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First detection of endosymbotic bacteria in *Culicoides pulicaris* and *Culicoides punctatus*, important Palearctic vectors of bluetongue virus

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**Abstract**

Heritable bacteria have been highlighted as important components of vector biology, acting as required symbionts with an anabolic role, altering competence for disease transmission, and affecting patterns of gene flow by altering cross compatibility. In this paper, we tested 8 UK species of *Culicoides* midges for the presence of 5 genera of endosymbiotic bacteria: *Cardinium*, *Wolbachia, Spiroplasma, Arsenophonus* and *Rickettsia. Cardinium* spp.was detected in both sexes of *C pulicaris* and *C. punctatus,* two known vectors of bluetongue virus. It was not detected in any other species, including the *C. obsoletus* group, the main vector of bluetongue and Schmallenberg viruses in northern Europe.The other endosymbionts were not detected in any *Culicoides* species. The *Cardinium* strain detected in the UK *Culicoides* species is very closely related to *Candidatus Cardinium hertigii* group C, previously identified in *Culicoides* in Asia. Further, we infer that the symbiont is not a sex ratio distorter and shows geographic variation in prevalence within a species. Despite its detection in several species of *Culicoides* that vector arboviruses worldwide, the absence of *Cardinium* in the *C. obsoletus* group suggests that infections of these symbionts may not be necessary for arboviral vector competence of biting midges.

Species of midges in the genus *Culicoides* (Diptera: Ceratopogonidae) are among the most abundant of haematophagous insects and are important vectors of viruses affecting humans and livestock. Over 50 viruses have been isolated from *Culicoides* to date, including bluetongue virus (BTV) and the recently emerged Schmallenberg virus (SBV). *Culicoides obsoletus* group are the main vectors of BTV and SBV in Northern Europe, and include *C. montanus, C. scoticus*, *C. obsoletus, C. dewulfi and C. chiopterus.* However, at present there is insufficient data on the vector competence of specific *Culicoides* species for SBV. BTV is observed predominantly in sheep, but can infect all ruminants. In addition to welfare implications, BTV has a devastating impact on the farming industry through loss of production and trade. SBV also infects ruminants, causing little or no clinical disease in adult animals but leading to a high frequency of abortion or developmental abnormality in newborn offspring (Mellor *et al.*, 2000; De Regge *et al.*, 2012).

Microorganisms and insects commonly form symbiotic associations, which may have implications for control of vector-borne disease.Endosymbiotic bacteria that reduce the longevity of their hosts can be used to interrupt onward viral transmission (McMeniman *et al*., 2009). In addition, endosymbionts may affect vector competence by decreasing (Hedges *et al.*, 2008), or increasing (Graham *et al.*, 2012) host susceptibility to viruses.

Endosymbionts have been detected in certain *Culicoides* species (Morag *et al.*, 2012; Nakamura *et al.*, 2009). Tests to date have focused on just two symbiont clades, *Cardinium* and *Wolbachia*. Reports to date indicate the presence of a phylogenetically distinct clade of *Cardinium* symbionts in some *Culicoides* (Nakamura *et al.*, 2009). However, there has been no study of European *Culicoides* species, and the role of *Cardinium* in midge biology remains unclear. In our study we aimed first to test UK species of *Culicoides* for a variety of common endosymbionts. Further, by screening male and female hosts separately, we sought to establish whether these symbionts show sex biased prevalence typical of host sex ratio distorting activity.

*Culicoides* were collected from Leahurst Campus, University of Liverpool, England and Bala, Wales, between July and October 2012. Samples were captured using light traps that were active overnight, and the insects were trapped into 95% ethanol for rapid preservation. *Culicoides* were identified to species as per Downes & Kettle (1952) and sexed. *C. scoticus* and *C. obsoletus* females cannot be separated morphologically and so were grouped together. A total of 173 *Culicoides* midges of 8 species were collected, including both vectors and non-vectors of BTV.

DNA from individual specimens was extracted using the Wizard® SV 96 Genomic DNA Purification System (Promega) into two 96 well plates, each with 2 positive and 2 negative controls. The DNA quality of each sample was tested using a PCR amplification of part of the COI gene in the mtDNA of its host (Folmer *et al.*, 1994), and this assay was used to optimize DNA dilution where necessary. All *Culicoides* that passed this initial assessment were tested for the presence of endosymbiotic bacteria in the genera *Wolbachia, Cardinium, Spiroplasma, Rickettsia* and *Arsenophonus*. To test for the presence of *Wolbachia* a PCR based assay was undertaken using primers 81F/691R designed to amplify part of the wsp gene. *Spiroplasma* presence was tested using PCR assay with primers GPO-1/MGSO that amplify part of the 16S rRNA gene from Mollicutes only, and *Cardinium* assays utilized Car-sp-F/Car-sp-Rwhich amplify part of the 16S rRNA gene. For *Rickettsia*, PCR assay utilized primers R1/R2 based on the 17kDa omp and for *Arsenophonus* primer pair ArsF/ArsR2that amplifies part of the 16S rRNA gene. Details of primer sequences and amplification conditions can be found in Duron *et al.* (2008) (*Wolbachia, Rickettsia, Arsenophonus*), van Kuppeveld *et al*. (1992) (*Spiroplasma*) and Nakamura *et al.* (2009) (*Cardinium*). PCR assays included positive controls from insect material known to be infected with the relevant symbiont (taken from Duron *et al.* (2008)), and negative (water) controls. It should be noted that our screening, because it relies on single PCR assays for each microbe, may create a low rate of false negative results ([Simoes *et al.*, 2011](#_ENREF_1)). However, it does permit direct comparison with the results of other screens.

When amplicons were obtained in PCR assays, the sequence of the amplicons was obtained to confirm that the result represented a true positive. To this end, PCR products deriving from one male and female midge of each species that was positive for a symbiont were purified using an ExoSAP digest to remove unincorporated primers and nucleotides, and cycle sequencing was performed according to the Sanger method using each of the initial primers separately. The products were visualised on an ABI automated sequencing machine at the University of Liverpool, and aligned using MEGA5 (Tamura *et al*., 2011).

PCR screening revealed 2 out of 8 species of *Culicoides* were positive for *Cardinium* infection (Table 1). The prevalence in the two infected species was significantly different (Fisher exact test: p≤0.05, d.f.=1). In *C. punctatus*, *Cardinium* prevalence was nearly fixed at 0.960 (Binomial Confidence Interval (CI): 0.796**≤**p≤0.999), whilst in *C. pulicaris* the endosymbiont was at a lower prevalence of 0.256 (Binomial CI: 0.130≤p≤0.471). For three of the *Cardinium* negative species, reduced availability of material allows us to conclude that there is no high prevalence/fixed infection, but do not give sufficient power to establish absence of low prevalence infection (<30%). The 16S rRNA sequences for the two infected species were identical, and were 99% similar to *Candidatus Cardinium hertigii* group C, previously discovered in Japanese *Culicoides* (Nakamura *et al.*, 2009) (Accession codes: HG380245, HG531389). No other endosymbionts were detected in any of the samples.

This is the first detection of *Cardinium* in UK *Culicoides.* The 16S rRNA gene is slow evolving, and thus we additionally obtained the sequence of the GyraseB gene of our detected strains to produce a more fine grained phylogenetic analysis in comparison to other *Cardinium* strains in the clade (Nakamura *et al.*, 2009). 1200 bp of this gene were amplified using primer pair gyrB23F (5’ GGA GGA TTA CAT GGY GTG GG) and gyrB1435R (5’ GGA GGA TTA CAT GGY GTG GG). PCR amplifications were performed under the following conditions: initial denaturation at 95°C for 2 minutes, 35 cycles of denaturation (94°C, 15 seconds), annealing (57°C, 60 seconds), extension (72°C, 90 seconds) and a final extension at 72°C for 5 minutes. The product was then purified and sequenced through both strands using the original and two internal primers. The *Cardinium* *gyrB* sequence was identical in *C. punctatus* and *C. pulicaris*, and forms a monophyletic clade with *Cardinium* reported from other species of *Culicoides* (Accession codes: HG380244, HG531390) (Figure 1).

In our study, *Cardinium* infection occurs in a higher proportion of species than is generally observed in insects. To date, 6 of 33 (18%) *Culicoides* species tested have been observed to carry *Cardinium* across two surveys. This compares to past unbiased surveys which report *Cardinium* global incidence of 4.4% of arthropod species (n=136), and 0% of sampled insect species (n=100) (Duron *et al*., 2008)(Fisher exact test: *Culicoides* vs all insects, p<0.001). It is notable that the strains identified in our study confirmed the presence of a particular clade of *Cardinium* (elsewhere termed clade C) that is present in this group, and not observed to date in other arthropod species. This conclusion is based on information from two markers (16S rRNA and *gyrB*) and awaits confirmation from further markers.

The ‘hotspot’ presence of *Cardinium* in sampled *Culicoides* contrasts with *Wolbachia. Wolbachia* predominates in both arthropods and insects (22.5% of arthropod species tested, 18% of insects: Duron *et al*., 2008). In contrast, *Culicoides* appears to be a ‘cold spot’ for *Wolbachia* infection; the symbiont has only been detected in 1 of the 33 screened *Culicoides* species (Nakamura *et al*., 2009) (Fisher exact test *Culicoides* incidence vs all insects: p<0.05).

Our results also suggest the presence of geographical variability in the *Culicoides-Cardinium* interaction. In our study, the prevalence of infection in *C. punctatus* is 96%, which contrasts with absence of infection in this same species in Japan (0/7) (Test of null hypothesis of same prevalence in each population: Fisher exact test: p<0.0001). This was also seen with *C. oxystoma*,which was infected with *Cardinium* in Israel but not in Japan (Morag *et al.*, 2012; Nakamura *et al.*, 2009). Geographic differentiation within a species is common for heritable symbionts (Duron *et al.*, 2008), but the drivers of geographical variation are commonly not known.

It is interesting to observe that the results of this study produced two different ‘types’ of *Cardinium* infection, one nearly fixed, and one with low prevalence. This echoes the results of the study by Nakamura *et al*. (2009), where three out of four species that tested positive had a fixed infection, and one carried *Cardinium* in a minority of individuals sampled. The fixed infections are reminiscent of those causing a cytoplasmic incompatibility (CI) phenotype, as this reproductive alteration drives the bacterium to high prevalence within the population, with infection found in both sexes (Brelsfoard & Dobson, 2009). The factors maintaining the low prevalence infection are more enigmatic. The presence of infected male hosts make sex ratio distortion an unlikely explanation, and the precise phenotype of *Cardinium* in *C. pulicaris* requires further research.

Phylogenetic analysis has grouped both *C. pulicaris* and *C. punctatus* within the subgenus *Culicoides*. *C. impunctatus*, the Scottish biting midge, is also within this subgenus (Meiswinkel *et al.*, 2004). Both *C. pulicaris* and *C. punctatus* are vectors of BTV and this study showed they are both infected with *Cardinium.* *C. impunctatus* however is not a vector, and this study showed it is not infected. This is an interesting result as it may suggest the bacterium is associated with vector competence. However, there are contrasting results in our study within the subgenus *Avaritia*. In Israel it was demonstrated that *C. imicola*, a major vector of BTV, harbors *Cardinium* (Morag *et al.*, 2012). However, all tested species belonging to the subgenus were uninfected with *Cardinium* despite all of these species acting as vectors of BTV. Overall, it is interesting to note that although *Cardinium* is not present in all vectors (and thus may not be necessary for competence), the 4 species in the Western Palearctic in which it is detected are all vectors (*C. punctatus, C. pulicaris, C. imicola, C. oxystoma*). Further research is required to determine if *Cardinium* does influence the ability of *Culicoides* biting midges to transmit viruses.

This study confirms *Culicoides* carry a clade of *Cardinium* that on the basis of the sequence of two markers forms a monophyletic assemblagefound only within biting midges, and there is evidence for geographic variation in infection in a species. It is not known what drives *Cardinium* infection into *Culicoides* populations; however presence in an equal fraction of male and female hosts are not consistent with *Cardinium* acting as a sex ratio distorter, a phenomenon commonly seen with other endosymbionts. Although *Cardinium* was detected in two species that are vectors of BTV, failure to detect *Cardinium* in the major vector in Europe, the *C. obsoletus* group, suggests this endosymbiont may not be necessary for BTV vector competence of *Culicoides*.

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**Author contributions** G. D. D. H. and M. B. conceived the study. S. E. L. and M. B. collected and identified the *Culicoides.* S. E. L. and A. R. undertook laboratory work. S. E. L. wrote the manuscript and all authors contributed to editing.

**References**

Brelsfoard, C. L. and Dobson, S. L. (2009) *Wolbachia*-based strategies to control insect pests and disease vectors. *Asia-Pacific Journal of Molecular Biology and Biotechnology,* **17**, 55-63.

De Regge, N., Deblauwe, I., De Deken, R., Vantieghem, P. Madder, M., Geysen, D., Smeets, F., Losson, B., van den Berg, T. and Cay, A. B. (2012) Detection of Schmallenberg virus in different *Culicoides* spp. by real time RT-PCR. *Transboundary and Emerging Diseases,* **59**, 471-475.

Downes, J. A. and Kettle, D. S. (1952) Descriptions of three species of *Culicoides* *Latreille* (Diptera: Ceratopogonidae) new to science, together with notes on, and a revised key to the British species of the *pulicaris* and *obsoletus* groups. *Proceedings of the Royal Entomological Society of London (B*), **21**, 3-78.

Duron, O., Bouchon, D., Boutin, S., Bellamy, L., Zhou, L., Engelstädter, J. and Hurst, G. D. (2008) The diversity of reproductive parasites among arthropods: *Wolbachia* do not walk alone. *BMC Biology,* **6**, 27-38.

Folmer, O., Black, M., Hoeh, W., Lutz, R. and Vrijenhoek, R. (1994) DNA primers for amplification of mitochondrial cytochrome c oxidase subunit I from diverse metazoan invertebrates. *Molecular Marine Biology and Biotechnology,* **3**, 294-299.

Graham, R. I., Grzywacz, D., Mushobozi, W. L. and Wilson, K. (2012) *Wolbachia* in a major African crop pest increases susceptibility to viral disease rather than protects. *Ecology letters*, **15**, 993-1000.

Hedges, L. M., Brownlie, J. C., O’Neill, S. L. and Johnson, K. N. (2008) *Wolbachia* and Virus Protection in Insects. *Science*,**322**, 702-702.

McMeniman, C. J., Lane, R. V., Cass, B. N., Fong, A. W. C., Sidhu, M. Wang, Y-F. and O’Neill, S. L. (2009) Stable Introduction of a Life-Shortening *Wolbachia* infection into the Mosquito *Aedes aegypti. Science*,**323**, 141-144.

Meiswinkel, R., Gomulski, L. M., Delécolle, J.-C., Goffredo, M. and Gasperi, G. (2004) The taxonomy of *Culicoides* vector complexes – unfinished business. *Veterinaria Italiana*, **40**, 151-159.

Mellor, P. S., Boorman, J. and Baylis, M. (2000) *Culicoides* Biting Midges: Their Role as Arbovirus Vectors. *Annual Review of Entomology*,**45**, 307-340.

Morag, N., Klement, E., Saroya, Y., Lensky, I. and Gottlieb, Y. (2012) Prevalence of the symbiont *Cardinium* in *Culicoides* (Diptera: Ceratopogonidae) vector species is associated with land surface temperature. *The Journal of the Federation of American Societies for Experimental Biology*,**26**, 4035-4034.

Nakamura, Y., Kawai, S., Yukuhiro, F., Ito, S., Gotoh, T., Kisimoto, R., Yanase, T., Matsumoto, T., Kageyama, D. and Noda, H. (2009) Prevalence of *Cardinium* Bacteria in Planthoppers and Spider Mites and Taxonomic Revision of “*Candidatus Cardinium* hertigii” Based on Detection of a New *Cardinium* Group from Biting Midges. *Applied and Environmental Microbiology,* **75**, 6757-6763.

Simoes, P. M., Mialdea, G., Reiss, D., Sagot, M. F. & Charlat, S. (2011) Wolbachia detection: an assessment of standard PCR Protocols. *Molecular Ecology Resources,***11**, 567-572.

Tamura K., Peterson D., Peterson N., Stecher G., Nei M., and Kumar S. (2011) **MEGA5: Molecular Evolutionary Genetics Analysis using Maximum Likelihood, Evolutionary Distance, and Maximum Parsimony Methods.** *Molecular Biology and Evolution*,**28**, 2731-2739.

van Kuppeveld, F. J., van der Logt, J. T., Angulo, A. F., van Zoest, M. J., Quint, W. G., Niesters, H. G., Galama, J. M. and Melchers, W. J. (1992) Genus and species specific identification of mycoplasmas by 16S rRNA amplification. *Applied and Environmental Microbiology*,**58**, 2606-2615.

Table 1. Endosymbiont assay results for *Culicoides* species under study, given by species, sex and location. Assays for other symbionts (*Wolbachia*, *Arsenophonus*, *Rickettsia*, *Spiroplasma*) were negative.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Subgenus | Species | Location | Sex | N | Proportion of Individuals positive for *Cardinium* |
| *Culicoides* | *C. punctatus* | Leahurst | M | 7 | 1.00 |
| *Culicoides* | *C. punctatus* | Leahurst | F | 19 | 0.94 |
| *Culicoides* | *C. pulicaris* | Leahurst | M | 20 | 0.35 |
| *Culicoides* | *C. pulicaris* | Leahurst | F | 19 | 0.16 |
| *Culicoides* | *C. impunctatus* | Bala | M | 26 | 0.00 |
| *Culicoides* | *C. impunctatus* | Bala | F | 30 | 0.00 |
| *Avaritia* | *C. obsoletus & C. scoticus* | Leahurst | F | 38 | 0.00 |
| *Avaritia* | *C. dewulfi* | Leahurst | M | 5 | 0.00 |
| *Avaritia* | *C. chiopterus* | Leahurst | M | 3 | 0.00 |
| *Silvaticulicoides* | *C. achrayi* | Bala | F | 6 | 0.00 |

**Figure 1.** Relatedness of the *Cardinium* Gyrase B gene across different arthropod host species and the nematode *Heterodera glycines*, based on 1200 bp of nucleotide sequence. *Cardinium* isolates are denominated by host of origin, rooted with Cand. *Amoebophilus asiaticus,* symbiont of *Acanthamoeba* spp.. Tree was estimated by Maximum Likelihood inference using the Tamura-Nei method, as implemented in MEGA, using the Nearest Neighbour Interchange heuristic algorithm. Support for individual nodes is % of 500 bootstrap replicates.

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