Veterinary Parasitology: Regional Studies and Reports 61 (2025) 101263

Contents lists available at ScienceDirect

Veterinary Parasitology: Regional Studies and Reports

journal homepage: www.elsevier.com/locate/vprsr

Original Article

First report of anti-*Toxoplasma gondii* antibodies in sea turtles

Anna Elisa Athayde-Gusmão [a], Bianca Cardozo Afonso [b], Edwards Frazão-Teixeira [b,c,d,*], Antônio Calais [e], Regiane de Fátima Ferreira [b,d], Leandro Egert [f], Luis Felipe Mayorga [f], Maria Ferreira Rosa [e], Leonardo Serafim da Silveira [b,g], Daniel Guimarães Ubiali [h], Andressa Ferreira da Silva [a]

[a] *Programa de Pós-Graduação em Medicina Veterinária (Patologia e Ciências Clínicas), PPGMV, Universidade Federal Rural do Rio de Janeiro (UFRuralRJ), Rodovia BR-465 Km 7, Seropédica, RJ 23890-000, Brazil*
[b] *Programa de Pós-Graduação em Medicina Veterinária, Universidade Estadual do Norte Fluminense Darcy Ribeiro (UENF), Brazil*
[c] *Laboratório de Biologia Estrutural, Instituto Oswaldo Cruz (IOC), Fundação Oswaldo Cruz (Fiocruz), Av. Brasil, 4.365, Manguinhos, Rio de Janeiro, RJ 21040-361, Brazil*
[d] *Laboratório de Sanidade Animal, Centro de Ciências e Tecnologias Agropecuárias (CCTA), UENF, Av. Alberto Lamego, 2000, Campos do Goytacazes, RJ 28013-602, Brazil*
[e] *Instituto de Pesquisa e Conservação Marinha (IPCMar), Av. Beira Mar, 169, Anchieta, ES 29230-000, Brazil*
[f] *Instituto de Pesquisa e Reabilitação em Animais Marinhos (IPRAM), Av. Zircônio, 663, Praia dos Recifes, Vila Velha, ES 29125-315, Brazil*
[g] *Laboratório de Morfologia e Patologia Animal, CCTA, UENF, Brazil*
[h] *Setor de Anatomia Patológica (SAP), Instituto de Veterinária, UFRuralRJ, Brazil*

ARTICLE INFO

Keywords:
Toxoplasma gondii
Sea turtles
Seroprevalence
Zoonosis
Marine ecosystem

ABSTRACT

Toxoplasma gondii is a zoonotic protozoan with an emerging ecological impact, particularly in coastal and marine ecosystems affected by terrestrial runoff. This study presents the first evidence of anti-*T. gondii* antibodies in sea turtles along the Espírito Santo coast, Brazil. A total of 102 serum samples were analyzed, primarily from green turtles (*Chelonia mydas*), with one loggerhead turtle (*Caretta caretta*). Samples were collected between 2017 and 2024 from two institutions: IPCMar and IPRAM. The modified agglutination test (MAT) revealed an overall seroprevalence of 8.8 % (9/102), with titers ranging from 1:25 to 1:100. Notably, most positive samples (80.0 %) were detected in 2024, suggesting a potential increase in environmental contamination, possibly linked to climate change and anthropogenic factors. The results provide serological evidence supporting the hypothesis that sea turtles might be susceptible to *T. gondii* exposure through contaminated prey, such as bivalves, algae, and fish, as well as runoff from terrestrial sources. Given their ecological importance and conservation status, these findings raise concerns about the health impacts of *T. gondii* on sea turtles and highlight the need for further research into their role in the parasite's transmission cycle. These findings underscore the significance of monitoring zoonotic pathogens in marine ecosystems to better understand the interplay between environmental changes, wildlife health, and pathogen spread.

1. Introduction

Toxoplasmosis is a zoonosis with a global distribution, caused by the intracellular parasite *Toxoplasma gondii*, which infects animals and humans worldwide (Dubey, 2022). Felids, whether domestic or wild, are the definitive hosts, as they are the only ones responsible for shedding oocysts within their feces, thereby contaminating the environment (Dubey, 2022). Infection occurs through the ingestion of food or water contaminated with sporulated oocysts or by consuming the meat of infected animals (Shapiro et al., 2019). Notably, during the two-week period when oocysts are excreted, felids can release up to 20 million oocysts, which, under favorable environmental conditions, become infective within 72 h through sporulation (Dubey, 1995; Dubey et al., 2011).

There is growing concern about the impact of *T. gondii* oocyst contamination on marine environments (Li et al., 2022b), especially in

* Corresponding author at: Laboratório de Biologia Estrutural, Instituto Oswaldo Cruz (IOC), Fundação Oswaldo Cruz (Fiocruz), Av. Brasil, 4.365, Manguinhos, Rio de Janeiro, RJ 21040-361, Brazil.
E-mail address: edwards.teixeira@ioc.fiocruz.br (E. Frazão-Teixeira).

https://doi.org/10.1016/j.vprsr.2025.101263
Received 19 February 2025; Received in revised form 2 April 2025; Accepted 16 April 2025
Available online 18 April 2025

areas with high anthropogenic pressure, economic growth, and population increase (Ahmadpour et al., 2022). Terrestrial-marine runoff via coastal watersheds facilitates the transport of organic materials, leading to the contamination of beaches, coastal, and oceanic waters with zoonotic pathogens like *T. gondii* (Minuzzi et al., 2021; Li et al., 2022b). Once in ocean waters, *T. gondii* oocysts remain viable for up to 24 months (Lindsay and Dubey, 2009) and have been detected in various marine animals (Dubey et al., 2020), in biofilms coating algae (Nayeri et al., 2021), in the digestive tracts of fish (Massie et al., 2010), and in bivalves (Shapiro et al., 2014). In Brazil, *T. gondii* has been found in oysters and mussels along the coast of Santos, indicating coastal water contamination (Esmerini et al., 2010). Ocean currents also facilitate oocyst dispersal, as shown by Mosquera et al. (2024), who detected *T. gondii* on an island with neither felid populations nor significant anthropogenic impact, thus indicating potential for oocysts to reach offshore waters.

Sea turtles are reptiles widely distributed across all oceans, except in polar regions, and they play a crucial role in marine ecosystems (Simantiris, 2024). According to the International Union for Conservation of Nature (IUCN) Red List of Threatened Species, all species of sea turtles are classified with some degree of extinction threat. Five species are found in Brazil: the green turtle (*Chelonia mydas*) (Seminoff, 2023), the loggerhead turtle (*Caretta caretta*) (Casale and Tucker, 2017), the olive ridley turtle (*Lepidochelys olivacea*) (Abreu-Grobois and Plotkin, 2008), the hawksbill turtle (*Eretmochelys imbricata*) (Mortimer and Donnelly, 2008), and the leatherback turtle (*Dermochelys coriacea*) (Wallace et al., 2013). These species have coastal foraging habits or, in the case of leatherbacks, in coral reefs and rocky habitats, where they feed on sponges, algae, jellyfish, crustaceans, mollusks, plankton, and small fish (Castro and Huber, 2012; Simantiris, 2024).

Given the potential for oocyst ingestion due to environmental contamination and the dietary habits of these species, this study aimed to present preliminary findings on the detection of anti-*T. gondii* antibodies in sea turtles rescued or captured along the coast of Espírito Santo state, in southeastern Brazil.

2. Material and methods

2.1. Ethics

The samples provided by Instituto de Pesquisa e Conservação Marinha (IPCMar) were obtained in accordance with the procedures approved under environmental license SISBIO No. 42232–12. The samples from Instituto de Pesquisa e Reabilitação de Animais Marinhos (IPRAM) were obtained from the supernatant of those collected for the hematological evaluation of hospitalized animals. The serological analysis of these samples does not require authorization from the environmental agency or the Animal Ethics Committee.

2.2. Animal origin and sample collection

A total of 102 sea turtle serum samples were analyzed: 101 from green turtles (*Chelonia mydas*) and one from loggerhead turtle (*Caretta caretta*). Samples were sourced from the biological sample banks of the IPCMar ($n = 92$) and IPRAM ($n = 10$), both located in Espírito Santo state, Brazil. Samples from IPCMar were collected between 2017 and 2019 in Anchieta municipality during health monitoring and ecological data collection, as an environmental requirement for Samarco mining operations. Turtles were captured using encirclement and cast net techniques. IPRAM samples were obtained in 2024 from rescued turtles along the coastline of Espírito Santo municipalities, including Marataízes ($n = 3$, including the *C. caretta* specimen), Vitória ($n = 2$), Guarapari (n = 2), Vila Velha ($n = 1$), Conceição da Barra (n = 1), and Linhares (n = 1), under the Petrobras Beach Monitoring Project.

Blood was collected from the cervical venous sinus using 5 mL syringes and 25 × 0.7 mm needles, by physical restraint of the animals. Blood samples were stored in tubes without anticoagulant, centrifuged at 900*g* for five minutes to separate serum, and stored at −20 °C in plastic microtubes until further analysis at Laboratório de Sanidade Animal (LSA), Universidade Estadual do Norte Fluminense Darcy Ribeiro (UENF).

2.3. Modified Agglutination Test (MAT)

The Modified Agglutination Test (MAT) was conducted following the protocol established by Dubey and Desmonts (1987) and the antigen used was commercially acquired from the Zoonosis Diagnostic Service, Department of Animal Production and Preventive Veterinary Medicine, FMVZ-UNESP, Botucatu, SP, which prepares it using RH strain tachyzoites fixed in formalin. An antigen solution containing the tachyzoites, borate buffer, Evans blue dye, and 2-β-mercaptoethanol was added (25 μL per well) to 96-well U-bottom microplates, followed by a 1:1 addition of serum samples diluted 1:25 in PBS. The plates were incubated at 37 °C for 12 h. Positive and negative control sera of cats were included in each test. Samples were considered negative when a blue button was observed at the bottom of the well, and positive when the bottom was clear. For antibody titration of positive samples, serial two-fold dilutions were performed. Each positive sample was tested three times.

3. Results

The overall seroprevalence was 8.8 % (9/102), and titers ranged from 1:25 to 1:100; most animals presented with titers of 1:50 (Table 1). Eight *C. mydas* specimens and the only *C. caretta* specimen (titer 1:50) were considered positive. The highest titer (1:100) was observed in a *C. mydas* rescued in the municipality of Linhares. Additionally, among the sera analyzed in 2024 (10/102), only one turtle rescued in Vitória and another in Conceição da Barra tested negative, whereas among the samples collected in previous years in Anchieta only one tested positive (1/92).

4. Discussion

The Modified Agglutination Test (MAT) is widely used for detecting anti-*T. gondii* antibodies and is considered a safe, effective, and highly sensitive method for the identification of previously infected animals (Dubey, 2022). This serological test is designed to detect IgG-type antibodies in mammals, including humans, as well as in birds (Dubey and Desmonts, 1987; Dubey et al., 2003), since warmblood animals are the only known intermediate hosts of *T. gondii*. Although there are no reptile reference sera to help validate MAT in sea turtles, the present study employed the known simplicity, sensitivity and specificity of MAT to start scratching the surface of the role of sea turtles in the complex cycle of *T. gondii*. Studies on sea turtle immunology remain scarce, but it is known that *Chelonia mydas* has three identified Ig structures, including IgY7S, which exhibits functions similar to human IgG. This immunoglobulin contains two heavy chains of different sizes bound to light chains, presumably associated non-covalently with a 90 KDa portion, which is secreted during chronic antigenic stimulation (Nash and Ryan, 2023). Based on these data, we hypothesized that serological testing on sea turtles' sera would allow satisfactory investigation of *T. gondii* antibodies.

Recent studies in Brazil have detected anti-*T. gondii* antibodies in free-ranging alligators (*Melanosuchus niger* and *Caiman crocodilus*) (Ferreira et al., 2020) and reptiles in a zoo, including a spectacled caiman (*Caiman crocodilus*), dwarf caiman (*Paleosuchus palpebrosus*), and red-footed tortoise (*Chelonoidis carbonaria*) (Feitosa et al., 2018). Ferreira et al. (2020) used MAT and IHA (Indirect Hemagglutination Assay) and showed that MAT was extremely sensitive and specific for detecting antibodies in alligators, reducing the number of seropositive animals by over 50 % compared to IHA, proving it to be a reliable technique for analyzing ectothermic animal serum samples. In this context,

Table 1
Seroprevalence of anti-*Toxoplasma gondii* antibodies by MAT in sea turtles from Espírito Santo state, Brazil.

Year	n	n Pos.	%	No. sea turtles with titers of:							
				25	50	100	200	400	800	1600	>3200
2017	43	1	2.3	1							
2018	13	0	0								
2019	36	0	0								
2024	10	8	80.0	2	5	1					
Total	102	9	8.8	3	5	1					

considering that MAT was also used in this study, we provide evidence of seropositive animals, and the sensitivity of the test strongly indicates prior exposure of these animals to *T. gondii*.

We know that *T. gondii* is temperature-dependent and that sea turtles experience fluctuations in body temperature directly influenced by the environment, unlike homeothermic animals, whose stable internal temperature traditionally facilitates *T. gondii* infection cycles (Yang et al., 2020; Dubey, 2022). However, *T. gondii* tachyzoites remain viable and replicate within certain ectothermic organisms when environmental temperatures mimic the conditions typically maintained within mammalian hosts (Stone and Manwell, 1969; Nasiri et al., 2016). A study by Yang et al. (2020) observed that in marine fish cells exposed to tachyzoites, parasite invasion and replication occurred at temperatures of 30 °C to 35 °C and a study by Stone and Manwell (1969) reported that red-eared sliders (*Pseudemys scripta elegans*) and horned toads (*Phrynosoma cornutum*) maintained at 37 °C showed persistent infection and active parasite replication. Furthermore, *T. gondii* DNA was detected in tissues of snake (Nasiri et al., 2016; Aziz-Anah and Al-Mayali, 2018), Greek tortoise (*Testudo graeca*) (Aziz-Anah, 2023), and Arctic char (*Salvelinus alpinus*) (Merks et al., 2024).

Sea turtles' immune function is sensitive to fluctuations in temperature and pollutants in marine environments, with rapid changes making these organisms more vulnerable to infectious diseases (Nash and Ryan, 2023). Thus, as environmental temperatures rise, the turtles' poikilothermic physiology could allow their internal temperatures to occasionally reach levels that support *T. gondii*'s lytic cycle, enabling parasite invasion and replication in tissues in ways previously associated with homeothermic hosts (Smith et al., 2023). This adaptability of *T. gondii* to variable thermal environments broadens the range of potential hosts and underscores the possibility that sea turtles could play an intermediate role in the transmission cycle under certain conditions. Given climate change and its impact on marine temperatures, with recorded to have increased by up to 2 °C in recent years, this hypothesis underscores the need to consider how fluctuating ocean temperatures might expand *T. gondii*'s ecological reach and impact in marine ecosystems (Fuentes et al., 2023).

Land runoff is considered the primary risk factor for ocean contamination. Studies have shown that the transport of *T. gondii* oocysts from land to coastal waters is linked to geographic conditions and environmental factors (Li et al., 2022a). Research has found associations between land runoff, rainfall, and temperature with an increased number of oocysts in oceans, causing contamination of marine ecosystems and infection of organisms by *T. gondii* (Shapiro et al., 2015; VanWormer et al., 2014; Cong et al., 2021; Li et al., 2022a). Sporulated oocysts are known to be resistant in saltwater (Lindsay and Dubey, 2009). A recent study showed that high runoff, caused by extreme weather events, is linked to toxoplasmosis presence in marine animals (Shapiro et al., 2012; Robinson et al., 2023). It is noteworthy that extreme climate events are happening more frequently due to climate change (Smith et al., 2023).

Based on our results, it is speculated that these frequent climate changes are affecting the marine ecosystems of Espírito Santo and consequently the animals inhabiting them. Therefore, the significant increase of seropositive animals of around 90 % observed in the studied period (Table 1) is also consistent with the temperature increase identified by Bueno et al. (2024) for the coastline in Southeastern Brazil. We might hypothesize that this prevalence is related to high levels of terrestrial runoff caused by intense precipitation events, high temperatures, increased population density near coastal waters, and consequently a higher number of stray cats, leading to an elevated environmental contamination rate by *T. gondii* oocysts.

Migratory fish, which filter microparticles in their diet (such as Pacific sardines and northern anchovies), may serve as mechanical vectors of oocysts, as these can persist in the alimentary canal for up to eight hours, maintaining their infectivity (Massie et al., 2010) and even remaining on gills (Marino et al., 2019). A recent report detected *T. gondii* DNA in brain and heart tissues of fish, demonstrating the parasite's ability to persist in various environments and animal types (Merks et al., 2024). These reports suggest that sea turtles' exposure to *T. gondii* may be occurring via fish, which constitute part of their diet.

Bivalves and mussels are also effective filter feeders, and numerous studies have reported the presence of oocysts within them, making them valuable sentinels for ocean health (Mosquera et al., 2024; Kim et al., 2023; Shapiro et al., 2019; Cong et al., 2021; Cong et al., 2019; Fayer et al., 2004). In Brazil, there have been two reports of *T. gondii* in bivalves, one in São Paulo (Esmerini et al., 2010) and another in southern Bahia (Ribeiro et al., 2015), demonstrating that *T. gondii* oocyst contamination occurs along the Brazilian coast. However, in the state of Espírito Santo, there are no reports of *T. gondii* presence in bivalves and mussels. As these organisms also serve as food for sea turtles, exposure to the parasite could also occur through these filter feeders. Oocysts can also attach to the biofilm on marine algae (Nayeri et al., 2021; Mosquera et al., 2024), which green turtles consume.

Another factor in oocyst dispersal is ocean currents, as shown by Mosquera et al. (2024), who detected *T. gondii* on an island without felids, suggesting that oocysts could reach offshore waters. It remains unclear how sea turtles are exposed to the parasite, though the hypotheses raised in this study provide plausible explanations for the presence of anti-*T. gondii* antibodies in these species.

To date, there is no evidence of anti-*T. gondii* antibodies in sea turtles or of the parasite's ability to invade and multiply in these animals' cells. However, climate change and the detection of antibodies in this study raise concerns regarding potential shifts in toxoplasmosis and ectothermic animals, particularly in species already threatened by anthropogenic and climate impacts.

5. Conclusion

The results provide serological evidence supporting the hypothesis that sea turtles are susceptible to *T. gondii* exposure through contaminated prey, such as bivalves, algae, and fish, as well as runoff from terrestrial sources. Given their ecological importance and conservation status, these findings raise concerns about the health impacts of *T. gondii* on sea turtles and highlight the need for further research into their role in the parasite's transmission cycle. These findings underscore the significance of monitoring zoonotic pathogens in marine ecosystems to better understand the interplay between environmental changes, wildlife health, and pathogen spread. Further studies, including bioassays and molecular detection techniques, are essential to confirm active infection and better understand the role of sea turtles in the

epidemiology of *T. gondii*.

CRediT authorship contribution statement

Anna Elisa Athayde-Gusmão: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Bianca Cardozo Afonso:** Writing – original draft, Visualization, Methodology, Conceptualization. **Edwards Frazão-Teixeira:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Antônio Calais:** Resources. **Regiane de Fátima Ferreira:** Investigation. **Leandro Egert:** Resources. **Luis Felipe Mayorga:** Resources. **Maria Ferreira Rosa:** Resources. **Leonardo Serafim da Silveira:** Resources. **Daniel Guimarães Ubiali:** Writing – review & editing. **Andressa Ferreira da Silva:** Writing – review & editing, Supervision, Conceptualization.

Ethical statement

The present study was conducted in compliance with ethical principles for animal research, following the International Guiding Principles for Biomedical Research Involving Animals issued by the Council for International Organizations of Medical Sciences (CIOMS).

The serum samples analyzed in this study were provided by Instituto de Pesquisa e Conservação Marinha (IPCMar) and Instituto de Pesquisa e Reabilitação de Animais Marinhos (IPRAM). Sample collection at IPCMar was conducted under environmental license SISBIO No. 42232–12, and samples from IPRAM were obtained as supernatants from routine hematological evaluations of hospitalized animals.

As this study involved only the serological analysis of previously collected samples, no additional procedures were performed on live animals, and no further ethical approval was required.

Funding sources

This research was supported by the grants from CAPES (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Finance Code 001, Brazil), FAPERJ (Fundação Carlos Chagas Filho de Amparo à Pesquisa do Estado do Rio de Janeiro, Brazil, number E-26/010.002119/2019), and CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico, Brazil). Funding bodies were not involved in study design, data collection, analysis, interpretation, or writing of the manuscript.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Anna Elisa Athayde-Gusmao reports financial support was provided by CAPES (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Finance Code 001, Brazil). Edwards Frazao-Teixeira reports financial support was provided by FAPERJ (Fundação Carlos Chagas Filho de Amparo à Pesquisa do Estado do Rio de Janeiro, Brazil). Edwards Frazao-Teixeira reports financial support was provided by CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico, Brazil). If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We thank IPRAM (Instituto de Pesquisa e Conservação de Animais Marinhos), IPCMar (Instituto de Pesquisa e Conservação Marinha), Petrobrás and Samarco Mineração.

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