Mycobacterium ulcerans low infectious dose and atypical mechanical transmission support insect bites and puncturing injuries in the spread of Buruli ulcer.

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Abstract

Addressing the transmission enigma of the neglected disease Buruli ulcer (BU) is a World Health Organization priority. In Australia, we have been building a hierarchy of evidence implicating mosquitoes in transmission. Here we tested a contaminated skin model of BU transmission by dipping the tails from healthy mice in cultures of the causative agent, *Mycobacterium ulcerans*. Tails were exposed to mosquito blood feeding or punctured with sterile needles. Two of 11 of mice with *M. ulcerans* contaminated tails exposed to feeding mosquitoes developed BU. Eighteen of 20 mice subjected to contaminated tail needle puncture across developed BU. Mouse tails coated only in bacteria did not develop disease. We observed a low infectious dose-50 of four colony-forming units and a median incubation time of 12 weeks, overlapping data from human infections. We have uncovered a highly efficient and biologically plausible atypical transmission mode of BU via natural or anthropogenic skin punctures.

Introduction

Among the 17 neglected tropical diseases the World Health Organization (WHO) has targeted for control and elimination, only Leprosy and Buruli ulcer (BU) have unknown modes of transmission (1). The search to understand how humans contract BU spans more than 70 years since the causative agent, *Mycobacterium ulcerans*, was first identified (2). There are persistent and emerging foci of BU cases across the world, in particular Africa and Australia (3). BU is characterized by necrotizing skin lesions, caused by localized proliferation of *M. ulcerans* in subcutaneous tissue. BU is rarely fatal, but untreated infections leave patients with significant disfigurement and disability, with damaging personal and economic consequences (4, 5). Researchers have long been struck by the characteristic epidemiology of BU, with cases occurring in highly geographically circumscribed regions (sometimes less than a few square kilometres) and risk factors for infection that include gardening, insect bites and proximity to (but not necessarily contact with) lacustrine/riverine regions (6-14). Human-to-human spread is considered unlikely (14). Disease transmission is thought to occur by contact with an environment contaminated with *M. ulcerans* but exactly where the pathogen resides and why it appears so geographically restricted have yet to be determined. (15).

M. ulcerans is very slow growing (doubling time >48 hrs) and this poses a problem for source tracking efforts as it is difficult to isolate the bacteria in pure culture from complex environmental specimens (16). *M. ulcerans* has only once been isolated from a non-clinical source, an aquatic water bug (Gerridae) from Benin, West Africa (16). Quantitative PCR targeting *M. ulcerans*-specific DNA is the most frequently used technique in surveys of environmental specimens. A comprehensive review of the many field and lab studies that have examined reservoir and transmission of BU has highlighted the range of organisms from aquatic insects, fish, amphibia, and in Australia certain native marsupials that can serve as potential reservoirs for *M. ulcerans* (15, 17). Since the first observation that biting aquatic insects can harbour *M. ulcerans* (18), studies of BU transmission have largely focused on the potential for insects to biologically vector *M. ulcerans* implying that *M. ulcerans* undergoes a propagative or reproductive mode of development in an insect (19-23). Several case-control studies, including from both Australia and Africa have suggested insects may play a

role in transmission (10, 11). However, there is no compelling experimental evidence for single-mode biological transmission of *M. ulcerans* via insect vectors.

In southeastern Australia we noted Buruli lesions on exposed areas likely to attract biting insects, some patients with every brief exposure times to endemic areas (24, 25) and 2004 we began a study that identified *M. ulcerans* DNA associated with mosquitoes captured in endemic areas (19). Here, we provide laboratory evidence for atypical mechanical transmission of *M. ulcerans* to add to a hierarchy of evidence we have now assembled by formally addressing the Barnett Criteria (26). These are the vector ecology equivalent of Koch's Postulates and are established stringent criteria used for indicting living and non-living vectors of pathogens (15). Reworded for Buruli ulcer, these criteria state: (i) an insect vector must acquire *M. ulcerans* from a reservoir host and become infected or contaminated, (ii) an insect vector must have close association with infected animals (including humans), (iii) an insect vector collected from a Buruli ulcer endemic area must be repeatedly found with *M. ulcerans*, (iv) transmission must be experimentally demonstrated. Previously we performed a case-control study (49 cases and 609 controls), with the main findings that infection risk was increased with frequent mosquito bites (odds ratio 2.6, 95% c.i. 1.2-5.5) and reduced by use of insect repellent (odds ratio 0.4, 95% c.i. 0.2 – 0.7) (11). Then, between 2004 and 2006 we trapped 11,504 mosquitoes and detected *M. ulcerans* in 4.28/1000 individual mosquitoes (95% c.i. 3.2 – 5.6/1000) (19). We next established that there was a consistent positive correlation between annual notifications of Ross River virus (known to be transmitted by mosquitoes) and Buruli ulcer cases in Victoria, suggesting that the year-to-year variation in incidence of these different diseases is influenced by the same environmental conditions (27). We also used genotyping to show *M. ulcerans* detected in mosquitoes was indistinguishable from *M. ulcerans* infecting humans (28). Finally, we continued to test mosquitoes and accumulated data from 41,797 mosquitoes across seven locations to reveal a strong dose-response relationship between risk of Buruli ulcer and the proportion of positive mosquitoes (20). We thus satisfied criteria (i), (ii) and (iii) and here we describe experiments to address criterion (iv), to provide the laboratory evidence that *M. ulcerans* can be transmitted to a mammalian host by biting.

We have established two laboratory models of BU transmission and show for the first time a highly efficient atypical mode of mechanical transmission of *M. ulcerans* to a mammalian host that implicates both biting insects and puncturing injuries.

Materials and Methods

Bacterial isolates and culture conditions

M. ulcerans strain JKD8049 was cultured in 7H9 broth or Middlebrook 7H10 agar, containing 10% oleic-albumin-dextrose-catalase growth supplement (Middlebrook, Becton Dickinson, Sparks, MD, USA) and 0.5% glycerol (v/v) at 30°C. Colony counts from bacterial cultures or tissue specimens were performed using spot plating. Five x 3µl volumes of serial 10-fold dilutions (10^{-1} to 10^{-5}) of a culture or tissue preparation were spotted onto 7H10 agar plates with a 5x5 grid marked. The spots were allowed to dry, the plates loosely wrapped in plastic bags and then incubated as above for 10 weeks before counting colonies. Data analysis was performed using GraphPad Prism (v 6.0). All culture extracts were screened by LC-MS for the presence of mycolactones as previously described to ensure bacteria used in transmission experiments remained fully virulent (29).

Experimental animals

The animal ethics committee (AEC) of the University of Melbourne approved all animal experiments under approval number AEC: 1312775.2. BALB/c mice were purchased from ARC (Canning Vale, Australia) and housed in individual ventilated cages. Upon arrival, animals were acclimatizing for 5 days. Food and water were given *ad libitum.*

Aedes notoscriptus and Aedes aegypti rearing. Wild caught mosquitoes were sourced from around Cairns, Queensland, Australia. *A. notoscriptus* and *A. aegypti* colonies were reared in a Physical Containment Level 2 (PC2) laboratory environment at 26±1°C using previously described methods, with the addition of brown

paper used as the oviposition substrate for *A. notoscriptus* (30).

Mosquito-mouse transmission experiments

Two infection models were established as summarized in Fig. 1. In model-1 (Fig. 1A), 4-week old female BALB/c mice were anaesthetized and their tails coated in a thin film of *M. ulcerans* by dipping the tails in a Petri dish containing 20mL of bacterial culture (concentration ~10^6 CFU/mL). The tail only was then exposed to a 200mm x 200mm x 200mm cage containing 20 adult, female mosquitoes for a period of 15 minutes. The number of insects biting each mouse was recorded over the exposure period by continuous observation. Mice were then observed weekly for up to six months for signs of tail lesions. Sterile needle stick (25G or 30G needle) and no-trauma were used as controls. An additional control consisted of tails dipped in sterile culture broth only and subjected to mosquito biting or sterile needle stick. In model-2 (Fig. 1B), 180 adult female *A. notoscriptus* mosquitoes were fed for 48h via a 4 x 5 cm sponge saturated with a 0.5% sucrose solution (w/v) containing ~10^5 CFU/mL *M. ulcerans*. The solution was withdrawn and 24h later the mosquitoes were allowed to bite and feed to repletion for the same 15-minute exposure period, with each bite recorded.

Real time quantitative PCR. For each mosquito that blood-fed under transmission model-1 and for every mosquito exposed to the mice under transmission model-2, DNA was individually extracted from the dissected head, abdomen and legs of each insect using the Mo Bio Powersoil DNA extraction kit following manufacturer's instructions (Mo Bio Laboratories Inc., Carlsbad CA USA). DNA was similarly extracted from mouse tissue. Procedural extraction control blanks (sterile water) were included at a frequency of 10% to monitor potential PCR contamination, in addition to no-template negative controls. IS*2404* quantitative PCR (qPCR) was performed as described (31). IS*2404* cycle threshold (Ct) values were converted to genome equivalents (GE) to estimate bacterial load within a sample by reference to a standard curve (r^2=0.9312, y=[-3.000Ln(x)+39.33]*Z, where y=Ct and x=amount of DNA [fg] and Z=the dilution factor]), calculated using dilutions of genomic DNA from *M. ulcerans* strain JKD8049, quantified using fluorimetry (Qubit,

Invitrogen) (31).

Preparation of mouse tissue for analysis. At the end of the experimental period or when a clinical end-point was reached mice were humanely killed. The region of a mouse-tail spanning a likely lesion was cut into three equal sections for histology, qPCR and CFU counts. Individual tail pieces for CFU counts were weighed and placed into sterile 2ml screw capped tube containing 0.5g of 0.1mm glass beads and 600µl of sterile 1x PBS. Tissues were homogenized using four rounds of 2 x 30second pulses in a high-speed tissue-disruptor at 6500 rpm, with tubes placed on ice for 5 minutes between each round. A 300µl volume of this homogenate was decontaminated with 300µl of 2% NaOH (v/v) and incubated at room temperature for 15 minutes. The preparation was neutralized drop-wise with a 10% solution of orthophosphoric acid (v/v) with added bromophenol blue until the solution changed from blue to clear. The mixtures were diluted in PBS and CFUs determined by spot plating as described above.

Histology. Sections of mouse-tails were fixed in 10% (w/v) neutral-buffered-formalin and imbedded in paraffin. Each mouse-tail was sectioned transversely (four micron thickness) and subjected to Ziehl-Neelson and hematoxylin/eosin staining. The fixed and stained tissue sections were examined by light microscopy.

Infectious Dose. To estimate the infectious dose we measured the surface area of five dissected mouse-tails to obtain an average surface area (493.3 ± 41.1 mm^2). Using ten mouse-tails, we then calculated the average volume of *M. ulcerans* 7H9 Middlebrook culture adhering to the tail surface (32.4 ± 4.2 mL), the concentration of bacteria in the cultures used, and the surface area of the tips of 25G and 30G needles used to deliver the puncture wounds (0.207 mm^2 and 0.056 mm^2, respectively). These parameters were then used to calculate the infectious dose, assuming the bacteria were evenly distributed over the tail surface (Fig. 1C). A standard curve was interpolated using non-linear regression and an ID_{50} estimated using GraphPad Prism (v 7.0a).

Results

M. ulcerans is efficiently transmitted to a mammalian host by an atypical mechanical means.

We established a murine model of *M. ulcerans* transmission (model-1) that represented a skin surface contaminated with the bacteria and then subjected to a minor penetrating trauma, via either a mosquito bite or needle stick puncture. In our first experiment, two of six mice with their tails coated with *M. ulcerans* and then bitten by mosquitoes developed lesions (Table 1, Fig. 1C, Fig. 2A). Histology of these lesions confirmed a subcutaneous focus of AFB, within a zone of necrotic tissue. There was also characteristic epithelial hyperplasia adjacent to the site of infection (Fig. 2B,C). Material extracted from the lesions was IS*2404* qPCR-positive and culture positive for *M. ulcerans* (Supplementary Table S1). Mice bitten by mosquitoes but with tails coated only with sterile culture media did not develop lesions (Table 1). In the same experiment, we also subjected five mice to a single needle stick puncture. Each mouse had their tail coated with *M. ulcerans* as for the mosquito biting. Four of these five mice developed *M. ulcerans* positive lesions (Table 1, Fig. 2D), with subcutaneous foci of infection and viable bacteria (Fig. 2F). Six mice with their tails coated with *M. ulcerans* but not subjected to a puncturing injury did not develop lesions and remained healthy until the completion of the experiment at six months. This experiment suggested that minor penetrating skin trauma (defined here as a puncture <0.5mm diameter and <2mm deep) to a skin surface contaminated with *M. ulcerans* is sufficient to cause infection. It also revealed a means by which mosquitoes could act as atypical mechanical vectors of *M. ulcerans*.

M. ulcerans burden on mosquitoes correlates with transmission.

Then, using approximately the same dose of bacteria to coat the mouse-tails, we repeated experiment-1 but with *Aedes aegypti* because of the close association of this mosquito to humans world-wide and their vector competency for viral pathogens. Despite more mosquito bites per mouse than the first experiment, none of the five insect-exposed mice developed lesions (Table 1). In contrast however, four of five mice subjected to single, needle stick puncture developed *M. ulcerans* positive tail lesions (Table 1). We then conducted a third transmission experiment, but this time using mosquitoes (*Aedes notoscriptus*) in pools of 20 that had been

189 previously contaminated with the bacteria via a sugar meal solution and then allowed to bite the tails of naïve
190 mice. None of five mice exposed to mosquitoes developed tail lesions, despite repeated bites. Again, three of
191 three positive control mice with tails coated in *M. ulcerans* developed positive lesions after needle stick
192 puncture (Table 1). We assessed the burden of *M. ulcerans* by individual IS2404 qPCR of the head, abdomen
193 and legs for each mosquito that blood fed (Fig. 3). A summary of these results is shown in Fig. 3A. We noted
194 that the bacterial load (expressed as genome equivalents [GE]) was significantly higher in the heads of
195 mosquitoes associated with mice that developed lesions ($p<0.05$) (Fig. 3B). While *M. ulcerans* were present
196 on the head, abdomen and legs of mosquitoes fed an *M. ulcerans*-contaminated sugar solution, the bacterial
197 load on these insects was low (transmission model-2) (Fig. 3, Supplementary Table S2). These data point to a
198 threshold, above which mosquitoes can become competent mechanical vectors for *M. ulcerans* transmission.
199
200 *Estimation of incubation period and infectious dose of transmission model-1*
201 Based on the time until a tail lesion was first observed, we estimated a median incubation period (IP) of 12
202 weeks (Fig. 4A). This result overlaps with the IP in humans for BU, estimated in different epidemiological
203 studies from 4-10 weeks in Uganda during the 1960s (14) and 4 - 37 weeks in south east Australia (25). We
204 also estimated the infectious dose$_{50}$ (ID_{50}). We conducted a fourth experiment, using two doses of *M.*
205 *ulcerans* to coat the tails of mice, followed by needle stick puncture (Table 1). Seven of seven mice receiving
206 the higher dose and two of three mice receiving the lower dose developed *M. ulcerans* lesions (Table 1).
207 Thus across the four experiments at the maximum dose 18 of 20 mice developed lesions when subjected to
208 needle stick puncture through *M. ulcerans* contaminated skin. The data from all needle stick exposure
209 experiments were combined and we estimated an ID_{50} of 4 CFU (Fig. 4B). This assessment was based on
210 measurements of the surface area of the mouse-tail, the volume of bacterial culture adhering to the tail and
211 the diameter of the needle used in each experiment. To our knowledge this is the first estimate of an *M.*
212 *ulcerans* infectious dose and indicates that a surprisingly small quantity of this slow growing mycobacterium
213 is sufficient to cause disease in this model.
214

Discussion

This research was designed around established frameworks for implicating vectors in disease transmission and provides the necessary causational evidence to substantially resolve the 80-year mystery on how *M. ulcerans* is spread to people (15, 26, 32). We have assessed two different models of mechanical rather than biological transmission of BU under controlled laboratory conditions. We show that *M. ulcerans* can be efficiently transmitted to a susceptible mammalian host at a low infectious dose, via puncturing injuries involving an anthropogenic pathway (needle stick) or a natural pathway (mosquito bite).

The efficient establishment of BU we have shown here via minor penetrating trauma through a contaminated skin surface is an atypical form of mechanical transmission *sensu lato* (*s.l.)* but it nonetheless satisfactorily fulfills the Barnett Criteria. In vector ecology, mechanical transmission, *sensu strictu* (*s.s.*), is defined as a non-circulative process involving accidental transport of the pathogen. That is, the pathogen, in some fashion, nonspecifically associates or contaminates the mouthparts (stylet) of an arthropod vector. This stylet-borne theory suggests that the vector physically transmits or moves the pathogen from one host and inoculates another (33, 34). Mechanical transmission is often described as a 'flying pin' method of transmission and implies that mosquito vectors serve as an inoculating needle or pin, as we observed in this study (35). There is laboratory evidence for this mode of transmission, with pins used to inoculate baby chicks with the Eastern Equine Encephalitis virus (36). Insect mechanical transmission *s.s.* of BU implies that if *M. ulcerans* were ingested and then egested via regurgitation or salivation, the mechanism would act more like a syringe than a needle (33, 37). Such a mode of *M. ulcerans* disease transmission was supported through laboratory studies in which *Naucoris* and Belostmatid water bugs were contaminated via feeding on maggot prey that had been injected with *M. ulcerans* or fed naturally on dietary contaminated larval mosquito prey (21-23, 38). Whilst one of these reports said there was replication of the bacteria within the insect vector, suggesting biological transmission, infection spread in this model could also be explained by mouthparts of the water bugs remaining contaminated and then subsequently inoculating mice during blood feeding [(23)].

241

242 Adult mosquitoes generally acquire some form of carbohydrate or sugar meal from floral nectars for
243 necessary energy to feed and reproduce (39). To investigate this aspect of mechanical transmission *s.s.*, we
244 infected a sugar meal solution with *M. ulcerans* for adult mosquitoes to feed upon and later exposed these
245 mosquitoes to naïve mice without any tail surface contamination (experiment 3). While mosquitoes readily
246 fed on this solution and later fed on mouse tails, we found no ulcers after five months of observation (Table
247 1). The lack of ulcer development may have been to due insufficient concentration of *M. ulcerans* used in the
248 sugar solution or the inability of mosquitoes to act as mechanical vectors *s.s.* of *M. ulcerans* under these
249 laboratory conditions.

250

251 Our demonstration of mechanical transmission *s.l* implies there are potentially multiple or parallel
252 pathways of *M. ulcerans* infection (26). Examples of bacterial diseases with multiple transmission modes
253 include tularemia, plague and trachoma (40, 41). Support for our mechanical transmission *s.l.* model also
254 comes from the many field reports over the decades of *M. ulcerans* infection following trauma to the skin.
255 Case reports have noted BU following a suite of penetrating injuries ranging from insect bites (ants,
256 scorpions), snake bite, human bite, splinters, gunshot, hypodermic injections of medication and vaccinations
257 (42-45). Epidemiologists in Uganda during the 1960s and 70s suggested sharp-edged grasses might introduce
258 the bacteria (46). However a recent laboratory study established that abrasions of the skin in Guinea pig
259 models and subsequent application of *M. ulcerans* was not enough to cause an ulcer, however, this same
260 study established that a subcutaneous injection would cause an ulcer (47). As a sequel to this study in Guinea
261 pigs, we raised the question of how likely it was that human skin could be sufficiently coated in *M. ulcerans*
262 that an injury from natural or anthropogenic sources could lead to infection. Other explanations for the
263 transmission of *M. ulcerans* include linkages with human behavior that increase direct contact with human
264 skin and contaminated water (15). A recent study from Cameroon recorded the persistence of *M. ulcerans*
265 over a 24-month period in a waterhole used by villagers (including BU patients) for bathing (48). A scenario
266 could be readily envisaged where a villager's skin surface becomes contaminated after bathing in such a

water body and is primed for infection if (i) the concentration of bacteria is sufficiently high, and (ii) an inoculating event occurs. Whereas, in Australia, earlier studies have shown that *M. ulcerans* contamination of possum feces in and around the gardens of BU patients might present a similar skin surface contamination model in this region (17, 49). Our needle stick experiments support this non-arthropod-borne trauma to the skin surface via an anthropogenic method, as suggested more than 40 years ago (45, 46). Future experiments will address the possibility that insect vectors may be able to move *M. ulcerans* from one source and inject it into an animal (including humans).

The research presented here has been driven by our observations in southeastern Australia, where we've implicated mosquitoes in transmission (19, 20, 27, 28, 50). However, a recent study in Benin, West Africa found no evidence of *M. ulcerans* in association with adult mosquitoes (51). The authors concluded that the mode of transmission might differ between southeastern Australia and Africa. Although, laboratory and fieldwork in West Africa suggest that aquatic insects, including mosquito larvae, play a role as reservoirs in nature for *M. ulcerans* that may be indirectly tied to transmission by serving as dispersal mechanisms (18, 23, 52). The contaminated skin model provides a rational but non-exclusive explanation for BU transmission in parts of the world, such as rural parts of West Africa where BU is prevalent, and access to clean water for bathing, drinking, and other hygienic purposes can be limited. However, epidemiological studies have shown that direct contact with water is not a universal risk factor for BU (8, 11). In temperate, southeastern Australia where patients in this region have no contact with open water sources, are generally older and are unlikely to have regular exposure to biofilms where skin contamination may occur. Our focus on mechanical mosquito transmission *s.s.* arose from previous surveys in southeastern Australia where a strong association between *M. ulcerans* positive mosquitoes and human cases of BU has shown that *M. ulcerans* has not only been found on adult mosquitoes from both lab and field studies but also a biological gradient, where maximum likelihood estimates (MLE) of the proportion of *M. ulcerans*-positive mosquitoes increased as the number of cases of BU increased (19, 27, 28, 38, 50, 53).

Case-controls studies in the region have also shown that prior exposure to insect bites and gardening are

independent risk factors for developing BU, while use of insect repellent is protective (11, 54). Laboratory support to show mosquitoes can be competent vectors to spread BU was the final piece of evidence required to satisfy accepted vector ecology criteria (15, 26). We found that infection was established following very minor penetrating trauma. *Aedes notoscriptus* mosquitoes feed by insertion of a stylet, sheathed within the proboscis, beneath the skin of a host. The stylet has a diameter around 10 μM tapering to 1 μM at its tip and extending 1-2 mm below the skin surface. We estimated the density of *M. ulcerans* on the mouse-tails surface was 100-200 CFU/mm^2. Thus the amount of bacteria potentially injected during mosquito feeding through this contaminated surface is likely to be low. Our infectious dose estimates from needle-stick punctures suggested an ID_{50} of 4 CFU (Fig. 4B). There are strong parallels here with *M. leprae*, the agent of leprosy. Like BU, the mode of transmission of the leprosy bacillus is unclear, but the infectious dose is known to be very low (10 bacteria) and epidemiological evidence suggests multiple transmission pathways, including entry of the bacteria after skin trauma (55, 56).

The failure of Aedes aegypti to successfully transmit M. ulcerans in experiment 2 might be explained by either vector competency variations or simple morphological/physiological differences such as proboscis length or blood meal feeding time among different mosquito taxa (34, 35). We coated the mouse-tails in this experiment with an equivalent amount of *M. ulcerans* as experiment 1. A mosquito proboscis should have contacted (on average) the same density of bacteria at the tail surface during blood feeding. The needle-stick controls showed effective inoculation of the mice (Table 1). Our follow-up on the blood-fed mosquitoes bacterial load was revealing and showed that *A. aegypti* (experiment 2) carried significantly less *M. ulcerans* post-biting compared to *A. notoscriptus* (experiment 1) (Fig. 3). Whether this was a chance event or is a physiological characteristic of the different *Aedes* species or their feeding behaviours remains to be investigated, but clearly, if insufficient bacteria adhere to the insect during feeding then transmission is unlikely to occur.

In southeastern Australia, but so far not elsewhere, outbreaks of BU in humans are closely associated

with the presence of native animals (17, 49) that appear to act as reservoirs of *M. ulcerans*. Hence an attractive hypothesis is that mosquitoes passively shuttle *M. ulcerans* from possums with active Buruli lesions to humans living nearby (17). Based on clinical observations of lesion location, local clinicians have proposed mosquito transmission may be the major mode of transmission, although we have not so far been able to demonstrate this experimentally. We recognize that no similar animal reservoir has yet been identified in Africa and that multiple modes of transmission via other methods of inoculation, either by trauma or other types of biting insect if MU is already present on the skin is likely and is strongly supported by our results.

In summary, we have uncovered a highly efficient and biologically plausible atypical transmission mode of *M. ulcerans* infection via natural or anthropogenic skin punctures. Reduction of exposure to insect bites, access to clean water for bathing, and prompt treatment of existing BU are concrete measures likely to interrupt BU transmission.

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Table 1: Summary of transmission experiments

Trauma source	Number of mice	Mouse tail coated	Number of mice bitten	Number of mice developing BU	Estimated dose (CFU)
Experiment 1: (Atypical mechanical transmission model, contaminated skin surface)					
Aedes notoscriptus	12 (4/mosquito cage)*	*M. ulcerans* (4.1×10^6 CFU/mL)	6	2 (#182, #191)	21
Aedes notoscriptus	4 (1/mosquito cage)	Media-only	2	0	-
Sterile needle (25G)	5	*M. ulcerans* (4.1×10^6 CFU/mL)	-	4 (#186, #200, #201, #202)	55
None	6	*M. ulcerans* (4.1×10^6 CFU/mL)	-	0	-
Experiment 2: (Atypical mechanical transmission model, contaminated skin surface)					
Aedes aegypti	5 (1/mosquito cage)	*M. ulcerans* (1.83×10^6 CFU/mL)	5#	0	9
Aedes aegypti	3 (1/mosquito cage)	Media-only	2	0	-
Sterile needle (25G)	5	*M. ulcerans* (1.83×10^6 CFU/mL)	-	4 (#216, #217, #218, #219)	40

None	5	*M. ulcerans* (1.83×10^6 CFU/mL)	-	0	-
Experiment 3: (Mechanical transmission model *sensu strictu* with adult mosquitoes passively fed *M. ulcerans*)					
Aedes notoscriptus	5		5	0	< 48 GE[§]
Sterile needle (30G)	3	*M. ulcerans* (3.9×10^6 CFU/mL)	-	3	14
None	3	*M. ulcerans* (3.9×10^6 CFU/mL)	-	0	-
Experiment 4: (Atypical mechanical transmission, contaminated skin surface model)					
Sterile needle (25G)	7	*M. ulcerans* (3.7×10^6 CFU/mL)	-	7	49
Sterile needle (25G)	3	*M. ulcerans* (3.7×10^5 CFU/mL)	-	2	5
None	5	*M. ulcerans* (3.7×10^6 CFU/mL)	-	0	-

Notes: [*]20 adult female mosquitoes per cage; [#]Multiple bites per mouse with 2 mice receiving 3 bites and 1 mouse receiving 2 bites; [§] "GE" is *M. ulcerans* genome equivalents as estimate based on IS2404 qPCR.

Fig. 1

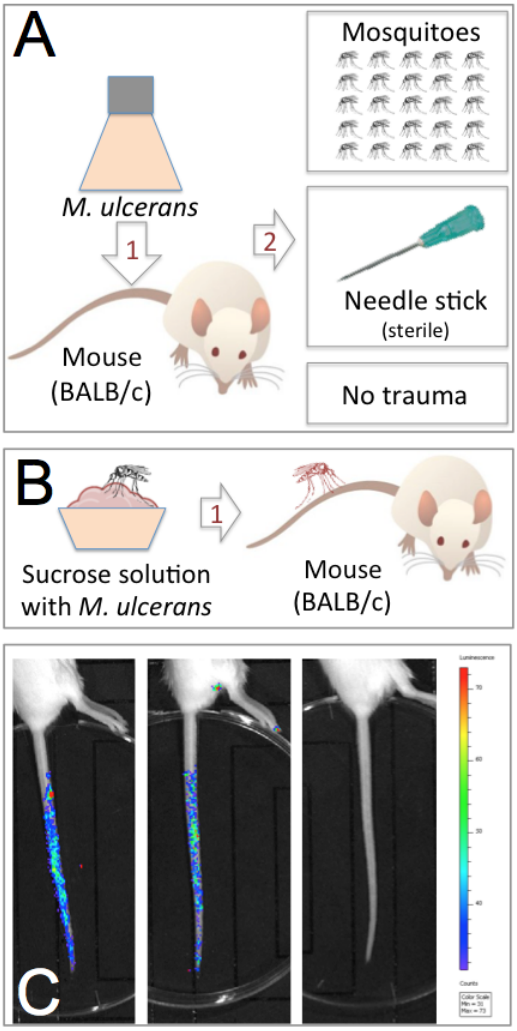

Fig.1: Schematic representations of the two BU transmission models tested in this study. (A) Model-1 tests transmission of *M. ulcerans* present on a skin surface following a puncturing injury created by mosquito blood-feeding or needle stick. (B) Model-2 tests transmission of *M. ulcerans* acquired by mosquitoes from a contaminated sugar feed solution. (C) Visualization of bioluminescent *M. ulcerans* JKD8049 (harbouring plasmid pMV306 *hsp*:*lux*G13) (57, 58) on the mouse-tail in model-1, showing the distribution of bacteria immediately after coating for two mice, versus an uncoated animal. *M. ulcerans* concentration was 10^6 CFU/mL.

Fig. 2

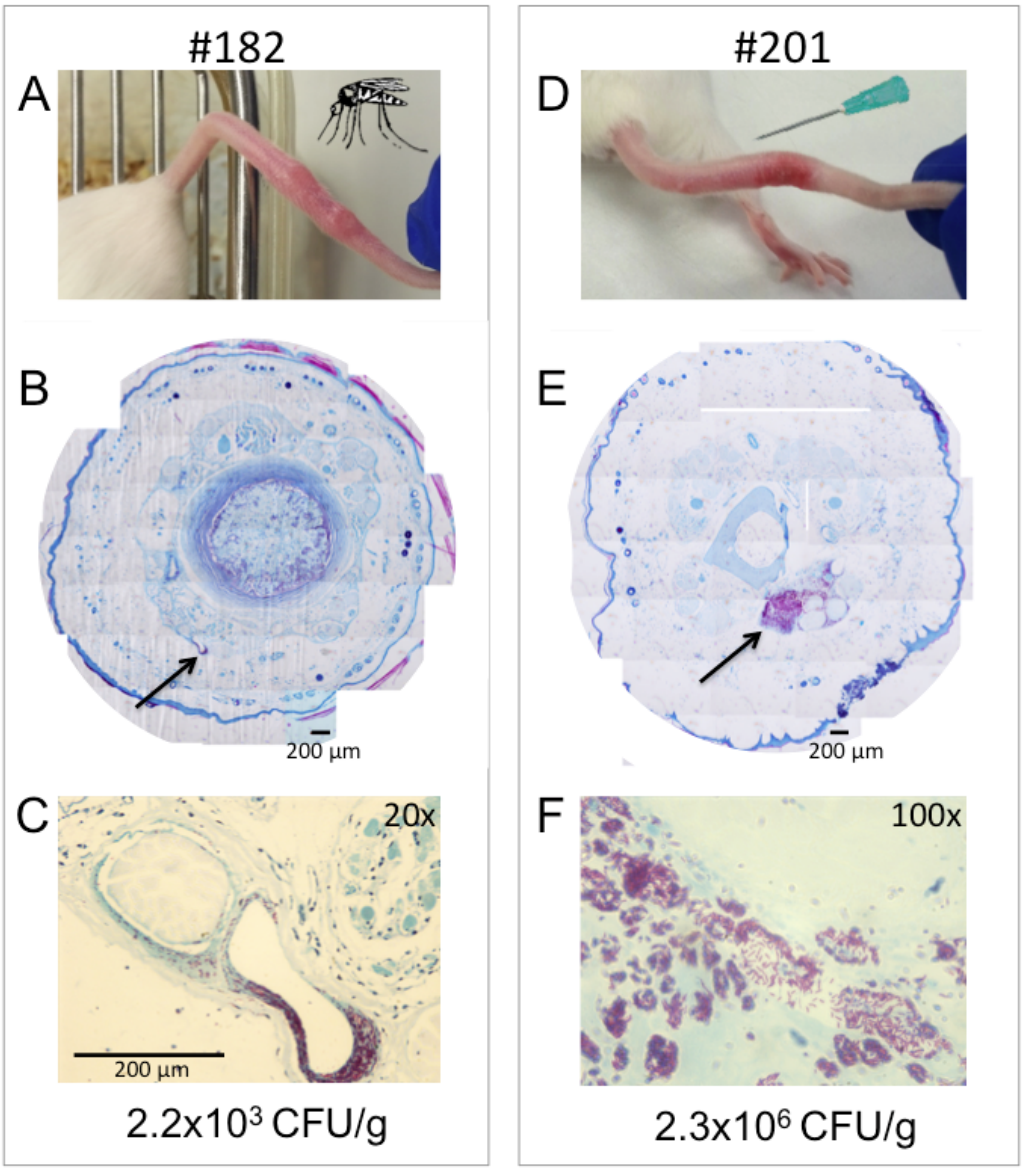

Fig. 2: Atypical mechanical transmission of *M. ulcerans*. (A) An example of the development of Buruli ulcer following mosquito blood-feeding through a skin surface (mouse-tail) contaminated with *M. ulcerans*. (B) Composite histological cross-section with Ziehl–Neelsen staining through the infected tail showing the focus of AFB bacteria (arrow) within the subcutaneous tissue. (C) Higher magnification view of the focus of infection, with the yield of viable M. ulcerans obtained from the infected tissue. Panels (D) – (F) show the same analyses as for the mosquito-bitten mouse #182, but for a mouse developing a lesion following sterile needle-stick puncture through a contaminated skin surface (mouse #201).

Fig. 3

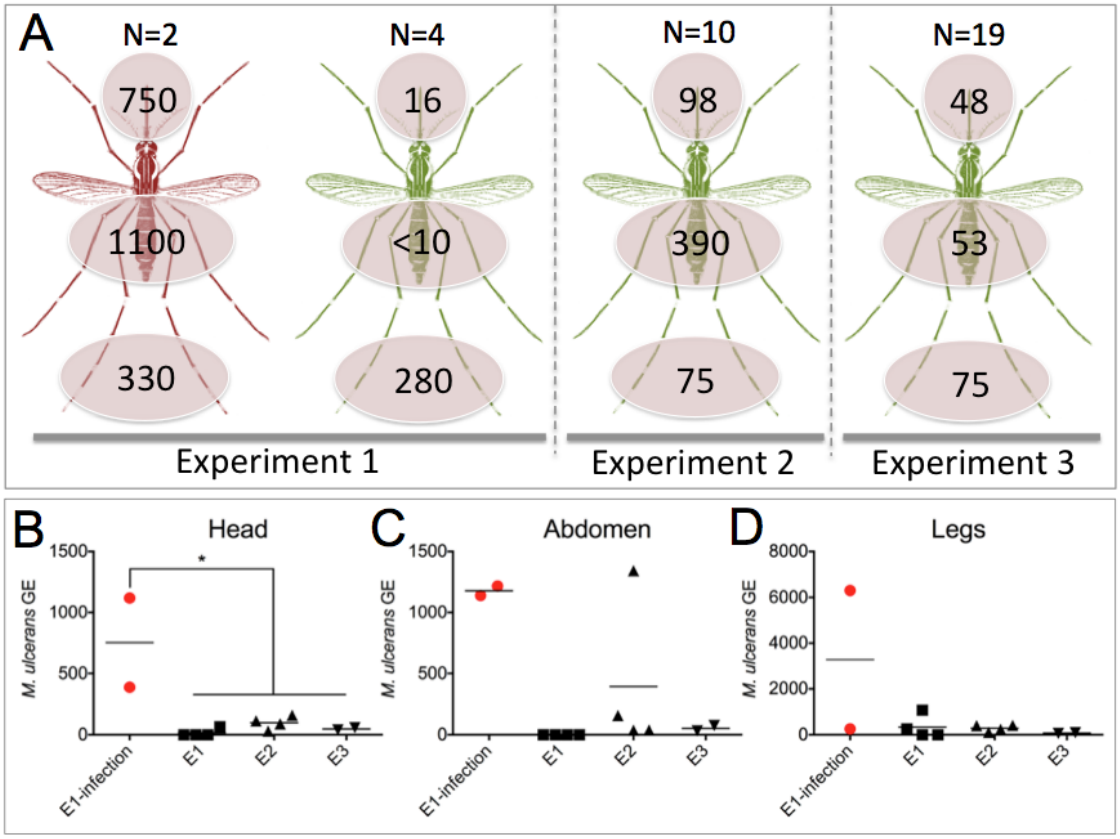

Fig. 3: Summary of *M. ulcerans* burden on mosquitoes post-feeding under two models of transmission. (A) Visualization of the mean number of *M. ulcerans* detected per dissected mosquito segment, as assessed by IS*2404* qPCR and expressed as genome equivalents (GE), for model-1 (experiments 1 and 2) and model-2 (experiment 3). 'N' indicates the total number of mosquitoes tested. Red-shaded mosquitoes transmitted *M. ulcerans*, leading to mouse tail lesions. Green-shaded mosquitoes blood-fed on mouse tails but lesions did not develop. (B, C, D) Plots of the individual qPCR results for each mosquito segment, listed by experiment. Red dots correspond to qPCR bacterial load for mosquitoes that transmitted *M. ulcerans* infection. Null hypothesis (no difference in bacterial load) was rejected ($p<0.05$)* (unpaired, two-tailed *t* test). Horizontal bar indicates the mean bacterial load per mosquito. The y-axis is GE and x-axis is experiment. The qPCR data for individual insects is contained in Supplementary Table S2.

Fig. 4

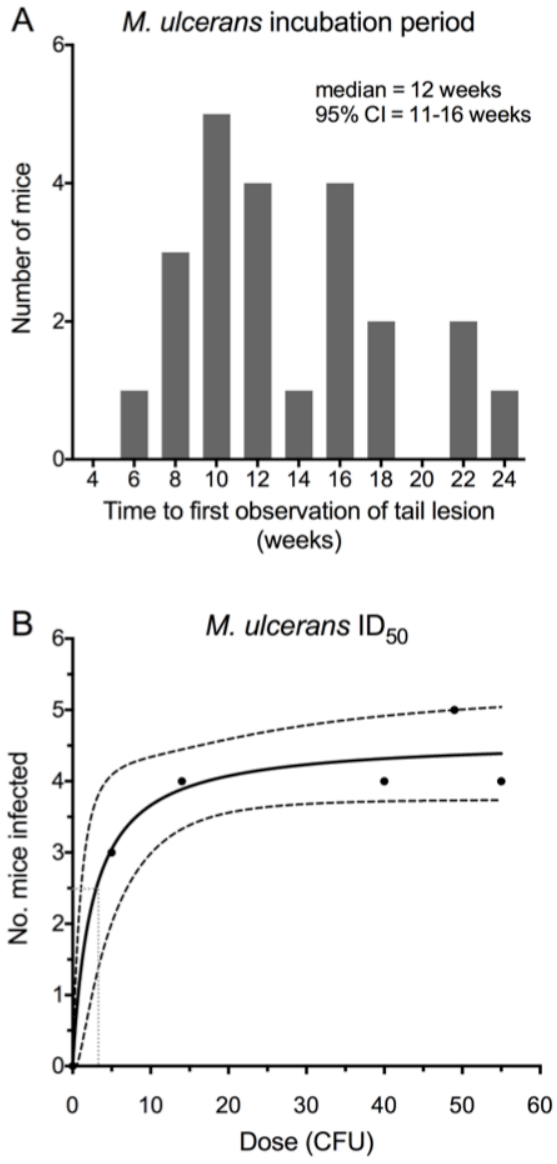

Fig.4: *M. ulcerans* incubation period and infectious dose$_{50}$. (A) Incubation period of *M. ulcerans* based on the time between sterile-needle puncture of an *M. ulcerans* contaminated mouse-tail and first observation of a lesion. (B) Estimated *M. ulcerans* ID_{50} for transmission model-1.