Characterization of tungiasis infection and morbidity in Kenya reveals increase in disease burden during COVID-19 school closures.

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Characterization of tungiasis infection and morbidity in Kenya reveals increase in disease burden during COVID-19 school closures.

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Keywords
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Abstract
Background: Tungiasis is a common but extremely neglected tropical skin disease caused by the sand flea Tunga penetrans. Female sand fleas penetrate the skin, particularly at the feet, and cause severe inflammation with pain and itching, acute and chronic morbidity. This study aimed to characterize disease burden in two highly affected regions in Kenya, to test the use of simple thermography to detect tungiasis-associated inflammation and to create a new two-level classification of disease severity that may be used for mapping, targeting, and monitoring interventions in future.

Methods: From February 2020 to April 2021, 3,532 pupils age 8-14 years were randomly selected in 35 public primary schools and examined for tungiasis and associated pathology. Of the infected pupils, 266 were randomly selected and their households visited. An additional 1,138 family members were examined.
Infra-red thermography was used to assess inflammation. An all-pathology score was created combining the number of locations on the feet with acute and chronic pathologies and infra-red hotspots.

**Results:** Based on multilevel mixed effects logistic models, the odds of infection with tungiasis among school pupils was three times as high in Kwale than in Siaya (adjusted odds ratio (AOR) 0.28, 95% CI 0.1-0.6); three times higher in males than in females (AOR 2.9, 95% CI 2.2-3.7) and three times lower among pupils sleeping in a house with a concrete floor (AOR 0.32, 95% CI 0.24-0.44). The odds of finding an infected person among the household population during active school terms was approximately a half of that when schools were closed due to COVID-19 (AOR 0.44, 95% CI 0.3-0.7). Infection intensity was positively correlated with inflammation (Spearman’s rho = 0.68, p < 0.001) and all-pathology score (rho 0.86, p < 0.001).

Based on the two-level classification, severe cases were associated with a threefold higher level of pain (OR 2.99, 95% CI 2-4.4) and itching (OR 3.31, 95% CI 2.2-4.9) than mild cases.

**Conclusions:** Thermography was a valuable addition for assessing morbidity and the proposed two-level classification of disease severity clearly separated patients with mild and severe impacts. The burden of tungiasis severely increased during COVID-19 restrictions and reinforced that underlying risks are found in the home environment more than in school.
Background

Tungiasis is a highly neglected tropical skin disease (NTSD) caused by the female sand flea, *Tunga penetrans*, which penetrate the skin, usually of the feet, of their mammalian hosts and stay embedded for their remaining life [1]. The flea grows 2000-fold in size over seven days as a result of eggs developing in the abdomen. A small opening is maintained in the skin through which the last segments of the abdomen stay in contact with the environment. Via this opening, the male copulates with the embedded female and the female expels eggs, respires, and defecates. Eggs fall to the ground and, if conditions are favorable, the larvae hatch and grow over several larval stages, pupate and emerge as adults over the course of 3-4 weeks [2]. The embedded female dies after egg-laying and is removed by skin repair mechanisms if not extracted by the host.

*Tunga penetrans* is endemic in the tropics of the Americas and in Sub-Saharan Africa with an estimated 668 million people considered to be at risk of infection in Sub-Saharan Africa alone [3, 4]. In endemic areas, tungiasis is heterogeneously distributed with the poorest part of the population bearing the highest burden [5]. In Kenya, human tungiasis is considered a significant individual and public health threat, with an estimated two million people currently infected [6] although there is no systematically collected data from national level surveillance. In general, males, children, elderly people and people with disabilities carry the highest disease burden [5] with prevalence ranging between 7% and 60% in affected villages and schools [7-9]. Intensity of infection is also heterogeneously distributed among the infected population, with the majority of patients having only a few embedded fleas, but a few individuals having a high number, some even over 100 fleas [8].

Sand fleas cause severe morbidity in humans, companion animals and livestock [10-12]. Morbidity results from the intense inflammatory response around the rapidly growing female sand fleas firmly embedded in the epidermis [10]. The inflammation is further intensified by frequent bacterial superinfection of the lesions and bacterial superinfection may result in tetanus, gangrene or septicemia [13].

A study conducted in Brazil 20 years ago carefully documented the clinical features of tungiasis [14]. Acute pathology included itching, pain, edema, erythema, warmthness, desquamation, ulcers and fissures.
Chronic pathology, thought to be the result of repeated infection with large numbers of fleas, included hyperkeratosis, peri-ungual hypertrophy, deformation and loss of nails [14]. The authors developed systematic methods to quantify the severity of disease with severity scores for acute tungiasis (SSAT) and chronic tungiasis (SSCT). Modified versions of these morbidity scores have also been applied to estimate morbidity in pigs and dogs and to quantify the effects of successful treatment on disease severity [15, 16]. Overall, these pathology scores have only rarely been used since they were published. One of the reasons may be that edema, erythema and warmness-to-touch, the signs of inflammation, are difficult to assess, particularly on a dark skin and by non-clinical staff. The SSAT also included scores for the number of sites with flea clusters, and the patient’s experience of pain, itching and sleep disturbance. It was demonstrated that those individuals with the highest infection rate (newly embedded live fleas over time) had the highest SSAT [14]. A separate study showed that the number of live fleas and the SSAT scores were negatively correlated with quality of life as measured using the modified Dermatological Quality of Life Index (mDQLI) [17].

Now that tungiasis has been added to the World Health Organization (WHO) list of NTDs (under scabies and other ectoparasites), governments and organizations will start to plan surveillance and intervention programs, and these will need carefully defined indicators and targets. As has been implemented for other NTDs, initially it will be appropriate to target those individuals with the highest morbidity. For instance, the WHO NTD Roadmap 2021-2030 [18] recommends targets using the prevalence of medium and high infection intensity for schistosomiasis and soil-transmitted helminths. The thresholds to define low, medium, and high intensity infection, such as eggs per gram of stool, were set by the WHO Technical Working Groups and were based on the morbidity caused by differing levels of infection intensity [18-20]. Similar measures and thresholds will be needed for tungiasis.

To date, disease intensity for tungiasis has been classified in three-tiers, defined using embedded flea counts; mild cases being defined as having 1 to 5 fleas, moderate cases having 6 to 30 fleas and severe cases more than 30 fleas [8, 9, 21]. However, the first studies describing this classification did not explain the reasoning behind the thresholds and they have not been associated with levels of morbidity. As has happened for some other NTDs whose targets focus on medium and high intensity disease[22], i.e.
reducing the classification from three groups to two, it may be more appropriate to define two disease groups for tungiasis rather than three. Consequently, in the current study we set out to (i) describe the prevalence and intensity of infection in two regions of Kenya with suspected high disease burden; (ii) simplify the pathology scoring method; (iii) test the use of thermography to assess inflammation; (iv) evaluate the past disease severity classification with respect to pathology in these populations in Kenya and develop a new classification with only two disease severity groups. The data reported here is part of a larger project aimed at characterizing the disease ecology of tungiasis in East Africa, including a better understanding of the parasite, risk factors for severe tungiasis and its impact on child development and well-being.

Methods

Study design

A cross-sectional observation study of children in primary schools, their families, and homesteads in two regions of Kenya was carried out between February 2020 and April 2021. Primary school children between the age of 8 and 14 years were selected since this is the age group most affected by tungiasis in Kenya [21].

Study area and population

Surveys, following the same procedures, were conducted in the sub-counties of Matuga and Msambweni of Kwale county on the south east coast of Kenya, and in Ugenya sub-county of Siaya county in western Kenya near the border with Uganda (Fig. 1). These counties were chosen since they lie in similar ecological zones but are inhabited by people with different ethnicity, cultures and livestock-keeping habits. Both counties are major areas of sugar cane-production and thus a proportion of the population is engaged in this agro-industry. Both areas were among the counties with the highest tungiasis prevalence rate according to the Kenyan Ministry of Health in 2014 [6].

Average rainfall amount (mm) for each month of the study from October 2019 to April 2021 was retrieved from World Weather Online [23] for the nearest possible sites with available data; Siaya town near Ugenya sub-county and Matuga town in Kwale. For data analyses the average rainfall for the two months prior to the survey month was calculated, for example the average rainfall in mm for April and May.
for all households visited in June. Both measures, average rainfall in the month of the visit and average rainfall in the two months before the visit, were converted from mm to cm (by dividing by 10) of rainfall for ease of interpretation of the outcomes from regression analyses.

**Sampling procedure**

Within Kwale and Siaya counties, sub-counties were selected that were known by the county Department of Health to have a high tungiasis burden. Lists of all existing public primary schools in the sub-counties were provided by the county education departments and 35 schools randomly selected using a paper lottery approach. In each school, a maximum of 51 boys and 51 girls between the age of 8 and 14 years (the age with the highest prevalence and intensity of tungiasis [21]) were randomly selected by lining all boys and girls up and selecting every n\(^{th}\) (depending on the total number in the group) child until the required number was reached. All selected pupils were examined for tungiasis, and a small questionnaire was administered asking about the floor of the house they sleep in and whether other people in the family are infected. Out of all examined pupils in a school, a maximum of ten tungiasis infected children living in a home with an unsealed soil or sand floor were randomly selected for household surveys. We specifically targeted households with unsealed floors since this risk factor has been well-established for tungiasis [7, 24, 25] and for our risk factor study to be reported elsewhere we wanted to explore other possible factors. COVID-19 restrictions forced the closure of schools from March to December 2020. Field research activities were however free to recommence from July 2020. Consequently, the survey strategy was adapted to recruit cases and controls through a household-based survey only. In the catchment areas of 11 schools already selected randomly before COVID-19 closures, community health volunteers (CHVs) were asked to invite any children aged 8 to 14 years they considered to be infected, to a location where they could be screened by the study team. Out of all infected children seen through this approach, a maximum of ten were randomly selected for household surveys. This survey strategy was used between August and October 2020 (survey round 2) returning to school-based surveys in January to May 2021. Figure 1 shows the location of the schools screened in round 1 and 3 and the catchment areas in round 2, demonstrating their equal distribution across the study area.
Clinical assessment procedures

The clinical assessment procedures were the same for the pupils in schools and for the household members of the selected pupils. The feet of the 102 children in each school were washed and dried and systematically examined for the presence of tungiasis by observing nine zones on each foot in order from the largest toe to the smallest toe, the medial side, lateral side, the sole and the heel. Those pupils found to have sand fleas embedded in the feet, were assessed for intensity of infection by counting the number of fleas that were: alive (round white lesion with dark spot at center); dead (black, irregular-shaped lesion); manipulated (lesion from where a flea had clearly been removed) or large clusters of embedded fleas in which individual fleas could not be counted as they were too close together. Infected individuals were also assessed for acute and chronic pathology by modifying the technique described by Kehr et al. [14]. Both feet were examined systematically by nine zones each (five toes, medial side, lateral side, sole and heel). For each of the zones, the presence or absence of each pathology was recorded. These included desquamation, fissures, ulcers and abscess for acute pathology signs and hyperkeratosis, peri-ungual hypertrophy, deformed nails and lost nails for chronic pathology signs. In comparison to the original description of the score by Kehr et al.[14], the signs of inflammation; edema, erythema and warmness, were not recorded due to the difficulty of assessing these for non-clinicians. Infected individuals were also asked to report the amount of pain and, separately, the amount of itching they felt in their feet associated with the embedded fleas using the options: “none at all”, “a little”, “some” or “a lot”.

Fig. 1 Map of the study sites to show the location in Kenya, schools and catchment areas by survey round and the prevalence of tungiasis in the schools during round 1 & 3 (squares and triangles respectively). Prevalence is not indicated for round 2 catchment areas surveyed during COVID-19 restrictions (blue circles).
Infra-red thermography

A low-resolution (220x160) infra-red camera detecting wavelengths of 8-14 µm (Hti Thermal Imaging Camera, HT-A1, Dongguan Xintai Instrument Co. Ltd, Dongguan, Guangdong province, China) was used to observe the nine zones, both upper and lower surfaces of both feet. These cameras convert the different temperatures detected into a range of colors (Fig. 2.) The hottest being white or yellow in the rainbow spectra transformation used. The presence or absence of such a “hot spot” was recorded for each of the 18 zones on the feet. If there was more than one hotspot in a zone it was recorded as one site. Elevated temperature as detected by thermography around embedded fleas, has been shown to be associated with acute tungiasis [26].

Fig. 2 Infrared thermography of an infected foot showing four sites (toes) with inflammation associated with embedded fleas. Infra-red image with rainbow transformation (A). Normal photograph of the same foot (B). White arrows indicate embedded live fleas. White arrows indicate sites with hotspots (white) associated with embedded live fleas.

Sample size

The number of pupils screened per school was based on the assumption that we would find a maximum of 10% of the pupils in any given school infected. With an average school size of 300 children in the target age group, disease prevalence of 10% surveys would require screening at least 95 pupils to achieve 80% power and 95% confidence. To allow for pupils to opt out, we randomly selected 102 in each school. The number of clusters surveyed over the study duration was largely driven by another research question on risk factors which will be reported elsewhere.

Data analyses

All analyses were conducted in Stata IC 15.1. For the pupil and household populations surveyed in schools and homes, prevalence (proportion of examined participants) and 95% confidence intervals were calculated for geographic regions, sexes, age groups and survey round. To test for associations between tungiasis infection status (infected and not infected) and geographic region, sex, age, survey round and rainfall (independent variables), multilevel mixed effects (MLME) logistic models were used with an
exchangeable correlation matrix. The unique school ID was included as a random effect for the pupil population and the household unique ID for the household population. Initially, bivariable analyses were run for each independent variable and then multivariable analysis with all variables. Backward elimination was used to develop the final model using Akaike information criteria (AIC) to compare goodness of fit of the models. Bivariable outcomes are presented as odds ratios (OR) and multivariable outcomes as adjusted odds ratios (AOR) calculated as the exponential of the coefficient with 95% confidence intervals and p-values.

For analysis of infection intensity and associated pathology, a new dataset was created merging all infected participants from both school and household-based surveys. The infection intensity for each infected individual was calculated as the sum of all flea types (live, dead and manipulated) on both feet, plus the number of flea clusters multiplied by 5 (as an estimate for an average number of fleas/cluster). Since infection intensities were not normally distributed, medians and interquartile ranges (IQR) were calculated for schools, regions, sexes, age groups and survey round. Since infection intensity was a positively skewed count variable for cases only, with no zeros, associations with region, sex, age, survey round and rainfall were tested using MLME linear regression models with zero-truncated negative binomial probability distributions and log link functions. The unique school ID was included as a random effect. Backward elimination was used to develop the final model using AIC to compare the goodness of fit of multivariable models. Bivariable outcomes are presented as incidence rate ratios (IRR) and multivariable outcomes and adjusted incidence rate ratios (AIRR) with 95% confidence intervals and p-values.

The correlation of school level prevalence and median infection intensity was tested using linear regression setting the intercept at zero since median infection intensity can only be zero if prevalence is zero. The coefficient is presented as $R^2$ and the p-value.

Acute pathology scores were calculated by summing the number of zones on the feet exhibiting each pathology, and then the scores for desquamation, fissures, ulcers and abscess were totaled, with a maximum possible score of 72 (9 zones x 2 feet x 4 pathologies). Chronic pathology scores were calculated by summing the number of zones on the feet exhibiting each pathology and then the scores for hyperkeratosis, peri-ungual hypertrophy, deformed nails and lost nails totaled, with a maximum of 38 (10
for peri-ungual hypertrophy, 10 for either deformed nails or lost nails, 18 for hyperkeratosis). This was different to the previously described method of Kehr et al [14] who assigned a score of 0.5, 1, 2 or 3 based on the number of sites affected for each pathology. We then went on to add the acute and chronic scores together in a ‘Total Pathology’ score with a maximum of 110.

For the thermography, the infra-red hotspots were considered as a sign of pathology and the total number of zones on the feet with a hotspot was totaled for each patient, with a maximum possible value of 18. Correlations were explored between infra-red scores, the three pathology scores and intensity of infection using Spearman rank correlation coefficient since these variables were positively skewed and are presented as rho values in a correlation matrix. Once the infra-red scores were seen to correlate with the other variables, they were added to create a new ‘All-Pathology’ score.

To evaluate the association of the old disease intensity groups based on flea counts with the All-Pathology score, bivariable MLME linear models were used with negative binomial probability distributions, log link functions and exchangeable correlations. The unique school ID was included as a random effect. Outcomes are presented as incidence rate ratios (IRR) with 95% confidence intervals and p-values. To identify a possible new two-level classification for disease severity, a scatter plot was created of infection intensity by All-Pathology score for all infected cases. All-Pathology scores were used as these were a measure of overall morbidity and reflect actual disease severity. The nonparametric Loess regression technique was used to fit a smooth curve through the scatter plot to help see the relationship between the two variables. The previous threshold levels for defining three levels of disease severity based on infection intensity alone [8, 9, 21] are marked at infection intensity of 5 and 30. Pain and itching levels were coded as 0 (none to a little) or as 1 (“some” to “a lot”). To assess the association of the new disease severity groups with the pain and itching levels MLME logistic models with an exchangeable correlation matrix and unique school ID was random effect were used.

Results

Pupil participants

Children age 8 to 14 years were screened for tungiasis in 35 primary schools, 15 schools in Msambweni/Matuga (Kwale) and 20 in Ugenya (Siaya), of which 8 were completed in 2020 (survey round
1) and the remainder in 2021 (survey round 3) when schools re-opened after the COVID-19 shut-down (Fig. 3, Table 1). In total we examined 3,535 pupils in schools, 810 in 2020 and 2,723 in 2021. As targeted, there were equal numbers of boys and girls enrolled, and the median age was 11 years (IQR 9-12). In total, 62.5% of pupils reported they sleep in a house with a mud or sand floor and the remaining 37.5% have a concrete floor. In survey round 2, during COVID-19 school closures, 338 children aged 8 to 14 years were clinically examined in the communities, 207 in Kwale and 131 in Siaya. During community-based surveys in round 2, the aim was to find infected participants hence overall community prevalence could not be assessed. Consequently, in line with expectations, more males than females were examined, given that risk of infection is usually higher in boys than girls.

### Table 1 Study population examined for tungiasis. Number of individuals in each group.

<table>
<thead>
<tr>
<th>Survey Round</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. schools</td>
<td>8</td>
<td>-</td>
<td>27</td>
<td>35</td>
</tr>
<tr>
<td>No. pupils</td>
<td>810</td>
<td>338</td>
<td>2723</td>
<td>3871</td>
</tr>
<tr>
<td>Region</td>
<td>Kwale</td>
<td>Siaya</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(#schools/#pupils)</td>
<td>3/302</td>
<td>5/508</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sex (#pupils)</td>
<td>Female</td>
<td>Male</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age (years, median, IQR)</td>
<td>11 (9-12)</td>
<td>11 (9-12)</td>
<td>11 (9-12)</td>
<td>11 (9-12)</td>
</tr>
<tr>
<td>House floor</td>
<td>Sand/mud</td>
<td>concrete</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. households</td>
<td>55</td>
<td>91</td>
<td>120</td>
<td>266</td>
</tr>
<tr>
<td>No. individuals</td>
<td>242</td>
<td>401</td>
<td>495</td>
<td>1138</td>
</tr>
<tr>
<td>Region</td>
<td>Kwale</td>
<td>Siaya</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sex</td>
<td>Female</td>
<td>Male</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age groups (years)</td>
<td>&lt;8</td>
<td>8-14</td>
<td>15-21</td>
<td>22-41</td>
</tr>
<tr>
<td>Age (median years,, IQR)</td>
<td>12 (8-30)</td>
<td>11 (8-24)</td>
<td>12 (8-33)</td>
<td>12 (8-30)</td>
</tr>
</tbody>
</table>
Household participants

A total of 266 households of infected pupils, living in a house with an unsealed sand or mud floor, were recruited for the study (Fig. 3, Table 1). Within these households, 1,138 people were examined for tungiasis, the 266 pupils and 872 of their family members.

Fig. 3 Flow diagram describing selection of participant groups. Orange boxes represent people infected with tungiasis, green boxes represent people who were not infected.

Rainfall

Since there has been some evidence published that prevalence of tungiasis is associated with rainfall seasons [27], the rainfall patterns were assessed for the two regions. Figure 4 illustrates the study area in western Kenya (Ugenya, Siaya) had higher rainfall than the location in coastal Kenya (Kwale) for most of the study period, and the surveys were mostly conducted during the drier months in both regions.

Fig. 4 Proportion of household population infected by month and the monthly rainfall in Kwale (KW) and Siaya (SI).

Prevalence of tungiasis

The overall prevalence of tungiasis among all the school pupils who were randomly selected during survey rounds 1 and 3 was 9.3 % (95% CI 8.4-10.3). In multivariable models, boys had a three-fold higher odds of infection than girls (AOR 2.9 and 3.0, Table 2) and there was a negative association between infection and age (AOR 0.89), even within the narrow age range of examined pupils, 8 to 14 years. Pupils in Siaya had a nearly three-fold lower odds of infection (AOR 0.36) than those in Kwale, as did pupils who sleep in a house with an unsealed sand or mud floor compared to those with a concrete floor (AOR0.36). There was no association with rainfall. The maps in Fig. 1 illustrate the prevalence of infection in the surveyed schools for round 1 and 3 and school catchment areas for round 2. From this map it appears that in both regions the schools with highest prevalence are locally clustered.
By selection criteria, all the 266 households selected had at least one child age 8 to 14 years infected and an unsealed sand or mud floor. The overall prevalence in these households was 50.2% (95% CI 47.4-53.2). As among the pupils, males had a higher odds of infection than females (AOR 2.4, Table 2) when adjusted for other covariables. Children under 8 years had five-fold lower odds of infection than 8 to 14-year-old children (AOR 0.21), but adults and children over 14 years had 50 to 100-fold lower odds of infection compared to the youngest age group.

When adjusted for sex and age, households examined during round 1 had a three-fold lower odds (AOR 0.33) of being infected than those seen in round 2, and households seen in round 3 had a more than two-fold lower odds of infection to those in round 2 (AOR 0.44). Although spatial analysis was not conducted, geographic location is not likely to be a factor which impacted these observations for survey rounds. The map in Figure 1, shows that areas surveyed during round 2 were distributed evenly among those in round 1 and 3. There was no association of rainfall with prevalence of infection in the household population, so this difference between the survey rounds was unlikely to have been caused by changes in rainfall.

**Intensity of infection**

To investigate infection intensity and the pathology caused by embedded fleas, data for all infected individuals were combined. Since there were very few infected individuals in the age groups older than 14 years (n=44), they were excluded from analyses. Of the remaining 633 individuals with full data sets, 406 (64.1%) were from Kwale, 430 (67.9%) were male and 503 (79.5%) were age 8 to 14 years.

The infection intensity for the 633 cases ranged from 1 to 154 fleas, with a median intensity of 13 fleas (IQR 5-28) (Table 3). Infection intensity among patients was associated with the region, sex and survey round with no change between bivariable and multivariable outcomes. Infected children in Siaya had a lower infection intensity than those in Kwale (AIRR 0.67) which goes hand in hand with the overall lower prevalence in that region. Boys had a higher infection intensity than females (AIRR 1.27) and those examined in survey round 1 (AIRR 0.5) and 3 (AIRR 0.63) had lower infection.
intensity than those in round 2. There was no association between infection intensity with age nor rainfall.

Correlation of school prevalence and median infection intensity

The school prevalence ranged from 0% in four schools to 26% in one school (Fig. 5), with more than one third of schools having a prevalence higher than 10%. Using simple linear regression, there was a significant positive correlation between prevalence and median infection intensity in the schools ($r^2=0.502$, $p<0.001$). However, the scatter plot in Fig. 5 highlights six schools (in the circle) that did not fit well in this relationship. These schools were characterized by overall low prevalence of tungiasis in the pupil population but with the few infected pupils having a very high infection intensity.

![Fig. 5 Scatter plot of school prevalence and median infection intensity score. Each dot represents one school. Dashed blue line represents the linear regression line with the intercept set at 0, its coefficient and $R^2$ stated for all schools.]

Tungiasis associated pathology

Of the 633 infected participants, 598 (94.5%) were recorded to have at least one pathology. The most common was desquamation (88%), considered to be an acute pathology sign, followed by deformed nails (74%) and peri-ungual hyperkeratosis (58%) which are classified as chronic pathologies. The least common were lost nails (21%), and abscesses caused by secondary bacterial infection (27%). The median score for the acute pathology (desquamation, fissures, ulcers, abscess) using our simplified scoring system was 6 (IQR 2-12) while that for chronic pathology (hyperkeratosis, peri-ungual hyperkeratosis, deformed nails, lost nails) was 5 (IQR 1-11). Using Spearman correlation, both the acute and chronic pathology scores were each strongly correlated with the infection intensity score (rho 0.818 and 0.766, respectively) and with each other (rho 0.857,
A new score was introduced combining the acute and chronic pathology scores into a single Total-Pathology score which had a median of 12 (IQR 4-23) and had a slightly higher correlation with infection intensity than the two individual pathology scores (rho 0.822, Table 4).

### Table 2: Spearman rank correlation for pathology scores and intensity of infection (n=633)

<table>
<thead>
<tr>
<th>Spearman (rho)*</th>
<th>Infection intensity</th>
<th>Acute pathology score</th>
<th>Chronic pathology score</th>
<th>Total pathology score</th>
<th>Infra-red score</th>
<th>All pathology score (with IRb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infection intensity</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acute pathology score</td>
<td>0.818</td>
<td>1.000</td>
<td></td>
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<tr>
<td>Chronic pathology score</td>
<td>0.766</td>
<td>0.857</td>
<td>1.000</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Total pathology score</td>
<td>0.822</td>
<td>0.963</td>
<td>0.961</td>
<td>1.0000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Infra-red score</td>
<td>0.684</td>
<td>0.562</td>
<td>0.477</td>
<td>0.541</td>
<td>1.000</td>
<td></td>
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<tr>
<td>All-Pathology score (with IRb)</td>
<td>0.861</td>
<td>0.959</td>
<td>0.939</td>
<td>0.986</td>
<td>0.66</td>
<td>1.000</td>
</tr>
</tbody>
</table>

*a All rho values level of significance p<0.001.

*b IR=infra-red, had at least one hotspot indicative of inflammation.

Infra-red thermography

Infra-red thermography has been shown to be a good, non-subjective replacement for erythema, oedema and warmthness in assessments of pathology in tungiasis [26]. Figure 2 illustrates this well, where a patient has many fleas and other pathology but to the naked eye, inflammation is not obvious for a non-clinician. The accompanying thermograph, however, shows there was inflammation in four toes. In this study we have attempted to simplify the thermography by using more affordable cameras and simply counting the number of sites on the feet with hot spots. The median number of sites with a hotspot per patient was 2 (IQR 0-5) and the highest number of hotspots was 17 of the maximum 18 sites. The number of infra-red hotspots was correlated with the infection intensity (rho 0.684, Table 4), the acute pathology scores (rho 0.566), the chronic pathology scores (rho 0.477) and the Total Pathology scores (rho 0.541). Adding the infra-red scores to the Total Pathology scores created a score with the strongest correlation to the infection intensity (rho 0.861), the All-Pathology score. For this reason, the All-Pathology score was considered the strongest variable to represent overall pathology and its correlation to infection intensity is illustrated in Fig. 6.
Classifying disease severity

Using the previously published classifications of disease severity based on infection intensity [8] as mild (1-5 fleas), moderate (6-30 fleas) and severe (>30 fleas), of the 633 cases under 15 years, 172 (27.2%) were mild, 311 (49.1%) were moderate and 150 (23.7%) were severe. Bivariable models found individuals with moderate disease, had four-fold higher All-Pathology scores than those with mild disease, and individuals with severe disease had nine-fold higher All-Pathology scores (Table 5).

Table 3 Bivariable regression for All-Pathology scores by various disease severity groups

<table>
<thead>
<tr>
<th></th>
<th>N&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Median (IQR)</th>
<th>IRR&lt;sup&gt;b&lt;/sup&gt;</th>
<th>95% CI</th>
<th>P</th>
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<td>Intensity-based groups</td>
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<tr>
<td>Mild</td>
<td>172</td>
<td>3 (1-5)</td>
<td>1</td>
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</tr>
<tr>
<td>Moderate</td>
<td>311</td>
<td>15 (9-22)</td>
<td>4.1</td>
<td>3.6</td>
<td>4.7</td>
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<tr>
<td>Severe</td>
<td>150</td>
<td>36 (28-43)</td>
<td>9.3</td>
<td>8.1</td>
<td>10.7</td>
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<td>Pathology-based groups</td>
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<td></td>
</tr>
<tr>
<td>Mild</td>
<td>252</td>
<td>4 (2-7)</td>
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<td></td>
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</tr>
<tr>
<td>Severe</td>
<td>381</td>
<td>25 (16-34)</td>
<td>6.2</td>
<td>5.6</td>
<td>6.8</td>
</tr>
</tbody>
</table>

<sup>a</sup> N: number of individuals.  
<sup>b</sup> Incidence Rate Ratio

To explore whether the previous threshold of five fleas was appropriate to create the two groups; mild with 1-5 fleas and severe with more than five fleas, a scatterplot of infection intensity by All-Pathology scores (Fig. 6) was created. This revealed the five-flea threshold bisected a tight cluster of cases with low infection intensity and low All-Pathology scores, placing some of them in the moderate disease category. Based on this scatterplot, we suggest a single threshold based on the All-Pathology score of 10, at the upper limit of the low pathology cluster would be a better fit for this group of children. A Loess trendline was fitted to the data to visually estimate an All-Pathology score of 10 was equivalent to 10 fleas (red lines in Fig. 6). Using this proposed new classification, 60.2% of the 633 cases had severe disease and had six-fold higher pathology scores than individuals in the new mild category (OR 6.2, Table 5).

Fig. 6 Scatterplot of infection intensity and All-Pathology scores with Loess regression line fitted. Green lines indicate the past thresholds (5 and 30 fleas) used to define mild, moderate and severe disease. Red lines indicate the All-Pathology threshold of 10 and interpolation to 10 fleas.
Children with severe disease according to the proposed new classification, had a three-fold higher odds of reporting higher levels of pain and itching than those with mild disease (Table 6).

**Table 4** Association of pain and itching with the revised disease severity classification.

<table>
<thead>
<tr>
<th></th>
<th>N⁵</th>
<th>% with higher level</th>
<th>OR⁶</th>
<th>95% CI</th>
<th>P</th>
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<td><strong>PAIN</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Mild disease</td>
<td>231</td>
<td>20.9</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Severe disease</td>
<td>360</td>
<td>43.0</td>
<td>2.99</td>
<td>2.02</td>
<td>4.43</td>
</tr>
<tr>
<td><strong>ITCHING</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mild disease</td>
<td>231</td>
<td>25.2</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Severe disease</td>
<td>360</td>
<td>45.8</td>
<td>3.31</td>
<td>2.24</td>
<td>4.89</td>
</tr>
</tbody>
</table>

a N: number of individuals. b OR: odds ratio

**Discussion**

This study set out to characterize tungiasis in two different regions of Kenya, to simplify pathology assessments, to test the use of a simplified thermographic method to detect inflammation, to evaluate the previously developed disease severity classification and to develop a new two-level classification of disease severity that could be used to target and monitor interventions in future, as has been done for other NTDs. However, possibly the most important finding of this study was generated because the study was disrupted by the COVID-19 pandemic which caused the closure of schools throughout the country for approximately 10 months. Research activities resumed in August 2020, but schools were still closed, forcing a change in recruitment strategy for our study until schools re-opened in January 2021. Inadvertently, this enabled the study to identify an unexpected impact of COVID-19, a substantial increase in the burden of tungiasis while schools were closed. The proportion of the household population who were infected in round 2 when the schools had been closed for 5 months, was triple that seen in round 1 and double that in round 3 when schools reopened. Climate variables and sampling locations were not associated with these results. We suggest, that when schools were closed, the children were spending all day at home or at homes of friends and relatives resulting in more exposure per unit of time compared to spending the day in
This reinforces our previous finding [7] that children are at higher risk of infection at home than at school where they spend most of the day on concrete classroom floors. The infection intensity among infected children was also significantly higher in round 2. Since infection intensity was positively correlated with pathology levels and higher levels of pain and itching, this means that school closures due to COVID-19 resulted in more tungiasis-related suffering in children.

While the pandemic afforded the opportunity to observe the impact of school closures, it was also a limitation for this study. With schools being closed we could not continue the randomized sampling of pupils in all communities that was needed to obtain prevalence estimates across all sampling sites.

Our study has confirmed previous findings of the heterogeneity of tungiasis distribution [7, 21] with the prevalence in schools ranging from 0% to 18% in Siaya and from 1% to 26% in Kwale. In the current study, the overall prevalence among pupils in Siaya of 6.2% was significantly lower than in Kwale of 13.6% and lower than any previously published prevalence in schools [7, 28] or households [8, 9, 21, 29, 30] from targeted endemic areas. This difference in prevalence is likely due to many factors, including the fact that the current study randomly selected schools within sub-counties known to have tungiasis patients, while others specifically only targeted schools known to have pupils with tungiasis. Other possible causes could be the different age ranges included in the different surveys, differences in climate, cultures, and economic status of the community, and control efforts which may have been implemented prior to surveys. Indeed, in Siaya the survey teams were told that the county government and partners had been conducting intervention programs in some parts of the sub-county in the preceding year.

This study corroborates findings from past surveys from Brazil [31], Cameroon [32] and Kenya [21, 29], that males and children aged between 8 and 14 years have the highest prevalence, followed by those under 8 years and those over 60 years. The reasons for this sex and age distribution have yet to be determined, but may be due to the different exposure and hygiene behaviors of boys, particularly in the 8–14-year age group [7]. Boys of this age tend to receive less attention from their
caregivers, often must move out of their caregiver’s house and have to care for themselves [33]. The higher prevalence among the youngest and oldest members of the community may also reflect their inability to remove actively penetrating fleas with a sharp instrument [21]. The higher odds of infection among pupils with unsealed sand or mud floors was also as expected from past studies[21, 24, 25, 29] and likely reflects the developmental needs of the off-host stages and high odds of the emerging adults finding a suitable host.

As might be expected, the intensity of infection in school pupils was positively correlated to the prevalence, albeit with some outlier schools. The more children are infected in a community, the more contamination of the environment with off-host stages and the greater the exposure of others to infection. Even if most transmission is happening within homes [7], children of this age group often spend time visiting and even sleeping in the homes of friends and family, particularly during school holidays/closures (personal observations), and thus might be exposed to infection from other households. Further enquiries of the research team regarding the outlier schools where there was a prevalence of less than 7% but a high median intensity, found that in three of the six schools, two of the cases were siblings and some from families who were members of religious sects which do not accept any modern health care. In addition, these schools had received tungiasis interventions in the recent past and it is not inconceivable that these children/families refused treatment at that time, as they did when our study teams visited. Explaining these anomalies will probably require in-depth anthropological studies.

While some past studies have described tungiasis as a highly aggregated disease where the majority of cases had an intensity of infection of 1-5 fleas and only a few cases had a high intensity of infection with more than 30 fleas [8, 9, 21, 32], the current study found the majority of cases (47%) had 6-30 fleas, and 18% had more than 30 fleas. Our median intensity of infection of 13 among all infected individuals was also considerably higher than reported for other studies, which varied from a median of 2.5 in Cameroon [32] to 6 in Nigeria [30]. This suggests an overall higher burden of disease in the current study, and yet there was a lower prevalence of disease compared to
past studies. This difference may have been caused by our intensity of infection measure incorporating a count of five for every flea cluster, and not a straight flea count. Other studies do not mention how flea clusters were incorporated in the flea counts, but possibly the enumerators attempted to count the closely packed fleas, which we felt was unlikely to be accurate in our circumstances.

Our simplified pathology score is appropriate since both the acute and chronic pathology scores correlated significantly with the infection intensity, and with each other. The most commonly reported pathology in previous studies was deformed nails, ranging from 72% [34] to 98% of cases in a study focusing only on severe cases [14], and was seen on 73% of cases in the present study. This suggests most of the cases in this study have been heavily infected for some time, since deformed nails are the result of chronic infection. This is striking since toenail loss and deformity are permanent and may remain as a mark of past disease and a source of stigma, shame, and discrimination for life. In fact, as part of a previous shoe donation program one of the investigators (LE) has had teenage girls explicitly say they are happy to receive shoes as they enable them to hide their toenails deformed by past infections.

To further simplify the assessment of inflammation we adapted the methodology of Schuster et al [26] who demonstrated high resolution thermography can identify areas of inflammation by taking measurements of the temperature of the skin around embedded fleas and comparing that to other areas of the foot. Simple handheld infra-red cameras are affordable and readily available and can be used to locate areas of the skin that are hotter than others through a color transformation of the raw data. Instead of measuring temperatures of the skin we trained observers to record presence or absence of hot spots in the 18 zones of the feet used to record pathology. The fact that the infra-red images revealed inflammation where no edema or erythema was visible as in Fig 2, that the number of sites with hot spots correlated significantly with the intensity of infection and the acute pathology scores, suggests it is a good proxy measure for inflammation. Simple thermography
such as this will likely be very useful in clinical trials to monitor the impact of treatment without the
need of expensive equipment.

As governments and organizations begin to map tungiasis in their countries and to implement
intervention programs, it will be important to have clear definitions for identifying target
populations and intervention goals. Previously the three-tier classification of disease severity has
been used, based only on flea counts with no description of how this correlated with pathology.

Since WHO guidelines for the control of other NTDs use targets based on two-tier levels of morbidity
caused by different infection intensities, we propose a two-tier classification for tungiasis based on
the All-Pathology score of 10. As with other NTDs, assessment of pathology is time consuming, and
parasite counts quicker and simpler to conduct for large scale public health projects, so we
recommend a total flea count of 10 is an appropriate threshold for severe disease.

Conclusions

Tungiasis is a highly heterogeneous disease with the prevalence in schools varying
considerably. Prevalence of tungiasis was positively correlated with infection intensity and with
morbidity. Simplified thermography is a valuable addition for assessing morbidity associated with
tungiasis and will be useful to assess the efficacy of treatment in future clinical trials. Along with
other pathologies, thermography helped to classify mild and severe disease which will be used in our
future studies on the impact of tungiasis. Fortuitously, the survey spanned the COVID-19 school
closures and demonstrated that when children spent an extended period out of school, the
prevalence, intensity and morbidity of tungiasis increased significantly calling for targeted
prevention measures and education at the household level

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Amina Abubakar, Ulrike Fillinger and Charles Waiswa. Additional support was provided through icipe core funding by the Swedish International Development Cooperation Agency (Sida); the Swiss Agency for Development and Cooperation (SDC); the Federal Democratic Republic of Ethiopia; and the Government of the Republic of Kenya. LE was supported by a Wellcome Trust Career Re-Entry Fellowship (grant number 213724/Z/18/Z). This work was written with the permission of Director KEMRI-CGMRC. The views expressed herein do not necessarily reflect the official opinion of the donors. The funders had neither a role in the design of the study, nor in collection, analysis, interpretation of data nor in writing the manuscript.

Author Contributions

Conceptualization, LE, UF, HF, FM & JK; Methodology, LE, UF, FM & JK; Formal Analysis, LE, UF, JK; Investigation, AM, PO, NR; Resources, UF, JK.; Data Curation, LE, AM, NR.; Writing – Original Draft Preparation, LE.; Writing – Review & Editing, UF, JK, FM; Visualization, LE.; Supervision, UF, JK; Project Administration, UF, JK; Funding Acquisition, UF, JK.

Competing interests

All authors declare no conflict of interest.

Ethics approval and consent to participate

The study was approved by the KEMRI Scientific and Ethics Review Committee (approval number NON-KEMRI 644) as well as the Ethikkommission of the Charité Berlin (reference number EA2/100/16). During the community entry phase, a presentation was made to the county and sub-county health management teams and the department of education in both counties to obtain their approval. In each school a meeting was held with the school parent teachers’ association (PTA) or management board to obtain their permission to conduct the survey in their school. The head teacher and PTA chairperson signed the consent form on behalf of the parents and school. Each child gave verbal assent. Community health workers were hired and trained in each school to assist and
be the link with the community emphasizing that participation was completely voluntary, and subjects had the opportunity to withdraw from the study at any point in the study. At the households, the head of household or an adult representative, had the study explained to them and gave signed consent before the study team entered the homestead. All data were collected on PIN protected electronic tablets, stored on password protected RedCap databases on the icipe servers. Data were analyzed after export to Excel spreadsheets without inclusion of personal identifiers. All pupils with tungiasis were referred for treatment to the community health workers or the local health facility using benzyl benzoate, chosen by the county health managers, and provided by the study. For those with secondary bacterial infection and other illnesses requiring treatment, a referral was made to the nearest health facility.

**Consent for publication**

Not applicable

**Availability of data and materials**

The datasets supporting the conclusions of this article are available in the supplementary materials associated with this manuscript.

1. Elson Pupil dataset
2. Elson Households dataset
3. Elson child cases dataset
Acknowledgements

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References


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34. Aballa A. Morbidity, Risk Factors, and Flea Species Responsible for Tungiasis in Selected Villages in Kisumu County, Kenya 2015.
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<th>Infection status</th>
<th>N(^a)</th>
<th>Actual % infected</th>
<th>95% CI</th>
<th>OR(^b)</th>
<th>95% CI</th>
<th>P</th>
<th>AOR(^c)</th>
<th>95% CI</th>
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<td>&gt;60</td>
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<td>48.7</td>
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<td>40.8</td>
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<td>1.0</td>
<td>1.02</td>
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### Table 3: Intensity of Infection of all cases (n=633)

<table>
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<th>Intensity score</th>
<th>Region</th>
<th>N&lt;sup&gt;a&lt;/sup&gt;</th>
<th>IQR&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Bivariable</th>
<th>Multivariable</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>median</td>
<td>25%</td>
<td>75%</td>
<td>IRR&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Region</td>
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<td>14</td>
<td>6</td>
<td>32</td>
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<tr>
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<td>Siaya</td>
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<td>10</td>
<td>3</td>
<td>23</td>
</tr>
<tr>
<td>Sex</td>
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<td>203</td>
<td>10</td>
<td>4</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>430</td>
<td>14</td>
<td>6</td>
<td>29</td>
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<td>Survey round</td>
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<td>272</td>
<td>18</td>
<td>9</td>
<td>38</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>42</td>
<td>7</td>
<td>2</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>319</td>
<td>10</td>
<td>4</td>
<td>20</td>
</tr>
<tr>
<td>Rainfall cm same month</td>
<td></td>
<td>633</td>
<td>13</td>
<td>5</td>
<td>28</td>
</tr>
<tr>
<td>Rainfall cm previous 2 months&lt;sup&gt;e&lt;/sup&gt;</td>
<td></td>
<td>633</td>
<td>13</td>
<td>5</td>
<td>28</td>
</tr>
</tbody>
</table>

<sup>a</sup> N: number of individuals. <sup>b</sup> IQR: interquartile range <sup>c</sup> IRR: incidence rate ratio <sup>d</sup> AIRR: adjusted incidence rate ratio

<sup>e</sup> Average rainfall for the two months prior to the month a household was visited. Rainfall unit in cm for ease of interpretation, converted from mm by dividing rainfall in mm by 10.
Figure 1

Map of the study sites to show the location in Kenya, schools and catchment areas by survey round and the prevalence of tungiasis in the schools during round 1 & 3 (squares and triangles respectively). Prevalence is not indicated for round 2 catchment areas surveyed during COVID-19 restrictions (blue circles).
Figure 2

Infrared thermography of an infected foot showing four sites (toes) with inflammation associated with embedded fleas. Infra-red image with rainbow transformation (A). Normal photograph of the same foot (B). White arrows indicate embedded live fleas. White arrows indicate sites with hotspots (white) associated with embedded live fleas.
Figure 3

Flow diagram describing selection of participant groups. Orange boxes represent people infected with tungiasis, green boxes represent people who were not infected.
Figure 4

Proportion of household population infected by month and the monthly rainfall in Kwale (KW) and Siaya (SI).
Figure 5

Scatter plot of school prevalence and median infection intensity score. Each dot represents one school. Dashed blue line represents the linear regression line with the intercept set at 0, its coefficient and $R^2$ stated for all schools.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- ElsonHouseholddataset.xlsx
- ElsonPupildataset.xlsx
- ElsonchildCASESdataset.xlsx