The Influence of Temperature on Mosquito Life History and Implications for Transmission

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Predictive models are an essential tool in mitigating vector-borne diseases.

Current control methods include:
- Indoor residual spraying (IRS)
- Insecticide treated bed-nets (ITNs)
- Larval source reduction
- Genetically modified mosquitoes

Predictive models help mitigate disease by:
- Identifying key mosquito/parasite traits to target with interventions
- Forecasting disease risk to direct limited funding
- Predicting how VBDs will alter in response to global changes

However...
- Lack of public health infrastructure
- Limited funding
- Insecticide resistance

...severely comprises the efficacy of these control measures.

However...
...these models are only as accurate as the data they are derived from.
Generating predictive models are challenging as many factors influence vector-borne disease transmission.
Temperature is a major factor in the transmission of vector-borne diseases

1. Correlated with disease distribution

Temperature suitability

Endemicity

2. Profoundly affects mosquito physiology

- Metabolism
- Rate of development
- Susceptibility
- Contact rate
- Abundance
- Vector competence

Temperature affects many traits that are involved in disease transmission.
There is limited data on how temperature affects mosquito and pathogen biology.

Thermal performance curve (TPC)

Key Features:
- Thermal optimum
- Curve shape (asymmetric)

Limitations:
- Mixed species
- Poorly characterized

These temperature-by-trait relationships have important implications for vector-borne diseases transmission

**The basic reproductive number (R₀)**

\[
M = \frac{EFD \cdot P_{EA} \cdot MDR}{\mu^2}
\]

\[
R₀ = \sqrt{\frac{Ma^2 b c e^{-\mu/PDR}}{Nr \mu}}
\]

- **M** = mosquito density
- **μ** = daily probability of mosquito mortality
- **a** = daily biting rate
- **b** = probability of mosquito infection
- **EFD** = eggs produced per female mosquito per day
- **P_{EA}** = probability of egg to adult survival
- **PDR** = parasite development rate
- **N** = human density
- **r** = human host recovery rate
- **c** = probability of human infection

R₀ is primarily comprised of mosquito-specific traits.
Previous research indicates that further characterization of specific parameters could aid in reducing uncertainty in $R_0$

$$R_0 = \frac{Ma^2bc e^{-\mu/PDR}}{Nr \mu}$$

$$M = \frac{EFD_{PEA} MDR}{\mu^2}$$

More empirical data are required for the following parameters to resolve the:

**Thermal optimum:**
- Biting rate ($\alpha$)
- Mortality rate ($\mu$)
- Eggs / female per day ($EFD$)

**Thermal extremes:**
- Parasite development rate ($PDR$)

Johnson et. al. 2015. *Ecological Society of America.*
**Study Aim:** To generate a better understanding of how temperature impacts transmission dynamics

- Characterize *Anopheles stephensi* life history traits (EFD, a, µ)
  
  ***previous studies draw on a mixed-species approach of crude data***

**Specific Aims:**

1. Are these traits affected by temperature?
2. Do these traits change over the course of a mosquitoes’ lifespan?
3. Is there an interaction between temperature and mosquito age?
4. If these traits are affected by *age* and/or *temperature*, what are the implications for the transmission?
How does Temperature & Age integrate to affect mosquito-borne disease transmission in the *Anopheles*-Malaria system?

Followed 30 individual *An. stephensi* females in each temperature treatment till death

30 individuals x 6 temperatures x 2 replicates (n = 360 total)

Daily individual measurements:
- no. of females that died per day (daily mortality probability, $\mu$)
- no. of females blood feeding per day (daily biting rate, $a$)
- no. of eggs laid per day (eggs laid per female per day, $EFD$)

*Anopheles stephensi* were reared under standard laboratory conditions: 27°C, 80% RH, and a 12hr:12hr L:D photoperiod.
The effect of temperature on mosquito traits involved in transmission

These qualitatively different thermal responses complexly integrate to affect transmission.
The effect of **age** on mosquito traits involved in transmission

**A**

*Mortality* increases with **temperature** and changes with **age**

**B**

*Biting rates* decrease with **age** at higher **temperatures**

**C**

*Fecundity* varies with **age** in relation to **temperature**
What are the implications of these temperature and age effects for transmission?

\[ R_0 = \sqrt{\frac{Ma^2bce^{-\mu/PDR}}{Nr\mu}} \quad M = \frac{EFD\rho_{EA}MDR}{\mu^2} \]

The basic reproductive number (\( R_0 \))

- \( M \) = mosquito density
- \( \mu \) = daily probability of mosquito mortality
- \( a \) = daily biting rate
- \( b \) = probability of mosquito infection
- \( EFD \) = eggs produced per female mosquito per day
- \( \rho_{EA} \) = probability of egg to adult survival
- \( PDR \) = parasite development rate
- \( N \) = human density
- \( r \) = human host recovery rate
- \( c \) = probability of human infection

Shift in thermal optimal? Shift in thermal breadth?
There are several ways we can evaluate the effects of temperature and age...

**AGE-INDEPENDENT**

*Standard*

\[
R_0(T) = \left( \frac{a(T)^2 bc(T) e^{-\mu(T)/PDR(T)} EFD(T) p_{EA}(T) MDR(T)}{Nr \mu^3(T)} \right)
\]

*Reformulated*

\[
R_0(T) = \left( \frac{a(T)^2 bc(T) e^{-1/[E(T)PDR(T)]} p_{EA}(T) MDR(T) B(T) E(T)^2}{Nr} \right)
\]

**AGE-DEPENDENT**

*Averaged Daily*

\[
R_0(T) = \left( \frac{R_0(1) + R_0(2) + R_0(3) + R_0(4) \ldots}{N} \right)
\]

As in Mordecai et. al. 2012.

Replacing the assumption that \( EFD/\mu = B \) (Lifetime egg production) with our observed data

The average of a day-specific \( R_0 \) with the measured day-specific traits \( (EFD, u, a) \)
The thermal performance curve for transmission potential is altered with the inclusion of age-specific trait performance.

\[ R_n(T) = \left( \frac{a(T)^2 bc(T) e^{-a(T)/pDR(T)} EFD(T) P_{el}(T) MDR(T)}{N r^2 (T)} \right) \]

\[ R_n(T) = \left( \frac{a(T)^2 bc(T) e^{-a(T)/pDR(T)} P_{el}(T) MDR(T) B(T) E(T)^2}{N r} \right) \]

\[ R_n(T) = \left( \frac{R_n(1) + R_n(2) + R_n(3) + R_n(4)\ldots}{N} \right) \]
**Specific Aim 1:** Characterize the thermal performance for *Anopheles stephensi* life history traits relevant to malaria transmission

*Results:*  
- Temperature strongly influences *An. stephensi* life history traits.  
- The non-linear relationship is unique to each trait.

*Implications:*  
- The thermal performance curve for each life history trait integrates to complexly affect transmission. 
- Many models rely on a mixed species approach for parameterization (lack of data). 
  - how different are these responses between mosquito species? 
- (Future) How does individual variation in trait performance vary across temperature, implications?

**Specific Aim 2:** Evaluate the effects of temperature and age on malaria transmission dynamics

*Results:*  
- The standard $R_0$ closely resembles the reformulated $R_0$. 
- The averaged daily $R_0$ and standard $R_0$ have different thermal performance curve shapes.

*Implications:*  
- Mosquito population age-structures may modify trait performance across temperatures and play an important role in transmission dynamics.

$R_0$ is a powerful tool in the application and evaluation of interventions, however if current methods fail to capture important aspects of transmission, our ability to effectively reduce vector-borne disease is hindered.
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