Seropositivity and geographical distribution of *Strongyloides stercoralis* in Australia: A study of pathology laboratory data from 2012–2016

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Abstract

Background

There are no national prevalence studies of *Strongyloides stercoralis* infection in Australia, although it is known to be endemic in northern Australia and is reported in high risk groups such as immigrants and returned travellers. We aimed to determine the seropositivity (number positive per 100,000 of population and percent positive of those tested) and geographical distribution of *S. stercoralis* by using data from pathology laboratories.

Methodology

We contacted all seven Australian laboratories that undertake *Strongyloides* serological (ELISA antibody) testing to request de-identified data from 2012–2016 inclusive. Six responded. One provided positive data only. The number of people positive, number negative and number tested per 100,000 of population (Australian Bureau of Statistics data) were calculated including for each state/territory, each Australian Bureau of Statistics Statistical Area Level 3 (region), and each suburb/town/community/locality. The data was summarized and expressed as maps of Australia and Greater Capital Cities.

Principal findings

We obtained data for 81,777 people who underwent serological testing for *Strongyloides* infection, 631 of whom were from a laboratory that provided positive data only. Overall, 32
(95% CI: 31, 33) people per 100,000 of population were seropositive, ranging between 23/100,000 (95% CI: 19, 29) (Tasmania) and 489/100,000 population (95% CI: 462, 517) (Northern Territory). Positive cases were detected across all states and territories, with the highest (260-996/100,000 and 17–40% of those tested) in regions across northern Australia, north-east New South Wales and north-west South Australia. Some regions in Greater Capital Cities also had a high seropositivity (112-188/100,000 and 17–20% of those tested). Relatively more males than females tested positive. Relatively more adults than children tested positive. Children were under-represented in the data.

Conclusions/Significance
The study confirms that substantial numbers of \textit{S. stercoralis} infections occur in Australia and provides data to inform public health planning.

Author summary
\textit{Strongyloides stercoralis}, a parasitic roundworm, is endemic in many countries worldwide. In Australia, groups at risk for strongyloidiasis include Aboriginal and/or Torres Strait Islander people, who acquired this parasite locally, and immigrants and returned travellers who acquired the infection outside Australia. We obtained deidentified results of ELISA IgG antibody tests for \textit{Strongyloides} from diagnostic pathology laboratories during 2012 to 2016 and calculated the number of people who were positive at least once and the number who never had a positive result. We drew maps showing the number positive per 100,000 of population, the percent positive of those tested, and the number tested/100,000 for each region and the number positive in each suburb of residence according to the Australian Bureau of Statistics. The highest seropositivity (260-996/100,000 of population) was in Northern Australia, north-west South Australia and north-east New South Wales where many Aboriginal and Torres Strait Islander people live in remote communities. There were also some regions in Greater Capital Cities with a high number of people positive per 100,000 of population (112-188/100,000), likely reflecting higher populations of immigrants and returned travellers who were infected outside Australia.

Introduction
\textit{Strongyloides stercoralis} is a nematode parasite primarily of humans with a world-wide distribution, and is more common in areas of socioeconomic disadvantage [1]. The most recent global prevalence estimate (for 2017) was 8.1% corresponding to 613.9 million people infected [2].

In Australia, \textit{S. stercoralis} is endemic in many Aboriginal and Torres Strait Islander communities [3–13]. Previous surveys show seropositivity rates of up to 58% of those tested (33/57) in the Kimberley region of Western Australia in 1986 [5] and 59% (220/372) in the East Arnhem region of the Northern Territory in 1989 [7]. The highest rate in a clinical setting was 51% (88/172) in East Arnhem Land in 2012–2016 [14]. Non-Aboriginal people with strongyloidiasis may have acquired the disease locally, such as workers or visitors in Aboriginal and Torres Strait Islander communities [15], or while overseas, such as returned international travelers [16,17], returned Armed Services personnel [18–20] and refugees and immigrants [20–22]. \textit{S. stercoralis} is not a reportable infection and so the current prevalence in these high risk groups is uncertain.
S. stercoralis is a persistent infection due to internal autoinfection. Consequently, it is often present for many years before being diagnosed [18,21–23] and is usually a life-long infection unless treated effectively [18,22]. The chronic infection may be asymptomatic or exhibit mild intermittent symptoms primarily of the gut, respiratory system and skin [24,25]. In a seminal paper of chronic strongyloidiasis occurring in a group of Australian men deployed to South East Asia during World War 2, 27.5\% (44/158) of whom were positive for S. stercoralis, Grove found that indigestion, urticaria, pruritus ani, diarrhoea and weight loss were significantly more frequently reported in infected men compared to uninfected men [18]. Pelletier who studied American men who had been subjected to similar conditions reported similar findings [26]. People with immune suppression, most often due to the administration of corticosteroid drugs, may develop disseminated disease and fatal illness if the infection is not diagnosed and treated [24,27,28]. Other immunosuppressant drugs (eg azathioprine, methotrexate, mycophenolate, cyclophosphamide, biological agents, chemotherapies) which also raise the risk of precipitating hyperinfection are increasingly being prescribed [27,29–31]. In addition, comorbidities (eg diabetes, alcoholism, hypochlorhydria, malnutrition, HTLV-1) are increasingly prevalent and also pose a significant risk for hyperinfection [24,32–35]. Patients may suffer serious secondary infections often caused by gut bacteria carried into the tissues by autoinfective larvae [24,28,36]. Current data on the burden of infection in Australia, especially in high risk populations, is needed to inform public health policy and planning [37].

In this study, our primary aim was to determine the number of persons seropositive for Strongyloides per 100,000 in the Australian population using routine laboratory data. Our secondary aims were 1) to describe Strongyloides seropositivity rates as the percent positive of those tested; 2) to examine the geographical distribution in Australian states and territories as well as geographical areas defined by boundaries set by the Australian Bureau of Statistics (ABS) (regions); 3) to investigate trends over time; and 4) to explore differences between sex and age groups nationally and for each state.

Materials and methods

Ethics statement

The project was approved by nine Ethics Committees: La Trobe University Human Ethics Committee EC00226 Project Number HEC 15–113, Central Australia Human Research Ethics Committee EC00155 Project Number HREC-16-382, Human Research Ethics Committee of the Northern Territory Department of Health and Menzies School of Health Research EC00153 Project Number 2016–2562, Aboriginal Health & Medical Research Council of New South Wales Ethics Committee EC00342 Project Number 1168/16, Western Sydney Local Health District Human Research Ethics Committee EC00152 Project Number 4904: LNR/16/WMEAD/452 LNR/SSA/16/WMEAD/460, Royal Brisbane & Women’s Hospital Human Research Ethics Committee EC00172 Project Number LNR/2018/QRBW/48092, Aboriginal Health Research Ethics Committee (South Australia) EC00185 Project Number 04-16-670, Central Adelaide Local Health Network Research Ethics Committee EC00192 Project Number HREC/16/RAH/172 CALHN R20160438 and Western Australia Aboriginal Health Ethics Committee EC00292 Project Number PR 698. Formal consent was obtained from all the Ethics Committees in writing.

Study design and setting

We conducted a retrospective review of pathology laboratory data which had been recorded over the five years from 1 January 2012 to 31 December 2016 inclusive. It consisted of data from Strongyloides serology tests of people resident in all states and territories of Australia.
Persons included in the study

Criteria for inclusion. The data include persons tested for *Strongyloides* by serology across all age groups and sexes with a known residential address in Australia (suburb/town, community/locality).

Criteria for exclusion. Persons with unknown or overseas residential addresses and those from Christmas Island, Norfolk Island, Keeling Island, and Lord Howe Island were excluded. Persons from Jervis Bay were included with New South Wales (NSW) data as it is surrounded by NSW, but considered as an “other territory” by the ABS.

*Strongyloides* testing data

We requested *Strongyloides* testing data for the years 2012 to 2016 inclusive from all seven laboratories in Australia that undertake routine serological testing (that is, tests ordered by a health care professional). The data did not include any details about the reasons the tests were ordered, other helminth infections, other comorbidities or treatment. Some people had more than one test. Six of the laboratories provided *Strongyloides* serology data. One of those provided positive data only (Table 1). We were not able to obtain any information about the volume of testing from the private laboratory that did not contribute data to the study. It receives specimens from persons from every state and territory in Australia.

Variables

The *Strongyloides* serology data included the following fields: de-identified unique identifier, sex (male, female, unknown), age (years), suburb/town/community/locality of residence, postcode, state, date and result of test. For reporting, age was categorized as 0–4, 5–14, 15–24, 25–34, 35–44, 45–54, 55–64, 65–74, ≥75 years or unknown if age was missing.

Table 1. Contribution of each laboratory to the *Strongyloides* serology data, 2012–2016, number of people tested and percentage of the data contributed by each laboratory to each state or territory of residence.

| State /territory of residence | ACT | NSW     | NT     | QLD    | TAS    | VIC    | WA     | SA     | Total |
|--------------------------------|-----|---------|--------|--------|--------|--------|--------|--------|--------|
| Laboratory location           | n (%) | n (%) | n (%) | n (%) | n (%) | n (%) | n (%) | n (%) | n (%) |
| 1NSW                          | 296 (13.8) | 9,230 (44.5) | 7 (0.1) | 2,504 (18.6) | 1 (0.0) | 65 (0.3) | 9 (0.1) | 173 (14.1) | 12,285 (15.0) |
| 1QLD                          | 108 (5.0) | 50 (0.2) | 18 (0.3) | 4,293 (31.9) | 0 (0.0) | 35 (0.1) | 13 (0.1) | 8 (0.7) | 4,525 (5.5) |
| 2QLD P1                       | 1,728 (80.6) | 11,307 (54.6) | 58 (0.8) | 6,566 (48.8) | 294 (10.0) | 7,075 (30.2) | 717 (6.7) | 486 (39.6) | 28,231 (34.5) |
| 3VIC                          | 9 (0.4) | 119 (0.6) | 355 (5.0) | 85 (0.6) | 2,641 (89.9) | 16,276 (69.4) | 22 (0.2) | 29 (2.4) | 19,533 (23.9) |
| 3WA                           | 4 (0.2) | 11 (0.1) | 6,593 (92.5) | 10 (0.1) | 3 (0.1) | 8 (0.0) | 9,939 (92.8) | 12 (1.0) | 16,572 (20.3) |
| 4Subtotal                     | 2,145 (100) | 20,717 (100) | 7,031 (98.6) | 13,458 (100) | 2,939 (100) | 23,458 (100) | 10,692 (99.9) | 708 (57.7) | 81,146 (99.2) |
| 5SA                           | 0 (0.0) | 2 (0.0) | 97 (1.4) | 0 (0.0) | 0 (0.0) | 5 (0.0) | 8 (0.1) | 519 (42.3) | 631 (0.8) |
| **Total**                     | 2,145 (100) | 20,719 (100) | 7,128 (100) | 13,458 (100) | 2,939 (100) | 23,461 (100) | 10,700 (100) | 1,227 (100) | 81,777 (100) |
| % of data                     | 2.6 | 25.3 | 8.7 | 16.5 | 3.6 | 28.7 | 13.1 | 1.5 | 100 |

1Government laboratory.
2Private laboratory situated in QLD.
3Used for calculation of percent positive of those tested.
4Used for calculation of the number positive per 100,000 of population.
5The laboratory in SA contributed positive results only. ACT = Australian Capital Territory; NSW = New South Wales; NT = Northern Territory; QLD = Queensland; TAS = Tasmania; VIC = Victoria; WA = Western Australia; SA = South Australia.

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Measurements

Strongyloides serology methods. A list of the ELISA method and cutoff values for each laboratory are given in S1 Table. Three enzyme-linked immuno-sorbent assays (ELISA) that detect IgG antibodies to Strongyloides were used: Bordier ELISA (Bordier Affinity Products SA, Crissier, Switzerland) based on somatic antigens of S. ratti (three laboratories), an in-house method, also based on S. ratti somatic antigens (one laboratory), IVD ELISA (DRG Instruments GmbH, Marburg, Germany) based on somatic antigens of S. stercoralis infective larvae (two laboratories) one of which transitioned from an in-house method based on S. ratti antigens during 2012 [38,39]. The equivocal range represents an overlap in results between standard negative and standard positive sera. All Australian laboratories performing Strongyloides serology participated in an informal quality assurance programme. For the purposes of the statistical analysis, only positive results were considered as positive and equivocal results were included with the negative results as negative to avoid overestimation of the positive results. All these methods detect Strongyloides at the generic level and are not specific for S. stercoralis. However, S. stercoralis is the species that is prevalent in Australia. In a global genotyping survey of S. stercoralis and S. fueleborni, two specimens of S. fueleborni were said to come from Australia [40]. These samples actually came from Senegal and Guinea-Bisseau in Africa [41].

Terminology. In this study, seropositivity refers to both the number of people positive for Strongyloides by serological testing per 100,000 of population and the percent positive of those tested.

Bias

The persons included were those for whom a Strongyloides serology test was requested by a health care professional and therefore do not represent a random sample of the total population of Australia and so are not generalizable to the total population.

Study size

The Strongyloides serology test data in Australia for the five years 2012 to 2016 was not complete, as one private laboratory did not contribute data to the project. With the exception of the government laboratory in SA that provided positive serology data only, the laboratories provided de-identified positive, negative, and equivocal serology data. More than one laboratory contributed data for each state and territory of residence. Table 1 shows the contribution of each laboratory to the data for each state or territory of residence.

Data access and cleaning methods

A summary of the data processing and outcomes is given in Fig 1. The serology data set from each participating pathology laboratory was cleaned by JS and SB by identifying then correcting errors in postcode, suburb, and/or state/territory. This included assigning the most likely suburb, postcode or state in records where where this information was missing where there was sufficient information. Where postcodes crossed state borders, the state given in some records needed correction. As the names of many Aboriginal communities in the NT, SA and WA have recently changed, where records included the old name this was corrected to the current one.

Statistical methods

Data were processed using Statistical Software Stata/SE 15.1 (College Station, TX: StataCorp LLC).
Persons with one or more positive results were classified as positive and data from their first positive test result only was included in the data set. Persons with only negative or equivocal results were classified as negative and the data from their first test result only was included. The data from the laboratories was combined and merged with Australian Bureau of Statistics (ABS) 2011 census data on postcode to obtain the Statistical Area Level 3 (SA3) for each record. Each SA3 represents a region or one or two adjacent regions within each state. For those postcodes that were linked to more than one SA3, JS manually selected the most appropriate single SA3 using the person’s postcode, suburb, and state information together with the ABS postcodes map and Google maps. ABS = Australian Bureau of Statistics; SA3 = Statistical Area Level 3 (region defined by ABS, 2011); pos = positive; pop = population.

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ABS postcodes map [43] and Google maps [44] to locate the suburb. SA3 Special Purpose Codes were not included.

From the data, we reported the number of persons with at least one positive test result and the number of persons with at least one test result. We derived the number of persons with at least one positive test result per 100,000 of population using the (average of) population sizes projected for 2012–2016 from the 2011 census of the ABS for each state and each statistical area level 3 (SA3) [42] from the total data. Similarly, after excluding the data from the laboratory that provided positive data only, we derived the percent of people positive per those tested, the number tested per 100,000 of population and, for comparison, the number positive per 100,000 for Australia, each state/territory, for each SA3, for each year of testing and for each sex and age group. Clopper-Pearson exact two-sided 95% confidence intervals (CI) were calculated on proportions. In addition, maps of seropositivity (the number positive per 100,000 of population and the percent positive of those tested) for each ABS SA3 were created using the ABS shapefile for 2011 [42] and the Tableau mapping package. Geographical coordinates of the suburbs, towns, communities or localities of residence of people positive for Strongyloides were obtained from Google Maps and plotted on a map using Tableau mapping software. Greater Capital Cities were not included in this map, as the SA3 maps gave sufficient detail for closely populated areas.

The ABS shapefile is provided under Creative Commons Attribution 4.0 International. Tableau uses Mapbox and OpenStreetMap maps. This is acknowledged by the text: © Mapbox and © OpenStreetMap on each map. Mapbox.js is an open source project.

**Results**

**Participants and descriptive data**

The data represents 81,777 people who were tested for Strongyloides by serology in Australia during the five years 2012–2016 (Table 1). After excluding the 631 people from the SA laboratory, there were 81,146 people who underwent Strongyloides serology testing for whom both positive and negative results were available. Of these 46.2% were female, 53.5% male, 0.3% whose sex was unknown (S6 Table); 3.4% were 0–4 years, 11.3% 5–14 years, 15.4% 15–24 years, 18.5% 25–34 years, 15.9% 35–44 years, 13.1% 45–54 years, 10.7% 55–64 years, 7.0% 65–74 years, 4.5% ≥75 years and 0.1% whose age was unknown (S7 Table).

**Positive data from all six laboratories**

**Australia.** The total number of people who were positive in all states and territories was 7,497. The projected average population size for 2012–2016 was 23,465,538 (ABS data [42]) so 32 (95% CI: 31, 33) people per 100,000 of population were positive.

**States and territories.** The number of people positive per 100,000 of population for each state and territory is given in S2 Table. The SA laboratory that contributed positive data only to the study did not include tests for any residents of the ACT, TAS or QLD and included very few tests for NSW, VIC and WA, so the number of people positive per 100,000 for these states and territories was the same as for the data excluding the SA laboratory (Table 2). The number of people positive per 100,000 for Australia, NT and SA was substantially higher when including the SA laboratory data. The figures are given in the footnote to Table 2. The number of positives per 100,000 for the NT was an order of magnitude higher than that of any of the other states or territories.

**Regions (ABS SA3s).** The number of people positive per 100,000 of the population for each region is given in S3 Table and mapped in Fig 2. In general, the SA3s with the greatest number positive per 100,000 of population were in northern QLD, the whole of the NT except...
for outer Greater Darwin, the north of WA, the north-west of SA and the north-east of NSW. There were also SA3s with high seropositivity in the Greater Capital Cities except Perth.

**Suburbs, towns, communities and localities.** The number of people positive in each suburb, town, community or locality excluding the ACT and Greater Capital Cities is shown in S1 Fig. This shows that *Strongyloides*-positive residents are geographically widespread in Australia. The suburbs/towns/communities/localities with the greatest number of people positive for *Strongyloides* were in northern WA, NT and QLD, north-east NSW and north-west SA. Although the Outback-North and East SA3 in SA covers are very large area of land, S1 Fig shows that the main area of seropositivity was in the north-west, close to the border with the NT.

**Positive and negative data, excluding data from the laboratory that provided positive data only**

**Australia.** Positive and negative data was available from five laboratories for 81,446 people of whom 6,866 were positive. The percent positive of those tested and the number tested per 100,000 of population are given in Table 2. The number positive per 100,000 of population is given for comparison with the calculation based on positive data from all laboratories.

**States and territories.** The percent positive of those tested for each state and territory is presented in Table 2. We have also provided the number positive per 100,000 of population using this data set for comparison with the positive only data from all six laboratories (S2 Table). The main differences between Table 2 and S2 Table are also provided as a footnote.

**Regions.** The percent positive of those tested in each SA3 is given in S4 Table and mapped in Fig 3. The number tested per 100,000 is given in S4 Table and mapped in S2 Fig. In 20 SA3s, the number of people positive per 100,000 of population was >100/100,000. Seven of these were in Greater Capital Cities. Apart from Richmond Valley Hinterland in north-east NSW and Outback-North and East in SA, the SA3s with the highest seropositivity were in the north of Australia. In six SA3s both the number of people positive per 100,000 of population was >100/100,000 and percent positive of those tested was >20%. They were Kimberley in WA (996/100,000 (95% CI 898, 1102) and 22.3% (95% CI 20.4, 24.4) respectively), Outback-North (589/100,000 (95% CI 509, 677) and 40.4% (95% CI 36.0, 45.0) respectively), Port Douglas-

### Table 2. *Strongyloides* serology: summary of seropositivity for each state and territory, 2012–2016, excluding data from the laboratory that provided positive data only.

| State /territory of residence | No. of people tested | No. of people positive | % Positive of those tested (95% CI) | Average annualized population | No. tested /100,000 (95% CI) | No. positive /100,000 (95% CI) |
|------------------------------|----------------------|------------------------|------------------------------------|-----------------------------|--------------------------|-----------------------------|
| ACT                          | 2,145                | 117                    | 5.4 (4.5, 6.5)                     | 389,502                     | 551 (528, 574)           | 30 (25, 36)                 |
| NSW                          | 20,717               | 1,813                  | 8.8 (8.4, 9.1)                     | 7,513,103                   | 276 (272, 280)           | 24 (23, 25)                 |
| NT                           | 7,031                | 1,087                  | 15.5 (14.6, 16.3)                  | 242,180                     | 2,903 (2,837, 2,971)     | 449 (423, 476)              |
| QLD                          | 13,458               | 1,431                  | 10.6 (10.1, 11.2)                  | 4,712,802                   | 286 (281, 290)           | 30 (29, 32)                 |
| TAS                          | 2,939                | 117                    | 4.0 (3.3, 4.8)                     | 514,041                     | 572 (551, 593)           | 23 (19, 27)                 |
| VIC                          | 23,456               | 1,521                  | 6.5 (6.2, 6.8)                     | 5,092,834                   | 397 (392, 402)           | 26 (24, 27)                 |
| WA                           | 10,692               | 723                    | 6.8 (6.3, 7.3)                     | 2,505,342                   | 427 (419, 435)           | 29 (27, 31)                 |
| SA                           | 708                  | 57                     | 8.1 (6.2, 10.3)                    | 1,685,734                   | 42 (39, 45)              | 3 (3, 5)                    |
| Australia                    | 81,146               | 6,866                  | 8.5 (8.3, 8.7)                     | 23,465,358                  | 346 (343, 348)           | 29 (29, 30)                 |

*When the positive data from the SA laboratory that provided positive data only was included, the number positive per 100,000 of population for Australia was 32 (95% CI: 31, 33), for the NT was 489 (95% CI: 462, 517) and for SA was 34 (95% CI: 31, 37). CI = confidence interval, ACT = Australian Capital Territory; NSW = New South Wales; NT = Northern Territory; QLD = Queensland; TAS = Tasmania; VIC = Victoria; WA = Western Australia; SA = South Australia.

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Daintree (146/100,000 (95% CI 85, 234) and 22.1% (95% CI 13.4, 33.0) respectively) and Innisfail-Cassowary Coast (740/100,000 (95% CI 654, 835) and 21.1% (95% CI 18.9, 23.5) respectively) in QLD, and Daly-Tiwi-West Arnhem (747/100,000 (95% CI 602, 853) and 27.4% (95% CI 23.5, 31.6) respectively) and Katherine (284 (95% CI 212, 360) and 25.5% (95% CI 20.0, 31.7) respectively) in the NT. A further twenty-one SA3s with high seropositivity (more than 50 positive per 100,000 of population) (95%CI: 31, 33) were located in Central Highlands in QLD, Coffs Harbour in north-east NSW, Pilbara in WA as well as in Greater Capital Cities except Perth, WA.

S2 Fig shows that in general testing was highest in those SA3s that had the greatest seropositivity, in northern Australia.

Results by year. The percent positive of those tested, the number of people tested per 100,000 of population and the number positive per 100,000 for Australia and each state and territory in each year 2012–2016 (excluding data from the laboratory that provided positive

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S2 Fig shows that in general testing was highest in those SA3s that had the greatest seropositivity, in northern Australia.

Results by year. The percent positive of those tested, the number of people tested per 100,000 of population and the number positive per 100,000 for Australia and each state and territory in each year 2012–2016 (excluding data from the laboratory that provided positive
data only) are given in Fig 4 and S5 Table. There was an overall decline in the percent positive of those tested for Australia over the 5 year period (from an average of 12.7% (95% CI 12.1, 13.2) in 2012 to 7.2% (95% CI 6.8, 7.5)) in 2016. There was also a sharp decline in the number tested/100,000 of population in the NT over the five year period.

Sex and age group. The overall results for Australia for each sex and age group are given in Table 3. The frequency data for each state and territory for sex are given in S6 Table and S3 Fig and for age group, in S7 Table and S4 Fig. The low number of tests for SA is due to the exclusion of data from the SA laboratory that provided positive data only. Most of SA shows 0% positive because there was no negative data from the laboratory in SA. The % positive for the two southernmost SA3s in NT are likewise underestimated. A = ACT; Ad = Adelaide; B = Brisbane; D = Darwin; H = Hobart; M = Melbourne; P = Perth; S = Sydney; NSW = New South Wales; NT = Northern Territory; QLD = Queensland; SA = South Australia; TAS = Tasmania; VIC = Victoria; WA = Western Australia.

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Discussion

This study represents the most comprehensive analysis of *Strongyloides stercoralis* serology testing data ever undertaken in Australia. Our finding of 32 positive cases per 100,000 population for Australia, equivalent to 0.032% (0.032/100 of the population) is approximately three times the estimate of 0.01% by Buonfrate et al [2] for the Australian population and is similar to that of Italy, Belgium, France, Malta, Japan and New Zealand [2]. The true figure for Australia would be higher than this because our calculation represents only those tested. *S. stercoralis* infections are widespread as cases were detected across all states and territories and in most regions.
The high seropositivity in regions across northern Australia, north-east NSW and north-west SA confirming earlier work [5–7,9–14,45–47], likely reflected infections mainly in Aboriginal and Torres Strait Islander Australians who were infected in Australia. The high seropositivity in regions in Greater Capital Cities likely reflected mainly people who were infected in other countries: immigrants and returned international travellers including Armed Services personnel [17–19,21,22,48]. However, it was not known to what extent Aboriginal and Torres Strait Islander people resident in Greater Capital Cities had acquired *S. stercoralis* infection while previously living in or visiting communities where it is endemic [13]. Due to effective sanitation, transmission is less likely in the Australian urban environment [49].

Other similar countries with an endemic population and an immigrant population infected with *S. stercoralis* include the USA, Spain and Italy [25,50–52], whereas in Canada and north European countries, *S. stercoralis* infections are limited to immigrants and returned international travellers [16,53,54]. In the USA, a meta-analysis of community surveys in endemic regions found three percent positive, lower than in endemic regions of Australia [55], and in Spain and Italy, nearly all infected people were in older age groups [25,52], suggesting that transmission was rare.

Although the greatest number of people positive for *Strongyloides* was in NSW, the state with the largest population, the NT, the state with with the smallest population had by far the greatest number positive per 100,000 of the population and the greatest percentage positive of people tested. This higher infection rate was presumably reflecting a majority of cases within the Aboriginal and/or Torres Strait Islander population that reside in small remote communities where *S. stercoralis* is known to be endemic [8,14,20,45].

The high rate of seropositivity in Central Australia (Alice Springs and Barkly region in the southern part of the NT, and adjacent communities in the Outback—North and East region in SA and in Goldfields region in WA) coincides with a high prevalence of HTLV-1 infection.

**Table 3. Strongyloides serology results for each sex and age group for Australia 2012–2016 (excluding data from the SA laboratory that provided positive data only).**

| Sex   | No. of people tested | No. of people positive | % Positive of those tested (95% CI) | Average annualized population | No. of people tested /100000 (95% CI) | No. of people positive /100000 (95% CI) |
|-------|----------------------|------------------------|-------------------------------------|-------------------------------|--------------------------------------|----------------------------------------|
| Female| 37,476               | 3,053                  | 8.1 (7.9, 8.4)                      | 11,803,929                    | 317 (314, 321)                      | 26 (25, 27)                            |
| Male  | 43,451               | 3,787                  | 8.7 (8.5, 9.0)                      | 11,661,609                    | 373 (369, 376)                      | 33 (31, 34)                            |
| Unknown| 219                  | 26                     | 11.9 (7.9, 16.9)                    |                               |                                      |                                        |
| Age (years) |                |                         |                                    |                               |                                      |                                        |
| 0–4   | 2,788                | 84                     | 3.0 (2.4, 3.7)                      | 1,537,150                     | 181 (175, 188)                      | 5 (4, 7)                               |
| 5–14  | 9,209                | 329                    | 3.6 (3.2, 4.0)                      | 2,901,067                     | 317 (311, 324)                      | 11 (10, 12)                            |
| 15–24 | 12,532               | 967                    | 7.7 (7.3, 8.2)                      | 3,129,417                     | 400 (393, 408)                      | 31 (29, 33)                            |
| 25–34 | 14,979               | 1,241                  | 8.3 (7.8, 8.7)                      | 3,455,515                     | 433 (427, 440)                      | 36 (34, 36)                            |
| 35–44 | 12,893               | 1,206                  | 9.4 (8.9, 9.9)                      | 3,216,414                     | 401 (394, 408)                      | 37 (35, 40)                            |
| 45–54 | 10,619               | 1,160                  | 10.9 (10.3, 11.5)                   | 3,102,036                     | 342 (336, 349)                      | 37 (35, 40)                            |
| 55–64 | 8,721                | 931                    | 10.7 (10.0, 11.3)                   | 2,681,694                     | 325 (318, 332)                      | 35 (33, 37)                            |
| 65–74 | 5,715                | 563                    | 9.9 (9.1, 10.7)                     | 1,931,354                     | 296 (288, 304)                      | 29 (27, 32)                            |
| >75   | 3,614                | 368                    | 10.2 (9.2, 11.2)                    | 1,510,891                     | 239 (231, 247)                      | 24 (22, 27)                            |
| Unknown| 76                   | 17                     | 22.4 (13.6, 33.4)                   |                               |                                      |                                        |
| Total | 81,146               | 6,866                  | 8.5 (8.3, 8.7)                      | 23,465,538                    | 346 (343, 348)                      | 29 (29, 30)                            |

CI = confidence interval.

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Complicated strongyloidiasis has been reported in coinfections with HTLV-1 leading to death in some patients [47], and conversion of asymptomatic HTLV-1 to clinical HTLV-1 [57] has also been reported in patients with S. stercoralis infection. Further research is needed to elucidate the relative risks of coinfection with these pathogens in this area.

Children (0–4 years and 5–14 years) were under-represented in the serology data even though there is considerable seropositivity in children. This is likely because venipuncture is more difficult in children. S. stercoralis has been associated with malnutrition and hypokalaemia in very young children [58] and carriage into adulthood [13]. The “community children’s de-worming program” for northern Australia recommends treating children with single dose oral albendazole twice a year (in line with WHO guidelines) and has been effective against hookworm [59–61]. Although albendazole is used as second line treatment for strongyloidiasis, repeated doses are necessary [62]. A routine Strongyloides serology test that utilises finger-prick blood would make routine testing and treatment of children possible and provide improved epidemiological data. The increasing seropositivity with age followed trends in other parts of the world [63–66].

Limitations
This paper is based on aggregated de-identified laboratory data and as such the reason for testing was not known, nor the outcome for the patients. Therefore the data are not representative of prevalence rates in the total population. The data did not distinguish between the various at-risk categories of people, so we made assumptions based on the geographic origin of the test and the known location of the two main at risk populations, Aboriginal and Torres Strait Islander Australians and immigrants.

The number of people reported positive in SA3s where there is a hospital may be overstated as in-patients may have used the address of the hospital instead of their usual residential address. This was particularly evident for the Darwin suburb of Tiwi, the location of the Royal Darwin Hospital, and affected the Darwin Suburbs SA3 figures. This would not have affected the overall results for the NT.

The serology data is incomplete. One major laboratory did not contribute data to the study. The number of people in the missing data is unknown. It included tests from all states and territories, predominantly QLD and northern NSW [67], so the results from these areas are likely to be underestimated. The data from the NT in this study showed a sharp decline in numbers of people tested between 2012 and 2016 (Fig 4, S5 Table). It is likely that the missing data is at this laboratory. The SA laboratory which provided positive data only, contributed the only positive data for the Outback—North and East region of SA and most of the positives for the Barkly region and more than half of the positives for the Alice Springs region of NT. These regions are recognized locally as areas of high endemicity for S. stercoralis. Because it was necessary to exclude this data for estimates of the percent positive of those tested for these regions, as well as for SA and the NT, these measures are likely underestimated, but this did not affect the number positive per 100,000 of population.

Some people may have been tested by more than one laboratory, in which case they would appear in the data twice with two different unique identifiers and a few people may have changed their name or date of birth between tests. However, this is likely to be a small number and therefore a minor influence on the overall result.

ELISA based IgG Strongyloides serology is currently the most widely used diagnostic test for Strongyloides in Australia because of the convenience of collecting and transporting serum to laboratories and the relatively high test sensitivity except in early infection and when the patient is immunosuppressed. False positives can occur with some other helminth infections.
acquired outside Australia [39]. The sensitivity and specificity of the tests used in this study when compared to a gold standard of larval microscopy have been estimated as follows: IVD ELISA: sensitivity 91%, specificity 99%; Bordier ELISA: sensitivity 90%, specificity 98%; in-house ELISA: sensitivity 93%, specificity 95% [38,39].

Conclusions
Overall, Strongyloides seropositivity in Australia for the 5 years 2012–2016 was low at 32 per 100,000 of population, and 8.5% of those tested in all states and territories.

*S. stercoralis* was detected in all states and territories. The number of people positive per 100,000 of population and the percent positive of those tested was highest in regions in the NT, the north of WA, north QLD, north-east NSW, and north-west SA (no percent positive estimate), where a high proportion of the population live in Aboriginal and/or Torres Strait Islander communities. It was also high in some regions in Greater Capital Cities where there is a large immigrant population.

National guidelines for controlling strongyloidiasis in Aboriginal and Torres Strait Islander communities with a focus on raising awareness in communities, improving health facilities and supporting and educating health staff would greatly assist in controlling this and other infectious diseases [68–70]. Population-based serosurveys would assist in determining the true prevalence in high risk populations and provide data to inform public health planning.

Supporting information

**S1 Fig.** *Strongyloides* serology: map of number of people positive for each suburb, town, community or locality, 2012–2016, including data from all six laboratories. This map was created using our data, Tableau software and a Mapbox base map. The ACT and greater capital cities have been omitted. The ranges of numbers positive are shown by colour and size of the dots. ACT = Australian Capital Territory; NSW = New South Wales; NT = Northern Territory; QLD = Queensland; SA = South Australia; TAS = Tasmania; VIC = Victoria; WA = Western Australia.

**S2 Fig.** *Strongyloides* serology: map of number of people tested for *Strongyloides* per 100,000 of population, for each Australian Bureau of Statistics Statistical Area level 3, 2012–2016, excluding data from the laboratory that provided positive data only. This map was created using our data, Tableau software, an ABS shapefile and a Mapbox base map. This accounts for the low number of tests in South Australia. ACT = Australian Capital Territory; NSW = New South Wales; NT = Northern Territory; QLD = Queensland; SA = South Australia; TAS = Tasmania; VIC = Victoria; WA = Western Australia.

**S3 Fig.** *Strongyloides* serology: frequency data for females and males for Australia and all states and territories 2012–2016 (excluding the data from the SA laboratory that provided positive results only). A. Percent positive of those tested. B. Number tested per 100,000 of population. C. Number positive per 100,000 of population. The values for SA in B and C are considerably underestimated because of the exclusion of data from the laboratory in SA. ACT = Australian Capital Territory; NSW = New South Wales; NT = Northern Territory; QLD = Queensland; SA = South Australia; TAS = Tasmania; VIC = Victoria; WA = Western Australia.
S4 Fig. *Strongyloides* serology: frequency data by age group (years) for Australia and each state or territory of residence, 2012–2016 (excluding the data from the SA laboratory that provided positive results only\(^1\)). A. Percent positive in each age group. B. Number of people tested per 100,000 of population in each age group and each state. C. Number of people positive per 100,000 of population for each age group. \(^2\)The values for SA in B and C are considerably underestimated because of the exclusion of data from the laboratory in SA.

ACT = Australian Capital Territory; NSW = New South Wales; NT = Northern Territory; QLD = Queensland; SA = South Australia; TAS = Tasmania; VIC = Victoria; WA = Western Australia.

(TIF)

S1 Table. *Strongyloides* serology: cutoff values for the ELISA IgG serum tests, as provided by each laboratory. \(^1\)Ratio of the optical density of the test/optical density of the weak positive control. \(^2\)OD = optical density of the test solution. \(^3\)The in-house *S. ratti* assay at the WA laboratory was replaced by IVD ELISA during 2012. NSW = New South Wales; QLD = Queensland; SA = South Australia; VIC = Victoria; WA = Western Australia; PI Private laboratory 1. (P2 did not contribute data to the study).

(DOCX)

S2 Table. *Strongyloides* serology: number of people positive for *Strongyloides stercoralis* infection per 100,000 of the population for Australia and each state and territory, 2012–2016, data from all six laboratories. CI = confidence interval, ACT = Australian Capital Territory; NSW = New South Wales; NT = Northern Territory; QLD = Queensland; TAS = Tasmania; VIC = Victoria; WA = Western Australia; SA = South Australia.

(DOCX)

S3 Table. *Strongyloides* serology: number of people positive per 100,000 of population for each Australian Bureau of Statistics Statistical Area Level 3 (SA3), 2012–2016, data from all six laboratories. ACT = Australian Capital Territory; NSW = New South Wales; NT = Northern Territory; QLD = Queensland; SA = South Australia; TAS = Tasmania; VIC = Victoria; WA = Western Australia.

(DOCX)

S4 Table. *Strongyloides* serology: percent of people positive of those tested and number tested per 100,000 of population for each Australian Bureau of Statistics Statistical Area Level 3 (SA3), 2012–2016, excluding data from the laboratory that provided positive data only\(^1\). \(^1\)This accounts for the low number of tests in South Australia. ACT = Australian Capital Territory; NSW = New South Wales; NT = Northern Territory; QLD = Queensland; SA = South Australia; TAS = Tasmania; VIC = Victoria; WA = Western Australia.

(DOCX)

S5 Table. *Strongyloides* serology: data by year, 2012–2016\(^1\), for Australia and each state and territory, excluding data from the laboratory that provided positive data only. The number of people were calculated separately for each year. \(^1\)The number of people were calculated separately for each year so a person who was tested in more than one year appears more than once in the data. ACT = Australian Capital Territory; NSW = New South Wales; NT = Northern Territory; QLD = Queensland; SA = South Australia; TAS = Tasmania; VIC = Victoria; WA = Western Australia.

(DOCX)

S6 Table. *Strongyloides* serology: percent positive of those tested and number positive per 100,000 of population, 2012–2016, for each sex for Australia and each state or territory of...
residence, excluding data from the laboratory that provided positive data only. F = female, M = male, U = unknown. ACT = Australian Capital Territory; NSW = New South Wales; NT = Northern Territory; QLD = Queensland; SA = South Australia; TAS = Tasmania; VIC = Victoria; WA = Western Australia.

S7 Table. Strongyloides serology: percent positive of those tested and number positive per 100,000 of population, 2012–2016, for Australia and each state and territory by age group in years, excluding data from the laboratory that provided positive data only. ACT = Australian Capital Territory; NSW = New South Wales; NT = Northern Territory; QLD = Queensland; SA = South Australia; TAS = Tasmania; VIC = Victoria; WA = Western Australia.

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References

1. Beknazarova M, Whiley H, Ross K. Strongyloidiasis: A disease of socioeconomic disadvantage. International Journal of Environmental Research and Public Health. 2016; 13(5):517. https://doi.org/10.3390/ijerph13050517 PMID: 27213420

2. Buonfrate D, Di Gregorio F, Odermatt P, Furst T, Greenaway C, French M, et al. The global prevalence of Strongyloides stercoralis infection. Pathogens. 2020; 9(6):468. https://doi.org/10.3390/pathogens9060468 PMID: 32545787

3. Jones H. Intestinal parasite infections in Western Australian Aborigines. The Medical Journal of Australia. 1980; 2(7):375–80. https://doi.org/10.5694/j.1326-5377.1980.tb131877.x PMID: 7453610

4. Reynoldson J, Behnke J, Gracey M, Horton R, Spargo R, Hopkins R, et al. Efficacy of albendazole against Giardia and hookworm in a remote Aboriginal community in the north of Western Australia. Acta Tropica. 1996; 71(1):27–44. https://doi.org/10.1016/s0001-706x(96)00048-5 PMID: 9778141

5. Sampson I, Smith DW, MacKenzie B. Serological diagnosis of Strongyloides stercoralis infection. Second National Workshop on Strongyloidiasis; 25–26 July 2003; Royal Brisbane Hospital, Brisbane, Australia 2003.

6. Hays R, Esterman A, McDermott R. Control of chronic Strongyloides stercoralis infection in an endemic community may be possible by pharmacological means alone: Results of a three-year cohort study. PLoS Negl Trop Dis. 2017; 11(7):e0005825. Epub 2017/08/02. https://doi.org/10.1371/journal.pntd.0005825 PubMed Central PMCID: PMC5552336. PMID: 28759583

7. Flannery G, White N. Immunological parameters in northeast Arnhem Land Aborigines: consequences of changing settlement patterns and lifestyles. Urban Ecology and Health in the Third World Cambridge University Press, Cambridge. 1993:202–20.

8. Holt DC, Shield J, Harris TM, Mounsey KE, Aland K, McCarthy JS, et al. Soil-transmitted helminths in children in a remote Aboriginal community in the Northern Territory: hookworm is rare but Strongyloides stercoralis and Trichuris trichiura persist. Tropical Medicine and Infectious Disease. 2017; 2(4). https://doi.org/10.3390/tropicalmed2040062 PMID: 30270919

9. Kearns TM, Currie BJ, Cheng AC, McCarthy J, Carapetis JR, Holt DC, et al. Strongyloides seroprevalence before and after an ivermectin mass drug administration in a remote Australian Aboriginal community. PLoS Negl Trop Dis. 2017; 11(5):e0005607. Epub 2017/05/16. https://doi.org/10.1371/journal.pntd.0005607 PubMed Central PMCID: PMC5444847. PMID: 28505198

10. Prociv P, Luke R. Observations on strongyloidiasis in Queensland aboriginal communities. The Medical Journal of Australia. 1993; 158(3):160–3. https://doi.org/10.5694/j.1326-5377.1993.tb121693.x PMID: 8450780

11. Robertson GJ, Koehler AV, Gasser RB, Watts M, Norton R, Bradbury RS. Application of PCR-Based Tools to Explore Strongyloides Infection in People in Parts of Northern Australia. Tropical Medicine and Infectious Disease. 2017; 2(4). https://doi.org/10.3390/tropicalmed2040062 PMID: 30270919

12. Walker-Smith J, McMillan B, Middleton A, Robertson S, Hopcroft A. Strongyloidiasis causing small-bowel obstruction in an Aboriginal infant. Medical Journal of Australia. 1969; 1263–5.

13. Fraser J. A case report suggestive of strongyloidiasis infection occurring in temperate Australia. Rural and Remote Health. 2019; 19(4787). Epub 15 May 2019. https://doi.org/10.22605/RRH4787 PMID: 31084034

14. Page WA, Judd JA, MacLaren DJ, Buettner P. Integrating testing for chronic strongyloidiasis within the Indigenous adult preventive health assessment system in endemic communities in the Northern Territory, Australia: An intervention study. PLOS Neglected Tropical Diseases. 2020; 14(5):e0008232. https://doi.org/10.1371/journal.pntd.0008232 PMID: 32401755

15. Soulsby HM, Hewagama S, Brady S. Case series of four patients with Strongyloides after occupational exposure. The Medical Journal of Australia. 2012; 196(7):444. https://doi.org/10.5694/mja11.111505 PMID: 22509872

16. Sudarshi S, Stumpfle R, Armstrong M, Ellman T, Parton S, Krishnan P, et al. Clinical presentation and diagnostic sensitivity of laboratory tests for Strongyloides stercoralis in travellers compared with immigrants in a non-endemic country. Tropical Medicine & International Health. 2003; 8(8):728–32.

17. Swaminathan A, Torresi J, Schlagenhauf P, Thursky K, Wilder-Smith A, Connor BA, et al. A global study of pathogens and host risk factors associated with infectious gastrointestinal disease in returned international travellers. Journal of Infection. 2009; 59(1):19–27. https://doi.org/10.1016/j.jinf.2009.05.008 PMID: 19552961

18. Grove D. Strongyloidiasis in allied ex-prisoners of war in south-east Asia. Br Med J. 1980; 280 (6214):598–601. https://doi.org/10.1136/bmj.280.6214.598 PMID: 7370602
19. Pattison DA, Speare R. Strongyloidiasis in personnel of the Regional Assistance Mission to Solomon Islands (RAMSI). Medical Journal of Australia. 2008; 189:203–6. https://doi.org/10.5694/j.1326-5377.2008.tb01982.x PMID: 18707563

20. Einsiedel L, Spelman D. Strongyloides stercoralis: risks posed to immigrant patients in an Australian tertiary referral centre. Internal Medicine Journal. 2006; 36(10):632–7. https://doi.org/10.1111/j.1445-5994.2006.01172.x PMID: 16958639

21. De Silva S, Saykao P, Kelly H, MacIntyre C, Ryan N, Leydon J, et al. Chronic Strongyloides stercoralis infection in Laotian immigrants and refugees 7–20 years after resettlement in Australia. Epidemiology & Infection. 2002; 128(3):439–44. https://doi.org/10.1017/s0950268801006677 PMID: 12113488

22. Rahmanian H, MacFarlane AC, Rowland KE, Einsiedel LJ, Neuhaus SJ. Seroprevalence of Strongyloides stercoralis in a South Australian Vietnam veteran cohort. Australian and New Zealand Journal of Public Health. 2015; 39(4):331–5. https://doi.org/10.1111/1753-6405.12360 PMID: 25903944

23. Salvador F, Sulleiro E, Sánchez-Montalvá A, Saugar JM, Rodríguez E, Pahissa A, et al. Usefulness of Strongyloides stercoralis serology in the management of patients with eosinophilia. The American Journal of Tropical Medicine and Hygiene. 2014; 90(5):830–4. https://doi.org/10.4269/ajtmh.13-0678 PMID: 24615124

24. Nonaka D, Takaki K, Tanaka M, Umeno M, Takeda T, Yoshida M, et al. Paralytic ileus due to strongyloidiasis: case report and review of the literature. The American journal of tropical medicine and hygiene. 1998; 59(4):535–8. https://doi.org/10.4269/ajtmh.1998.59.535 PMID: 9790425

25. Keiser PB, Nutman TB. Strongyloides stercoralis in the immunocompromised population. Clinical microbiology reviews. 2004; 17(1):208–17. https://doi.org/10.1128/cmrr.17.1.208-217.2004 PMID: 14726461

26. Wirk B, Wingard J. Strongyloides stercoralis hyperinfection in hematopoietic stem cell transplantation. Transplant Infectious Disease. 2009; 11(2):143–8. https://doi.org/10.1111/j.1399-3062.2008.00360.x PMID: 19140995

27. Keiser PB, Nutman TB. Strongyloides stercoralis in the immunocompromised host. Current infectious disease reports. 2011; 13(1):35–46. https://doi.org/10.1007/s11908-010-0150-z PMID: 21308453

28. Marcos LA, Terashima A, Canales M, Gotuzzo E. Update on strongyloidiasis in the immunocompromised host. Current infectious disease reports. 2011; 13(1):35–46. https://doi.org/10.1007/s11908-010-0150-z PMID: 21308453

29. Marcos LA, Terashima A, DuPont HL, Gotuzzo E. Strongyloides hyperinfection syndrome: an emerging global infectious disease. Transactions of the Royal Society of Tropical Medicine and Hygiene. 2008; 102(4):314–8. https://doi.org/10.1016/j.trstmh.2008.01.020 PMID: 18321548

30. Nucci M, Portugal R, Pulcheri W, Spector N, Ferreira SB, de Castro MB, et al. Strongyloidiasis in patients with hematologic malignancies. Clinical Infectious Diseases. 1995; 21(3):675–7. https://doi.org/10.1093/clinids/21.3.675 PMID: 8527567

31. Lim L-I, Biggs B-A. Fatal disseminated strongyloidiasis in a previously treated patient. The Medical journal of Australia. 2001; 174(7):355–6. https://doi.org/10.5694/j.1326-5377.2001.tb143315.x PMID: 11346112

32. Bourque DL, Leder K. Progress towards the Control of Strongyloidiasis in Tropical Australia? The American Journal of Tropical Medicine and Hygiene. 2020; 102(2):249. https://doi.org/10.4269/ajtmh.19-0922 PMID: 31912774

33. Grove D. Diagnosis. In: Grove D, editor. Strongyloidiasis a major roundworm infection of man. London: Taylor & Francis; 1989. p. 175–97.
39. Bisoffi Z, Buonfrate D, Sequi M, Mejia R, Cinino RO, Krolewiecki AJ, et al. Diagnostic accuracy of five serologic tests for *Strongyloides stercoralis* infection. PLoS neglected tropical diseases. 2014; 8(1): e2640. https://doi.org/10.1371/journal.pntd.0002640 PMID: 24427320

40. Barratt JL, Lane M, Talundzic E, Richins T, Robertson G, Formenti F, et al. A global genotyping survey of *Strongyloides stercoralis* and *Strongyloides fuelleborni* using deep amplicon sequencing. PLoS neglected tropical diseases. 2019; 13(9):e0007609. https://doi.org/10.1371/journal.pntd.0007609 PMID: 31525192

41. Bradbury RS. Addendum to *Strongyloides* genotyping paper. PLoS neglected tropical diseases. 2020.

42. ABS. 1270.0.55.001—Australian Statistical Geography Standard (ASGS): Volume 1—Main Structure and Greater Capital City Statistical Areas, July 2011 Canberra: Australian Bureau of Statistics; 2017 [cited 2017]. Available from: https://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/1270.0.55.001July_2011.

43. ABS. ABS Maps Canberra: Australian Bureau of Statistics; 2020 [cited 2017–2020]. Available from: https://itt.abs.gov.au/itt/r.jsp?ABSMaps.

44. Google. Google Maps USA: Google; 2020 [cited 2017–2020]. Available from: https://www.google.com/maps.

45. Mayer-Coverdale J, Crowe A, Smith P, Baird R. Trends in *Strongyloides stercoralis* faecal larvae detections in the Northern Territory, Australia: 2002 to 2012. Tropical medicine and infectious disease. 2017; 2(2):18. https://doi.org/10.3390/tropicalmed2020018 PMID: 30270877

46. Paltridge M, Smith S, Traves A, McDermott R, Fang X, Blake C, et al. Rapid Progress toward Elimination of *Strongyloidiasis* in North Queensland, Tropical Australia, 2000–2018. The American Journal of Tropical Medicine and Hygiene. 2020; 102(2):339–45. https://doi.org/10.4269/ajtmh.19-0490 PMID: 31802738

47. Einsiedel L FL. *Strongyloides stercoralis*: a cause of morbidity and mortality in Indigenous people in Central Australia. Internal Medicine Journal. 2008; 38:697–703. https://doi.org/10.1111/j.1445-5994.2008.01775.x PMID: 19143887

48. Caruana SR, Kelly HA, Ngeow JY, Ryan NJ, Bennett CM, Chea L, et al. Undiagnosed and potentially lethal parasite infections among immigrants and refugees in Australia. Journal of Travel Medicine. 2006; 13(4):233–9. https://doi.org/10.1111/j.1708-8305.2006.00045.x PMID: 16884406

49. Grove DI. *Strongyloidiasis*: is it transmitted from husband to wife? Sexually Transmitted Infections. 1982; 58(4):271–2. https://doi.org/10.1136/sti.58.4.271 PMID: 6896668

50. Siddiqui AA, Koenig NM, Sinensky M, Berk SL. *Strongyloides stercoralis*: identification of antigens in natural human infections from endemic areas of the United States. Parasitology research. 1997; 83(7):655–8. https://doi.org/10.1007/s004360050314 PMID: 9272553

51. Theunissen C, Bottieau E, Van Esbroeck M, Tsoumanis A, Florence E. Should We Screen HIV-Positive Migrants for *Strongyloidiasis*? Pathogens. 2020; 9(5):388. https://doi.org/10.3390/pathogens9050388 PMID: 32443596

52. Buonfrate D, Baldissera M, Abrescia F, Bassetti M, Caramaschi G, Giobbia M, et al. Epidemiology of *Strongyloides stercoralis* in northern Italy: results of a multicentre case–control study, February 2013 to July 2014. Eurosurveillance. 2016; 21(31):30310. https://doi.org/10.2807/1560-7917.ES.2016.21.31.30310 PMID: 27525375

53. Agbata EN, Morton RL, Bisoffi Z, Bottieau E, Greenaway C, Biggs B-A, et al. Effectiveness of screening and treatment approaches for schistosomiasis and *strongyloidiasis* in newly-arrived migrants from endemic countries in the EU/EEA: a systematic review. International journal of environmental research and public health. 2019; 16(1):11.

54. Gordon CA, Shield JM, Bradbury RS, Muhi S, Page W, Judd JA, Lee R, Biggs B-A, Ross K, Kurscheid J, Gray DJ, McManus DP. Advances in Parasitology. 2021; 111:119–201. https://doi.org/10.1016/bs.apar.2020.11.002 PMID: 33482974
58. Kukuruzovic R, Robins-Browne RM, Anstey NM, Brewster DR. Enteric pathogens, intestinal permeability and nitric oxide production in acute gastroenteritis. The Pediatric infectious disease journal. 2002; 21(8):730–9. https://doi.org/10.1097/00006454-200208000-00007 PMID: 12192160

59. CARPA. CARPA Standard Treatment Manual 7th Edition. Alice Springs, Australia: Central Australia Rural Practitioners Association; 2017.

60. Davies* J, Majumdar* SS, Forbes RT, Smith P, Currie BJ, Baird RW. Hookworm in the Northern Territory: down but not out. Medical Journal of Australia. 2013; 198(5):278–81.

61. Horton J. Albendazole: a review of anthelmintic efficacy and safety in humans. Parasitology. 2000; 121(S1):S113–S32. https://doi.org/10.1017/s0031182000007290 PMID: 11386684

62. Centers for Disease Control and Prevention. Parasites—Strongyloides. Resources for Health Professionals. Treatment. Atlanta, GA, USA: Centers for Disease Control and Prevention; 2020 [cited 2020]. 21 Sep 2020.

63. Paula F, Costa-Cruz J. Epidemiological aspects of strongyloidiasis in Brazil. Parasitology. 2011; 138(11):1331. https://doi.org/10.1017/S003118201100120X PMID: 21810305

64. Forrer A, Khieu V, Schär F, Hattendorf J, Marti H, Neumayr A, et al. Strongyloides stercoralis is associated with significant morbidity in rural Cambodia, including stunting in children. PLoS neglected tropical diseases. 2017; 11(10):e0005685. https://doi.org/10.1371/journal.pntd.0005685 PMID: 29059195

65. Aramendia AA, Anegagrie M, Zewdie D, Dacal E, Saugar JM, Herrador Z, et al. Epidemiology of intestinal helminthiases in a rural community of Ethiopia: Is it time to expand program controls to include Strongyloides stercoralis and the entire community? PLOS Neglected Tropical Diseases. 2020; 14(6):e0008315. https://doi.org/10.1371/journal.pntd.0008315 PMID: 32497042

66. Ngui R, Halim NAA, Rajoo Y, Lim YA, Ambu S, Rajoo K, et al. Epidemiological characteristics of strongyloidiasis in inhabitants of indigenous communities in Borneo Island, Malaysia. The Korean journal of parasitology. 2016; 54(5):673. https://doi.org/10.3347/kjp.2016.54.5.673 PMID: 27853126

67. QML. QML Pathology Brisbane: QML Pathology; 2020 [cited 2020 2 July 2020]. Available from: http://www.qml.com.au/AboutUs.aspx.

68. O’Donahoo FJ, Ross KE. Principles relevant to health research among Indigenous communities. International journal of environmental research and public health. 2015; 12(5):5304–9. https://doi.org/10.3390/ijerph120505304 PMID: 25996884

69. Shield JM, Kearns TM, Garrgulkpuy J, Walpalay L, Gundjirryirr R, Bundhala L, et al. Cross-cultural, Aboriginal language, Discovery Education for health literacy and informed consent in a remote Aboriginal community in the Northern Territory, Australia. Tropical Medicine and Infectious Disease. 2018; 3(1):15.

70. Beknazirova M, Barratt JL, Bradbury RS, Lane M, Whiley H, Ross K. Detection of classic and cryptic Strongyloides genotypes by deep amplicon sequencing: A preliminary survey of dog and human specimens collected from remote Australian communities. PLoS Neglected tropical diseases. 2019; 13(8):e0007241. https://doi.org/10.1371/journal.pntd.0007241 PMID: 31430282
