antibody response was observed in sera from rabbits inoculated with the remaining serotypes without Spa type (*E. tonsillarum* and *E. sp.* strain 1) [6]. The knowledge of the *Erysipelothrix* serotypes infecting cattle is limited; one study in Japan recovered 79 *Erysipelothrix* isolates from the tonsils of healthy slaughtered cattle of which only 43 out of these isolates were typeable and were classified into the serotypes 1b, 2, 3, 5, 9, 12, 13, 19 and 21. Responses against rSpaA415 were detected in rabbits infected with serotypes 1b, 2, 5, 9, 12, 19 and 21 but not with serotypes 3 and 13 [6]. There is no data of the serotypes of the *Erysipelothrix* serotypes circulating among the US and British herds but in Norway, a serotype 5 was isolated from an heifer with fatal metritis [13]. This study showed that FMIA was more sensitive and specific than the ELISA based on the same antigen. Higher sensitivity of FMIA assays than ELISA have been reported in other studies [21, 24–25]. Higher sensitivity of the FMIA in comparison to the ELISA using the rSpaA415 protein was observed in experimentally infected pigs, where the FMIA could detect more pigs with an *Erysipelothrix* IgG antibody response than the ELISA at day 7 post challenge [21]. The higher specificity of FMIA assays has been suggested due to proteins covalently coupled to microspheres, and antigen purity eliminates nonspecific reactions that often cause high background problems in ELISA [26]. The lower background may add increase the detection limit on samples with a low antibody concentration [21]. Because there are no studies outside Japan that have investigated the seroprevalence of *E. rhusiopathiae* in bovine samples, we considered this knowledge gap important. This work represents the first study investigating *E. rhusiopathiae* in British and US cattle. The results suggest that *E. rhusiopathiae* infections in cattle occurs at low likely subclinical levels. Although the percentage of farms with seropositive cows was nearly the same in
both countries; the overall prevalence in the British herd (13.8%) was significantly higher than in the US (6%) and positive British cattle had higher antibody titres when compared to the US herd. The reason for this is not clear; in Japan, higher cattle antibody rates were obtained where there were also areas of swine industry [3]. The seroprevalence in Japanese cattle (76%) was much higher than the obtained present prevalence [3]. Challenge studies in pigs have shown that a titre above 32 in the GAT indicates protective immunity against infection but it is unknown whether this applies also to cattle. The cattle vaccinated with the pig vaccine showed much higher antibody titres (GAT 256–1024, MFI 10,000–19,000) than the *E. rhusiopathiae* positive unvaccinated field cows (GAT 32–128, MFI 1074–6800).

Seroprevalence studies in other ruminant species besides cattle are virtually absent; only one Japanese study found a seroprevalence of *Erysipelothix* of 13.5% among 52 wild deer (*Cervus nippon yesoensis* and *Cervus nippon centralis*), also using the GAT [27].

The obtained results suggest that 13.8% and 6% of the farmed British and US cattle have had exposure to *Erysipelothrix* spp. and could be carriers of the bacteria and be a potential source of infection for other animals and humans. Furthermore, 34.4% and 34.7% of the sampled farms in Great Britain and the US had at least one seropositive animal. This data is of epidemiological importance as the bacterium has been isolated from cow slurry [3] and it is very resistant to environmental challenges [4], being able to survive in contaminated soil for several months [8]. Preventive measures should be implemented to avoid the transmission of the pathogen, especially among, abattoir workers, butchers, farmers and veterinarians that are at higher risk of exposure [28].

**Conclusions**

This work is the first one investigating the seroprevalence of *E. rhusiopathiae* among North American and British cattle and results showed that, although at low frequency,
cattle are exposed to the bacterium and therefore could act as a reservoir of transmission of the disease. The newly developed FMIA test represents an improvement on the serodiagnosis of this bacterium in cattle as it is fast, proving objective results, sensitive (89.7%), specific (92.9%) and has a good agreement with the reference assay GAT.

Methods

Serum samples

Cattle with known Erysipelothrix exposure

Two adult Angus feedlot cattle, part of the Iowa State University teaching herd and located in Ames, Iowa, USA were vaccinated with a commercial vaccine licensed for pigs (MaGESTic® 7 with SPUR®; Intervet Inc, DE, USA, serial number: 0784A009A) twice with 14 days interval by injecting 2 ml of the vaccine intramuscular into the neck area. Blood samples were collected before immunization (day 0) and at days 14, 28 and 42 post vaccination (dpv), centrifuged and the serum was collected and used for further analysis. The two cattle remained in the teaching herd after the experiment ended. In addition, 10 archived serum samples from gnotobiotic calves from an unrelated study (kindly provided by Dr Geraldine Taylor, Pirbright Institute, Surrey, United Kingdom) were used as controls.

Field samples

A total of 200 US feedlot cattle serum samples submitted for routine diagnostic were obtained from the Veterinary Diagnostic Laboratory at Iowa State University (kindly provided by Dr David Baum) and 370 serum samples were obtained from Scottish dairy cattle through the Scottish Agricultural College (SAC) (kindly provided by Dr Jill Thomson). All animals were at least one year old. The serum samples corresponded to 23 US farms with an average of 8.6 animals per farm (min = 1, max = 15, median = 10) and 70 Scottish farms with an average of 5.3 animals per farm (min = 1, max = 15, median = 3).

Serological assays
**ELISA and FMIA development**

The recombinant protein rSpaA415, based on the major surface protective antigen A (SpaA) [6, 21] was used as antigen in both ELISA and FMIA. The optimal dilution of the serum sample and regents was determined by a checkerboard titration in both assays.

For the FMIA, 18 µg of the polypeptide rSpaA415 was coupled to 5 million of microbeads (bead region 45, Luminex Corp., TX, USA) using a 2 step carbodiimide reaction [21]. All the incubations were carried out for 30 min at room temperature, in the dark and under continuous shaking. Washing steps were performed using a magnetic separator and 200 µl of washing buffer composed of PBS with 0.05% of Tween 20, pH 7.4 (PBST).

Coupled beads were diluted in blocking buffer (StabilGuard; Surmodics, MN, USA) to a final concentration of 2500 beads per well and 50 µl of this solution were incubated with 50 µl of each serum sample diluted 1:800 in assay buffer (PBST containing 10% goat serum).

The plate then was incubated and washed three times with washing buffer. Following this, 50 µl of a 20,000 dilution of a biotin conjugated goat anti-bovine IgG (Jackson Immuno Research, Cambridge, UK) was added to the wells and incubated for another 30 min. After three washings, 50 µl of streptavidin R-phycoerythrin conjugate (SAPE; MOSS, MD, USA) at 1:100 dilution in assay buffer were added to the wells. Finally, after the last incubation and washing steps, beads were re-suspended in 100 µl of assay buffer and analysed using a MAGPIX® reader system (Luminex corp., TX, USA).

The in-house ELISA was performed in 96 well plates (MaxiSorpTM; Nunc, NY, USA) coated with 0.3 µg/ml of rSpaA415 polypeptide and blocked using PBS with 10% chicken serum (Biowest, MO, USA) for 2 h at room temperature. The samples were diluted at 1:800 with PBS containing 10% rabbit serum (Biowest, MO, USA) and 100 µl was added to each well of the plate and left to incubate for 30 min at 37 °C. After washing the plates, 100 µl of a 1:30,000 dilution of peroxidase-conjugated rabbit anti-bovine (Jackson Immuno Research,
Cambridge, UK) was added to each well and left to incubate for 30 min at 37 °C. After the final washing, 100 μl of tetramethylbenzidine-hydrogen peroxide (TMB) was added to each well as a substrate (KPL, MD, USA) and left for 15 min for colour to develop. The peroxidase reaction was stopped by adding 50 μl of 1% HCl solution (KPL, MD, USA) into each well. The optical density was then read at 450 nm using a spectrophotometer.

**Growth agglutination test**

The growth agglutination test was conducted to determine the agglutinating antibody titres of the sera as described elsewhere [3, 17–18]. Briefly, 50 μl of each serum sample was incubated for 1 h at 37 °C with 50 μl of 0.2 M 2-Mercaptoethanol (Sigma Aldrich, MO, USA). Two-fold dilutions (1:2 to 1: 2048) of the serum were made in brain heart infusion broth supplemented with 0.1% Tween 80 (BHI-T80), 0.3% Tris-HCl (pH 8.0), kanamycin (100 μg/ml) and gentamicin (50 μg/ml) in a 96 well plate. Following this, 50 μl of the *E. rhusiopathiae* strain E1–6P (serotype 1a), diluted 1:10 after an 18 h incubation in BHI-T80, was added to each of the wells. The agglutination was read after incubation at 37 °C for 18 h. The titres were expressed as the reciprocal of the number of the highest dilution of serum that showed agglutination.

**Data analysis**

Statistical evaluations were performed with the package SPSS (v.19). Statistical significance was set at a p value of <0.05. The level of agreement between tests was determined using Cohen’s Kappa and the percentage of agreement. Pearson coefficient was used to measure the level of correlation between tests. Kappa coefficients (k) with values between 0–0.01, 0.02–0.2, 0.21–0.4, 0.41–0.6, 0.61–0.8 and 0.81–1 were interpreted as no agreement, slight, fair, moderate, substantial and almost perfect agreement respectively [29]. Marginal homogeneity of paired data was tested by McNemar’s Chi-square test [30]. Assay results were expressed as Median Fluorescent
Intensity (MFI) for FMIA and Optical Density (OD) and S/P value calculated as the (average OD sample/OD positive reference control) x 100 for the ELISA. The inter-assay variance was calculated using the coefficient of variance (CV) for a positive and a negative. CV with values <10%, 10%-15%, 15%-20%, > 20% were considered excellent, good, acceptable and excessive. A set of field samples (n = 163) were chosen based on MFI and OD values and all available controls (n = 18) and GAT was used as reference test to classify samples as positive or negative and MFI and S/P value were analysed in a ROC curve to generate an optimised cut-off [31].

Abbreviations
GAT: growth agglutination test; ELISA: enzyme-linked immunosorbent assay; FMIA: fluorescent microbead immunoassay; PCR: polymerase chain reaction; IgG: Immunoglobulin G; MFI: medium fluoresce intensity; PBS: phosphate-buffered saline; PBST: PBS with 0.05% of Tween 20; TMB: tetramethylbenzidine-hydrogen peroxide; HCl: Hydrochloric acid; BHI: brain heart infusion broth; T80: Tween 80; OD: optical density; CI: coefficient interval; CV: coefficient of variance; ROC: receiver operating characteristic; κ: kappa coefficient; SE: sensitivity; SP: specificity;

Declarations

Ethics approval and consent to participate

The immunisation of the two feedlot cattle of this study was approved by the Iowa State University, Ames, Iowa, USA Institutional Animal Care and Use Committee (IACUC; approval number: 1–11–7071-S). Field samples used in this study were obtained from veterinary diagnostic laboratories and were initially collected as part of routine health surveillance of the British and US cattle herds unrelated to this project. The archived experimental UK cattle samples were obtained as part of a previous project unrelated to
this study.

Consent for publication

Not applicable.

Availability of data and material

All data generated during this study is presented in an analysed format is this manuscript. Raw datasets generated during the current study are available from the first author (ana.cubasatienzar@lstmed.ac.uk) on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors’ contributions

TO and AICA conceived and designed the study; PG and AICA: performed the laboratory work; AICA: analysed the data; TO contributed financially; AICA: wrote the first draft of the paper; All authors read and contributed to the final draft of the paper.

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Table

Table 1 Distribution of growth agglutination test (GAT) Erysipelothrix rhusiopathiae antibody titers (cut-off 1:32) in cattle of unknown Erysipelothrix spp. status (British and US herds), cows experimentally vaccinated (VAC), or in gnotobiotic cows.

| GAT titre | 0     | 1:4   | 1:8   | 1:16  | 1:32  | 1:64  |
|-----------|-------|-------|-------|-------|-------|-------|
| British herds | 8     | 12    | 12    | 34    | 30    | 17    |
| US herds   | 12    | 14    | 3     | 6     | 6     | 4     |
| VAC cow 1  | dpv 0 |       |       |       |       |       |
| VAC cow 2  | dpv 0 |       |       |       |       |       |
| Gnotiobiotc| 10    |       |       |       |       |       |

Dpv = day post vaccination with an Erysipelothrix rhusiopathiae vaccine.

Figures
**Figure 1**

Erysipelothrix rhusiopathiae antibody levels in vaccinated cows. Median fluorescent intensity (MFI) (A) and ELISA optical density (OD) (B) values before vaccination (day 0) or at day post vaccination (dpv) 14, 28 and 42 days. Vaccination was done using an Erysipelothrix rhusiopathiae vaccine on dpv 0 and 14. Values represent the average of three repeats (+/- 2 SE).
Figure 2

Distribution of Erysipelothrix rhusiopathiae titers in field and experimental samples (n=181). Vertical dashed line represents the growth agglutination test (GAT) cut-off (1:32) and the horizontal line the fluorescent microbead-based immunoassay (FMIA) cut-off (1073.5).