Refining the resistance-to-damage (RD) score to predict operational Insecticide-Treated Net lifespan and identify paths to innovation

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1 Abstract

2 **Background:** Insecticide Treated Nets (ITNs) vary greatly in their physical characteristics yet
3 the relationship with field durability remains poorly understood. To address this, we refined
4 the existing resistance-to-damage (RD) metric for greater predictive power in estimating
5 operational lifespan and to identify key avenues of innovation.

6 **Methods**: The original resistance-to-damage (oRD) score was calculated by comparing four
7 physical attributes; snag strength, bursting strength, hole enlargement resistance and
8 abrasion resistance; against aspirational values previously determined to provide resistance
9 to routine damage. Here, the weighting of each is improved to provide a better prediction of
10 field life, resulting in a weighted resistance-to-damage (wRD) score. Durability data from 37
11 field sites (across 14 countries) involving 10,000 campaign ITNs was used to quantify the
12 relationship between physical characteristics and field life. Bivariable linear regression models
13 were used to assess the correlation between RD scores and ITN survival time. A Cox regression
14 survival analysis was applied to examine the impact of the RD score on physical survival,
15 adjusting for net care and environment variables (Risk Index), evaluating the risk of ITN failure
16 from the time they were first hung.

17 **Results** The bivariate analysis, not adjusting for differences between sites, shows that the wRD
18 was a better predictor for net lifespan than oRD (wRD r^2= 0.07 oRD r^2= 0.01). In the
19 multivariate analysis, adjusting for risk index, the wRD model was able to explain more than
20 70% of variability in net survival (wRD r^2 = 0.74). Consequently, when comparing nets with
21 different wRD scores in the same site, a 10-point increase in wRD score was associated with a
22 3.9-month gain in median survival (p=0.016). Increasing wRD from 35 to 70, the range of
23 current products, increases median field life by 13.65 months (95% CI: 3.03–24.16). An ITN
24 product with an wRD score of 68 is associated with a median lifespan of 2.7 years. The increase
25 in predictive power of the wRD score came primarily from increasing the weighting of the hole
26 enlargement resistance variable, which is a strong differentiator between ITN products. In
27 contrast, abrasion-resistance was a negligible contributor to predictive power.

28 **Discussion** The wRD score more accurately predicts ITN survival in the field than the oRD
29 score. These findings highlight that resistance to hole enlargement is the primary
30 differentiating factor in predicting field life, with some products performing far better than
31 others. Snag and bursting strength remain essential characteristics yet are similarly low
32 compared to aspirational values across available ITN products. All ITNs WHO prequalified in
33 2020 perform poorly on snag strength, indicating this as a core bottleneck in achieving longer
34 operational ITN lifespan. Consequently, resistance to snagging and hole enlargement should
35 be keys targets for future innovation to enhance the physical durability of ITNs.

36 **Keywords**: Resistance-to-damage score, ITNs, bed net, durability, operational lifespan,
37 mosquitoes, malaria, sub-Saharan Africa

1   Background

2   Insecticide Treated Nets (ITNs) are a core component of malaria vector control, presenting a
3   physical and chemical barrier against the bites of *Anopheles* mosquitoes [1]. ITNs are
4   proposed to be designed to be physically resistant against day-to-day use in the domestic
5   environment, historically being expected to provide three years of operational lifespan [2].
6   National Malaria Programmes commonly distribute ITNs via mass distribution campaigns
7   every three years, with timing set partly based on this expectation. However, recent modelling
8   of ITN monitoring data across sub-Saharan Africa indicates that the median ITN retention is
9   1.64 years [3], reducing effective coverage until the next campaign (Commonly every three
10 years). While ITN products vary in physical specifications, with different polymers being used
11 across a range of fabric weights and knitting patterns [4, 5], there is no consensus or evidence
12 base on which characteristics, if any, provide the longest operational use.

13 Owing to the high operational costs of malaria vector control programmes and heavily
14 constrained funding environment, there has been a strong incentive to keep the price per unit
15 of ITNs low [6]. This has made it difficult for more expensive but potentially more physically
16 durable designs to enter the market, with even a reduction in ITN physical durability reported
17 for the same products from 2013 to 2020[7]. There is now a groundswell amongst decision
18 makers and ITN procurers to identify products that are the most physically robust in order to
19 improve the coverage of ITNs in a cost-effective manner. Substantial improvements are
20 required across the board if ITNs are to become more durable, which requires deeper
21 understanding of the relationship between net physical characteristics and net lifespan.

22 While in principle ITNs could be made from a wide variety of available polymers and fabric
23 constructions, the current crop of ITN products is either based on polyester (PET -
24 polyethylene terephthalate) or polyethylene. Furthermore, all polyethylene nets use a tulle
25 knitting pattern and all polyester nets a traverse pattern. Consequently, the currently available
26 ITNs represent a very limited cross-section of what is technically possible. This may mean that
27 a stepwise change in net design is needed to expand variability and physical net durability,
28 which will be more expensive to produce. However a case could be made to fund more
29 expensive designs if they were demonstrated to offer an extended operational life [8].

30 ITN products recommended by the World Health Organization Pesticide Evaluation Scheme
31 (WHOPES) or, more recently, prequalified by the Vector Control Group of the WHO
32 Prequalification Team (PQT-VC) were assessed in 2013 and 2020 respectively for their physical
33 and design characteristics at the Nonwovens Innovation & Research Institute (NIRI)
34 laboratories. Building on research aimed at understanding the sources of damage leading to
35 holes in mosquito nets [9], the resistance-to-damage (RD) score was developed as a composite
36 metric for quantifying the physical durability of an ITN product relative to an aspirational value
37 [10-13]. The aspirational values were established based on analyses of human factors,
38 considering the associated real-life forces applied to ITNs during normal use [7]. The original
39 RD (oRD) score uses four performance indicators measured in the laboratory to evaluate an
40 ITN's resistance to routine stresses in the field; snag strength, bursting strength, hole
41 enlargement resistance and abrasion resistance [10, 12, 13]. These performance indicators

1   are included in the complete product dossier required for WHO prequalification assessment
2   of ITNs and will be mandatory to report for all WHO-prequalified ITNs from 2025 [14]. A
3   secondary analysis of ITN field durability by Killian et al (2021) demonstrated that the
4   calculated oRD scores and survivorship in the field are correlated, such that ITNs with oRD
5   scores >50 had an additional operational lifespan of 7 months (compared to those with oRD <
6   50) [15].

7   In this prior analysis for oRD, the four performance indicators were assumed to contribute
8   equally to the overall RD score. However, recent analysis indicates some types of damage are
9   more common than others, with abrasion contributing to just 3.7% of total hole area while
10   enlargement of existing holes through laddering and unravelling being responsible for 18.1%
11   of hole area [11]. With access to a larger field database than those available in 2021, when
12   oRD scores were first compared with field data [10], and greater insight into hole formation,
13   we investigated whether the RD metric could be refined to better predict operational lifespan
14   by optimizing the weighting of its performance indicators based. We refined the oRD score
15   using durability data from 13 ITN brands across 37 study sites in 15 sub-Saharan African
16   countries to strengthen the evidence linking RD scores to the survival of ITNs in serviceable
17   condition in the field.

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Methods

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Refining the Resistance-to-damage score

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22   The net characteristics previously associated with resistance to routine damage in the field
23   are summarised in Supplementary file 1 [7, 10-13, 15]. Four physical ITN fabric attributes,
24   which have been previously linked to field life, were quantified to calculate the oRD score:
25   snag strength, bursting strength, hole enlargement resistance and abrasion resistance (Table
26   1)[10]. The value of each performance indicator was assessed as a proportion of an
27   aspirational value, representing the ideal score needed to endure day-to-day stresses in the
28   field. The outcome of these four tests was combined in an algorithm to produce a single oRD
29   score (out of a maximum of 100). Each of the four indicators are weighted equally, meaning
30   they are implicitly assumed to be of equal importance for operational lifespan (Eq. 1).

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34   Table 1: Description of performance indicators used to calculate RD scores

Indicator	Type of damage measured	Aspirational value
Snag strength	Fabric catching on a solid protuberance	≥200 N
Bursting strength	Fabric multidirectionally tensioned	≥700 kPa

Hole enlargement resistance	An initial hole gradually tensioned	100 (No Laddering, No Unravelling, No Tearing)
Abrasion resistance	Cumulative rubbing of fabric against a rough surface	400 rubs

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3 $$RD = \left(\frac{\lambda_B}{\eta_B} \times \frac{100}{4}\right) + \left(\frac{\lambda_S}{\eta_S} \times \frac{100}{4}\right) + \left(\frac{\lambda_A}{\eta_A} \times \frac{100}{4}\right) + \left(\frac{\sigma_H}{4}\right) \qquad \text{(Eq. 1)}$$

4 RD = Resistance-to-damage; λ_B = Actual bursting strength; η_B = Aspirational bursting strength; λ_S = Actual snag
5 strength; η_S = Aspirational snag strength; λ_A = Actual abrasion resistance; η_A = Aspirational abrasion resistance;
6 σ_H = Hole enlargement resistance score. Calculation can be done automatically using the RD score app [16].

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9 **Correlating RD scores to field data**

10 **Data sources**

11 ITN performance data came from durability monitoring studies conducted in 37 study sites
12 across 15 countries in sub-Saharan Africa, representing 13 ITN brands. Primary data were
13 collected by U.S. President's Malaria Initiative (PMI)-funded studies conducted between 2015
14 and 2023, using standard protocols (Supplementary Table 2). We extracted site-level
15 estimates of ITN physical survival as the median ITN survival time from the date of distribution.
16 Estimates of median survival for each study site were determined using observations made at
17 the 12-, 24- and 36-month timepoints. Confidence intervals around estimates were calculated
18 using the Wald method. The median ITN survival time, from date of distribution, was 2.7 years.
19 Given that some ITN use environments and individual behaviours could have a greater risk of
20 damage to ITNs than others, we calculated a site-level risk index (RI) metric [14]. The risk index
21 (RI) is a weighted average score based on variables collected during the baseline durability
22 monitoring round. It reflects differences in environment factors, net handling behaviours, and
23 individual net care attitudes across study sites (*manuscript in preparation*). As all inputs are
24 percentages, the RI can vary from 0% to 100%, with higher values representing greater non-
25 textile risks to ITN physical integrity. Variables included in the RI were selected based on
26 hypothetical risk factors for net damage drawing on grey and published durability monitoring
27 literature [14, 16]. ITN-level data were extracted from the same primary data source for
28 survival analysis as described below.

29 The oRD scores were determined by NIRI and corresponded to the values presented by
30 Wheldrake et al. [7]. The wRD score was calculated by the study team from the RD score
31 components, obtained by NIRI. We used the 2013 published values for studies following ITN
32 campaigns conducted between 2015 and 2018 and used the 2020 published values for study
33 results from campaigns after 2018.

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35 **Analysis methods**

We used bivariable linear regression models to assess the correlation between both the oRD score and wRD score compared to median ITN survival time at the site level estimated at the 12-, 24- and 36-month timepoints. We assessed model fit using the adjusted R-square value. We also performed a multivariate analysis adjusted for the presence of different environmental, household, and net-care variables by included the risk index in the model.

Having defined the wRD score, we assessed the association on wRD values and ITN physical survival using a Cox proportional hazards model with individual ITN data.

Data was set up for survival analysis as a duration format data set where each time interval for a net was a separate observation. Survival analysis was done using a per-protocol approach, i.e. risk of failure was considered to start only on the first observation where the net was found hanging. Failure was defined as a net reported to have been discarded by the household or is present but no longer in serviceable physical condition. Physical condition was defined according to the results of a hole assessment using the proportionate hole index (pHI), with serviceable nets defined as those with a pHI equal to or less than 642 (i.e. nets failed if the pHI was greater than 642). The time of failure was directly calculated from the reported time of loss by the respondent or taken as the mid-point between the last two surveys if time of loss was unknown. Results are reported as the gain in median survival in months for a 10-point change in the wRD.

Data were analysed in Stata v.18. Analysis of of the association between oRD, wRD and median ITN survial used study-site as the unit of analysis. Frequency weights were applied using the number of cohort nets remaining in the study at the 36-month data collection point as the weight (or 24-months for studies that ended after 24 months). Cox proportional hazards models used ITN as the unit of analysis, were unweighted, and included country as a random effect. For continuous variables, arithmetic means were used to describe the central tendency and the t-test for comparison of groups for normally distributed data. Otherwise, median and Kruskal–Wallis tests were used. Proportions were compared by contingency tables and the Chi squared test used to test for differences in proportions. For calculation of confidence intervals around estimates, the intra- and between-cluster correlation has been taken into account using the *svy* command in Stata.

Determinants of survival in serviceable condition after the net was first hung were explored using Cox proportionate hazard models. Factors were tested first in individual models which were then used to construct the final multivariate models. Final model fit was tested using a linktest and Schoenfeld residuals and log–log plots were used to check the proportionate hazard assumption.

Results

Refining the Resistance-to-damage score

Although in principle the oRD score is nominally equally weighted, in practice it is primarily made up of measures of resistance to initial hole formation (snag strength, bursting strength

1   and abrasion resistance), with resistance to hole enlargement representing only 25% of the
2   score (Eq. 1).

3   Assessing the performance of ITNs on the underlying measures highlights that all ITN products
4   assessed perform poorly on snag strength relative to the aspirational value (Supplementary
5   file 3A). While snag strength is indeed linearly related to fabric areal density (a proxy of the
6   fabric weight), even the products with the highest areal density nets achieved only 25% of the
7   aspiration. It was also observed that snag and bursting strength are highly correlated
8   (supplementary file 4), yet high areal density is associated with good bursting strength
9   performance compared to the aspirational value (supplementary file 5).

10 Resistance to hole enlargement contributes only 25% of the oRD score yet is directly
11 responsible for the occurrence of large holes [7]. There is a notable difference in resistance to
12 hole enlargement between tulle/monofilament polyethylene (PE) and traverse/multifilament
13 Polyethylene terephthalate (PET), with PET nets consistently performing excellently on this
14 metric yet PE nets varying greatly, and two examples of PET nets with low wRD
15 (Supplementary file 3C). Mesh count was observed to correlate with performance on
16 resistance to hole enlargement, with ITNs with the highest number of geometric structures
17 per square inch performing best on this metric (Supplementary file 6).

18 While abrasion resistance was included as a performance indicator in the oRD when first
19 developed, field data collected in years since from across sub-Saharan Africa shows that
20 overall, only 3.7% of hole damage was caused by abrasion [11]. On this basis, we evaluate an
21 alternative resistance-to-damage metric where abrasion is not considered. Furthermore,
22 given that the same study observed most damage by hole area is caused by tearing of existing
23 holes we doubled the weighting of hole enlargement resistance. Consequently, the wRD score
24 was defined with the following weights: 25% snag resistance, 25% burst resistance, 50% hole
25 enlargement resistance (Eq. 2).

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27   $$wRD = \left(\frac{\lambda_B}{\eta_B} \times \frac{100}{4}\right) + \left(\frac{\lambda_S}{\eta_S} \times \frac{100}{4}\right) + \left(\sigma_H \times \frac{100}{2}\right) \qquad \text{(Eq. 2)}$$

28 wRD = weighted resistance-to-damage; λ_B = Actual bursting strength; η_B = Aspirational bursting strength; λ_S =
29 Actual snag strength; η_S = Aspirational snag strength; σ_H = Hole enlargement resistance score. Calculation can be
30 done automatically using the RD score app [16].

31

32 **Comparison of physical characteristics with oRD and wRD**

33 The measured physical properties of all ITNs studied by Wheldrake et al [7] were collated to
34 calculate both the oRD and wRD scores. Overall, we observed that wRD scores show a wider
35 distribution than oRD scores, with nets clustering into two distinct groups: those with wRD
36 scores of 30-40 and those with scores of 50-70 (Figure 1). Generally, ITNs in the lower group
37 are made of tulle/PE fabrics, while the upper group is a mix of tulle/PE and traverse/PET.
38 Consequently, these observations highlight that products cannot be judged on knitting pattern
39 and polymer composition alone, and both polymers are capable of higher performance ITN

1 products depending on quantitative design characteristics, including but not limited to,
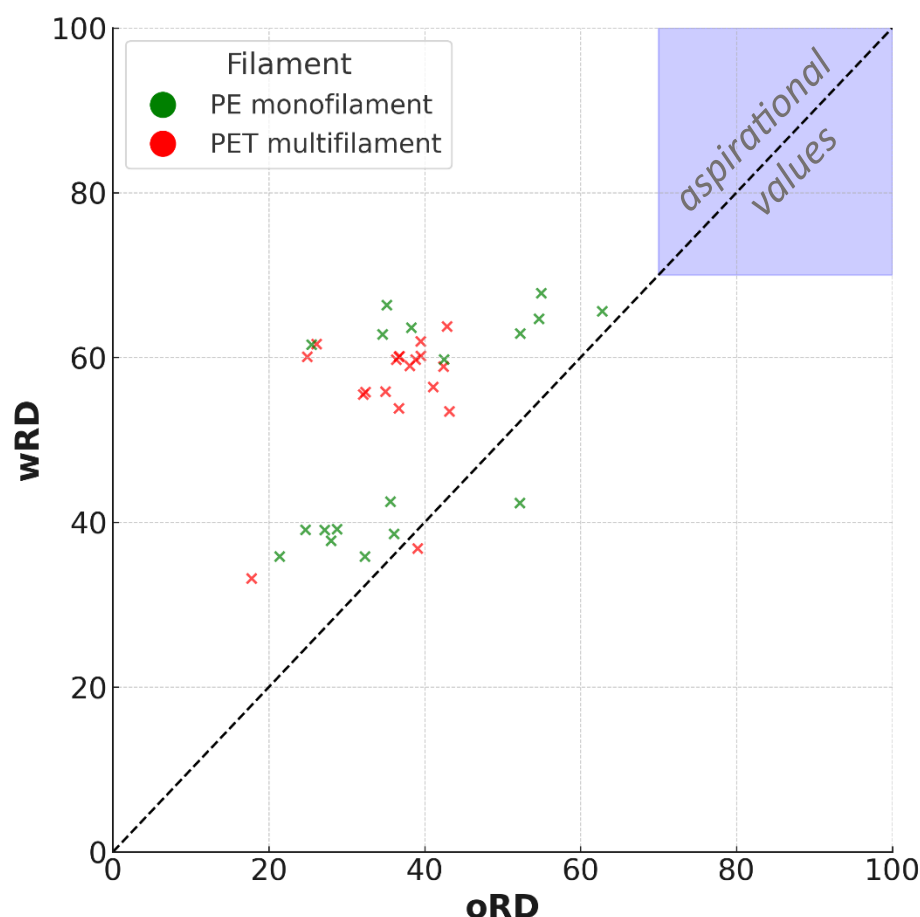2 constituent yarn dimensions and mechanical properties, as well as the knitted fabric structure.

3

Figure 1 Comparison of oRD and wRD scores for different insecticide-treated nets (ITNs), categorized by tulle knitting pattern with polyethylene (PE) nets, and traverse knitting pattern with polyethyelene terephthalate (PET) nets

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5 **Estimating median survival using oRD and wRD scores**

6 When predicting ITN survival time, accurate predictions in the early stages of net lifespan (i.e.
7 soon after distribution) is not as valuable as making accurate predictions lateron. In bivariable
8 linear regression models, the power of the oRD to predict median survival at a given timepoint
9 was highest for earlier study timepoints, when most nets are still present, with predictive
10 power decreasing as the trial progresses (the R-square value decreased from 0.12 at 12-
11 months to 0.00 at 36 months). In the same model, the wRD provided steady predictive power
12 through the course of a trial, with the adjusted R-square value staying in the range 0.07 to
13 0.08 across the three survey rounds. The greater predictive power of the wRD compared to
14 the oRD, particularly at later survey timepoints, came primarily from increasing the weighting

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1   of hole enlargement which is a strong differentiator between products. Differences in abrasion
2   resistance between products was a negligible contributor to predictive power.

3   In the site-level analysis, a 10-point increase in wRD score was associated with a 3.9-month
4   gain in median survival from first hanging (Figure 2). Furthermore, increasing wRD from 30 to
5   70, the approximate range for current products on the market, increases median survival by
6   13.7 months (95% CI: 3.1–24.2, P = 0.016, Figure 2). The wide error bars reflect country-level
7   variation.

8   Incorporating the Risk Index (RI) into the wRD model improved model fit, emphasizing the
9   significant role of net handling, net care and repair and environmental factors in explaining
10   variations in bednet lifespan across study areas (manuscript in preparation). Further
11   investigation on the RI is underway to understand these contributing risk factors and enhance
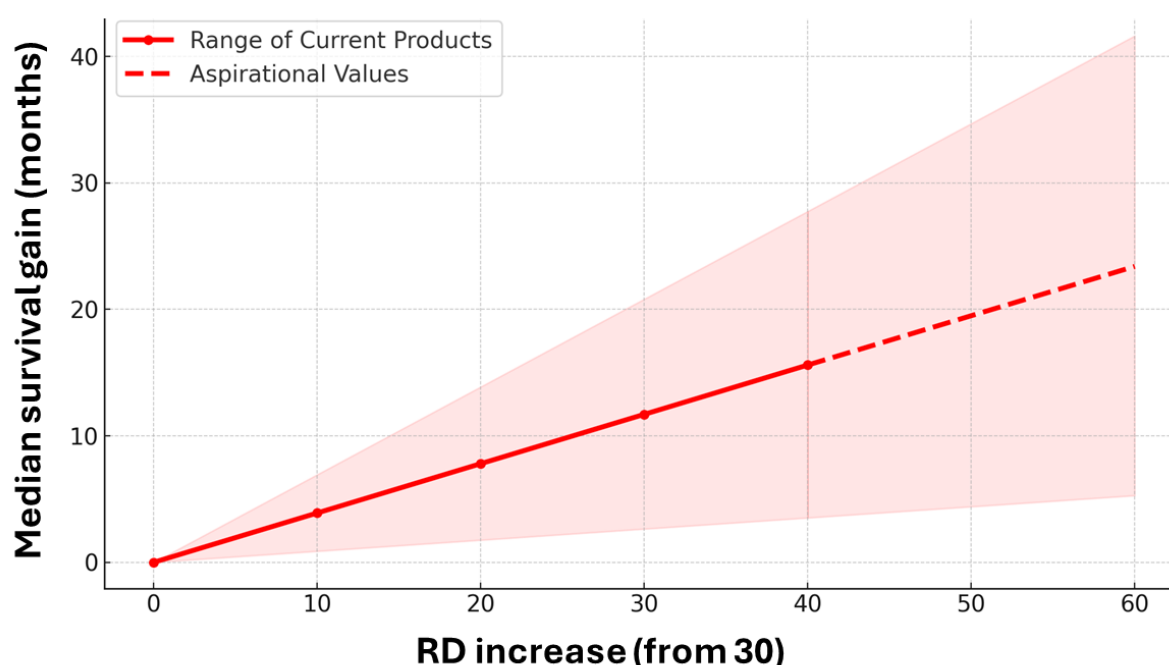12   its usability, similar to the RD score.

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15   Figure 2: Visualization showing relative impact of increasing wRD score on median survival
16   when increasing above a value of 30 (the lowest wRD score for ITN brands in our dataset)
17   up to 70 (the highest wRD score for brands in our dataset). The dashed line indicates
18   projected increases in survival by aspirational nets with physical durability beyond currently
19   available ITN products. Shaded area indicates 95% confidence interval

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21   ITN-level predicted survival from the Cox proportional hazards mixed effects regression model
22   (adjusted for net use environment, net handling and net care attitude fixed effects, and
23   country as a random effect) was plotted for wRD scores ranging from 38 to 68 (Figure 3).
24   Within six months of ITNs being first hung, better survival is evident for products with higher

1   wRD scores. The 50% survival point is reached approximately 1.2 years later for nets with a

2   wRD score of 68 compared to those with a wRD score of 38, extending survival of hanging
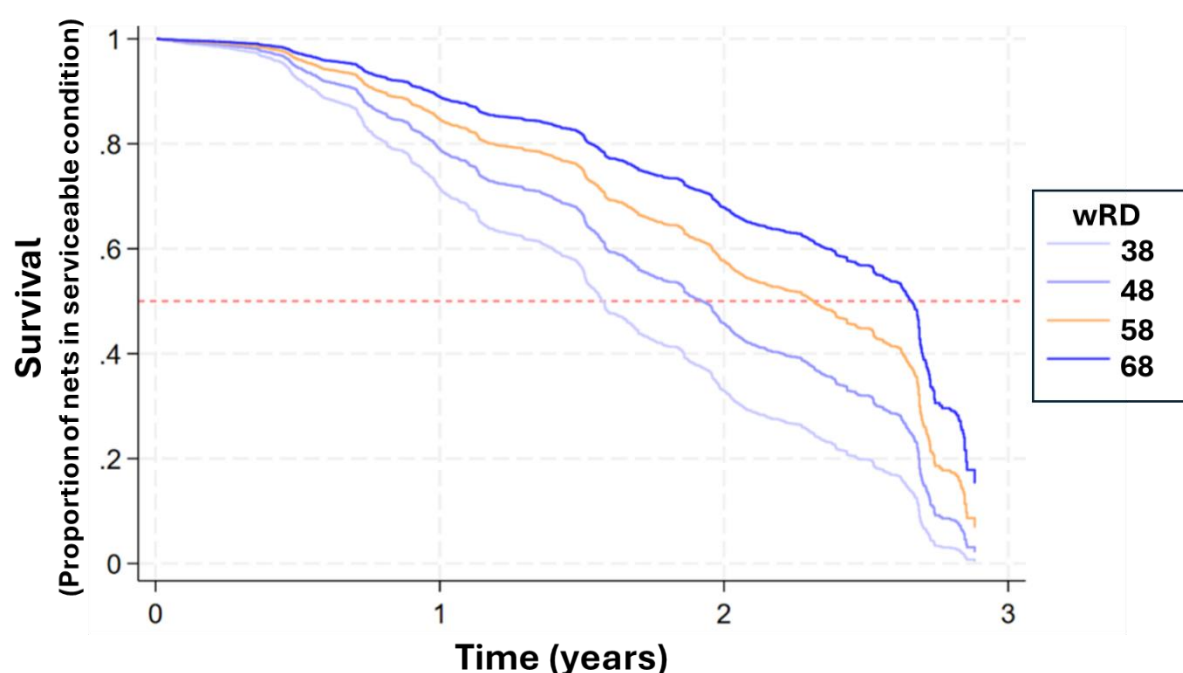
3   ITNs closer to the three-year target.

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7   **Figure 3. Predicted survival of ITNs with wRD values of 38, 38, 58, and 68, from ITN-level**
8   **regression model. Dotted horizontal red line indicates 50% survival, at which point half of**
9   **ITNs distributed are in serviceable condition**

10

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Discussion

13   Here we show the value of a resistance to damage (RD) metric that equally values preventing
14   holes from forming and minimising their propensity to enlarge, in predicting ITN lifespan
15   under typical household use environments in sub-Saharan Africa. The wRD score is more
16   predictive of net survivorship than the oRD score, due to increasing the weight of the
17   resistance to hole enlargement variable. A 10-point increase in wRD score was associated with
18   an estimated 3.9-month gain in median survival. This means, the expected difference in ITN
19   lifespan between the lowest performing and highest performing nets on the market in 2020
20   (minimum: wRD 35– maximum: wRD70) is more than a year (13.75 months). This highlights
21   the importance of both preventing holes from forming initially (e.g. due to snagging of the net
22   fabric) and preventing these holes from enlarging, which is a mechanically distinct and equally

1 important trait. We highlight that snag and bursting strength scores are very similar across the
2 ITN product range, yet resistance to hole enlargement is a major differentiator between
3 products. This differentiation is evident in the observation that wRD scores cluster into two
4 groups, reflecting brands with higher and lower hole enlargement scores. However, we also
5 draw attention to the observation that snag strength is poor across the entire product range,
6 thus any future design that provided even moderate performance on this metric would
7 compare well with current products on wRD. These findings support previous work by Kilian
8 et al (2021) demonstrating that the components of the RD metric are predictive of operational
9 lifespan [15].

10 We demonstrate that resistance to hole enlargement is a previously undervalued component
11 in the oRD. By weighting hole formation (snag resistance and bursting strength) and hole
12 enlargement equally in the rwRD score, we highlight that both traits should be a focus in the
13 procurement and development of durable ITN designs. That resistance to hole enlargement is
14 an important predictor of ITN lifespan is consistent with the observations by Wheldrake et al.
15 [11] that most damage (by surface area) is caused by tearing of initially small holes.
16 Furthermore, the finding that abrasion resistance alone is a negligible predictor of ITN lifespan
17 is consistent with observations by Wheldrake et al. [11] in that <5% of all damage by surface
18 area is caused by abrasion. Consequently, we summarise that the wRD is better aligned than
19 the oRD to the damage mechanisms that ITNs face in the field.

20 The performance of engineered structures such as textile fabrics, depend on multiple factors,
21 including their polymer composition, yarn and fabric structure, as well as dimensional and
22 mechanical properties. It is noteworthy that all but one traverse/multifilament polyester ITN
23 products exhibited excellent, near aspirational, resistance to hole enlargement. However, we
24 emphasise that there are also examples of tulle/monofilament polyethylene nets with very
25 good performance on the same metric. Consequently, the scoring of traverse/multifilament
26 polyester products generally improved in the wRD model as compared to oRD. However, to
27 attribute differences in the performance of a net solely to polymer content, e.g. polyester vs.
28 polyethylene is misleading, as it ignores other important factors such as the yarn and fabric
29 structure.

30 The ability of holes to enlarge following an initial yarn breakage is dependent primarily on the
31 geometric structure (knitting pattern) and dimensional stability of the fabric, rather than its
32 polymer composition. Unravelling and enlargement of an initial hole does not require
33 additional yarn breakage. Changing the knitting pattern, and thereby, the frictional interaction
34 of yarns within the knitted fabric structure to improve structural stability, is among the
35 strategies that could be pursued to improve performance. Better hole enlargement resistance
36 scores were also shown here to be positively correlated with mesh count, potentially due to
37 the higher number of inter-yarn frictional contact points that are available to resist unravelling
38 as the area between fibers gets smaller.

39 Investigating the physical design characteristics of ITNs in detail has highlighted two routes for
40 innovation, i.e. snag resistance and hole enlargement resistance. Even the highest performing
41 ITN products had poor snag strength relative to the aspirational target (Supplementary file 3).
42 Clearly, major innovation in ITN design is needed. Knitted fabrics currently used to make ITNs

are inherently susceptible to snagging on solid protuberances, leading to mechanical damage and yarn breakage. Consequently, snagging is the most common form of initial damage in nets retrieved from the field [11]. While holes associated with snagging are typically small, they are susceptible to enlarging over time, especially in net products with poor hole enlargement resistance. Further investigation to understand the mechanics of snagging and improve snag resistance is important. Hole enlargement resistance represents a completely different innovation path from snag strength, as it does not necessarily depend on filament breakage and requires distinct design considerations. To improve hole enlargement resistance, careful consideration should be given to the selection of knitting pattern and the tightness and dimensional stability of the fabric construction. These are all factors that can be modulated during textile manufacturing, but of course, potential trade-offs in terms of lower production speed, additional processing steps, higher fabric weight and therefore additional cost also need to be considered.

The long-term survivorship of ITN products depends on two basic factors. The first is the product design of nets in terms of their inherent physical durability, quantified by RD values. The second is the environment and the way in which the ITN is used, including net handling, net care and repair and environmental factors. While high-RD ITN products will withstand expected sources of mechanical damage in the household better than those with a lower value, certain household and environmental variables, as well as user care, expose the net to a heightened risk of damage. Consequently, even high-RD products would be expected to have short field life in very challenging conditions. However, as shown in our ITN-level regression, after adjusting for these known risks, ITN brands with wRD scores at the top of the current range were predicted to survive in serviceable condition for more than 14 months longer than brands with a wRD score and the bottom of the current range, on average. Understanding how much additional survival gain could be achieved from ITNs with even higher wRD scores is an important unanswered research question.

The ITN products investigated here fall well below the aspirational value of wRD score of 100[10, 12], particularly on snag strength, indicating room for considerable improvement in ITN design in terms of physical durability. Consequently, there is a need to explore fabric design characteristics that could result in a higher wRD score. For manufacturers, this requires new incentives to innovate, as at present there is no clear market willing to pay the costs associated with the development and manufacturing of more durable nets. Funding for malaria control is limited [1] and a case for value-for-money, rather than cost, needs to be made. The potential cost effectiveness afforded by longer-lasting nets may be considered by ITN procurers and country programmes. In addition, sufficient incentive must be afforded to manufacturers to be able to explore improved and innovative durability design. These innovations must go together with a renewed focus on net care to give these products the best opportunity to perform as expected in the field.

Conclusion

ITN products with higher wRD scores are projected to provide longer field life, with an increase from 35 to 70 estimated to provide 13.65 additional months in serviceable condition. This can

have immediate implications on ITN procurement decisions to encourage the purchase of nets that will last longer in the field and it provides direction on innovation to improve net retention. This study underlines the importance of determining the wRD score of an ITN product during ITN prequalification, to ensure nets can provide long-term physical protection in the field. The wRD score demonstrates greater accuracy in predicting net survivorship in the field compared to the oRD score. Therefore, we propose adopting the wRD score as the new RD score standard and encourage its endorsement, standardisation and uptake in procurement decisions by donors and country programmes. By giving equal weight to resistance against hole formation and hole enlargement, the wRD score highlights that preventing small holes from expanding is just as crucial as preventing their formation. To address this, alternative knitting patterns and new ways of producing nets could enhance resistance to hole enlargement, while innovations targeting snag resistance can further boost net physical durability. There is a pressing need for genuine innovation to produce more physically durable nets, and recognizing the long-term value of physical durability can justify the inevitable higher initial costs.

Declarations

Authors' contribution

FM, SP, SJR and AS designed the study protocol. FM, SP, JAT, MW and ES, AW and FJ participated on data analysis. FM, SP, JAT drafted the manuscript. MW, ES, AK, HK, CF, SJR and AS critically reviewed the manuscript. All authors read and approved the final manuscript.

Acknowledgments

The authors would like to acknowledge

Competing interests

We authors declare that we have no competing interests.

Availability of data and Materials

Data supporting the conclusions of this article are included within the article. Datasets are available on reasonable request to NIRI, UK.

Ethical approval

Not applicable

1   **Consent for publication**

2   Not applicable

3

4   **Funding**

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1 Supplementary files

2 **Supplementary file 1: List of physical characteristics of interest.**

Characteristics	Description	Outcome
Snag strength	Force is applied to a single loop of yarn in the knitted structure of the net at an elongation rate of 100 mm/s (Adapted from ISO 13934-2:2014 and BS EN 15598:2008).	The force in Newtons (N) required to break a yarn in the LLIN.
Bursting strength	An area of the net fabric is distended by an expanding diaphragm, after being fixed by a clamping ring (ISO 13938-2:1999).	The pressure in Kilopaskal (kPa) required to burst the net fabric.
Hole enlargement resistance	After creating an initial hole in the net fabric, the damaged area is clamped into a bursting strength testing instrument, and 80 kPa pressure is applied to the extending diaphragm below at a rate of 15 kPa/s for three sequential cycles. Any increase in hole size is measured. (adapted from BS 3423-38:1998).	Hole enlargement scores are determined from the absolute values to reflect both the size of the end hole and type of secondary damage.
Abrasion resistance	Samples of net fabric are rubbed against an abrasive surface. The number of rubs required to break a single yarn using a grade 7 (240-grit) sandpaper and an applied pressure of 9 kPa is counted to (adapted from ISO 12947- 1:1998).	The number of rubs required for yarn breakage and a resulting hole of at least 5 mm in diameter.
Polymer type	The material used to make filament yarns in the net.	Polyester terephthalate (PET) or Polyethylene (PE).
Knitting pattern	Standardized knitting patterns for netting (ISO 8388:2003).	Tulle, traverse or Marquisette.
Yarn type	The structure of the yarn in the net composed of either single or multiple filaments.	Monofilament or multifilament.
Linear density	The yarn count, which is a measure of the yarn fineness	Denier = weight in grammes of 9000 metres of yarn.
Area density	A measure of the fabric weight per unit area	Usually expressed in grammes per square metre (g/m^2).
Mesh count	Number of mesh aperture holes per unit area.	Normally expressed as holes/inch^2

3 Methodologies have been described in detail here [10-13]

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1   **Supplementary file 2: Summary of durability monitoring data collection**

Country	Number of sites	ITN brands	Mass campaign (year)	Endline round (year)
Mozambique	3	Royal Sentry (2 sites) MAGNet	2015	2018
Nigeria	3	DawaPlus 2.0	2015	2018
DRC	2	DawaPlus 2.0 Duranet	2016	2018
Zanzibar (United Republic of Tanzania)	2	Olyset PermaNet 2.0	2016	2019
Kenya	2	DawaPlus 2.0 Duranet	2017	2021
Ghana	2	Olyset DawaPlus 2.0	2018	2021
Liberia	2	Duranet	2018	2021
Madagascar	4	DawaPlus 2.0 (3 sites) PermaNet 2.0	2018	2021
Niger	2	Olyset	2018	2021
Burkina Faso	3	Interceptor G2 PermaNet 3.0 Interceptor	2019	2022
Burundi	2	PermaNet 3.0 Yorkool	2019	2022
Rwanda	4	Interceptor G2 PermaNet 3.0 Olyset Yahe	2020	2023
Sierra Leone	2	PermaNet 3.0 Olyset Plus	2020	2023
Zambia	2	Olyset Plus Veeralin	2020	2024
Cote d'Ivoire	2	Interceptor G2 PermaNet 3.0	2021	2024

2   Table presenting country, number of sites, ITN brands monitored, dates of data collection.

3   (https://www.durabilitymonitoring.org/?page_id=57).

4

1   **Supplementary file 3: Physical characteristics of nets in relation to their polymer**
2   **composition and filament types, snag strenghth, bursting strength, hole enlargement**
3   **resistance and abrasion resistance. Dotted, horizontal line indicates aspirational score.**

4
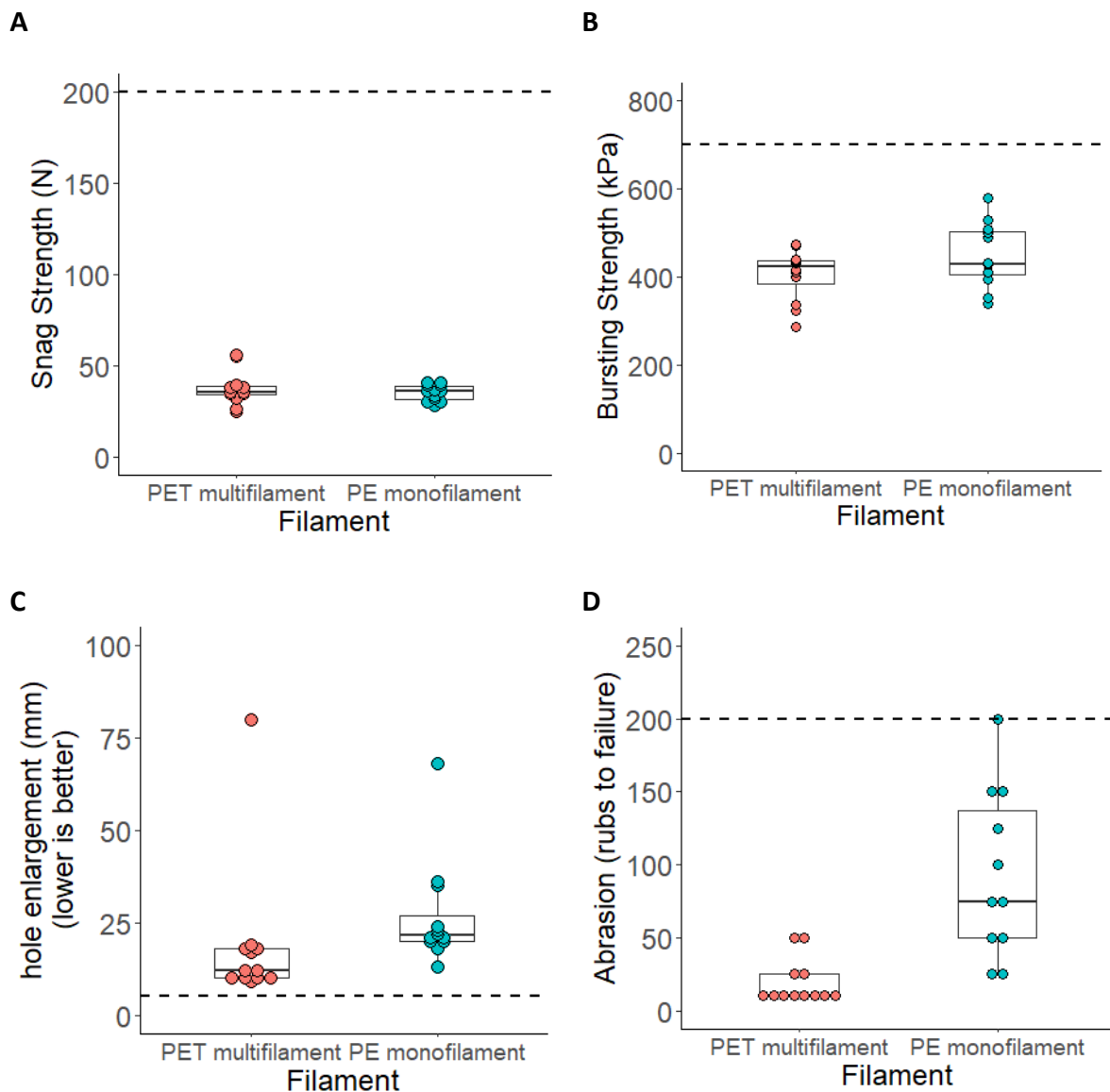
1 **Supplementary file 4: Correlation between Snag strength and Bursting strength. N=**
2 **Newtons, kPa = kilopascals. The snag strength and bursting strength are well correlated with**
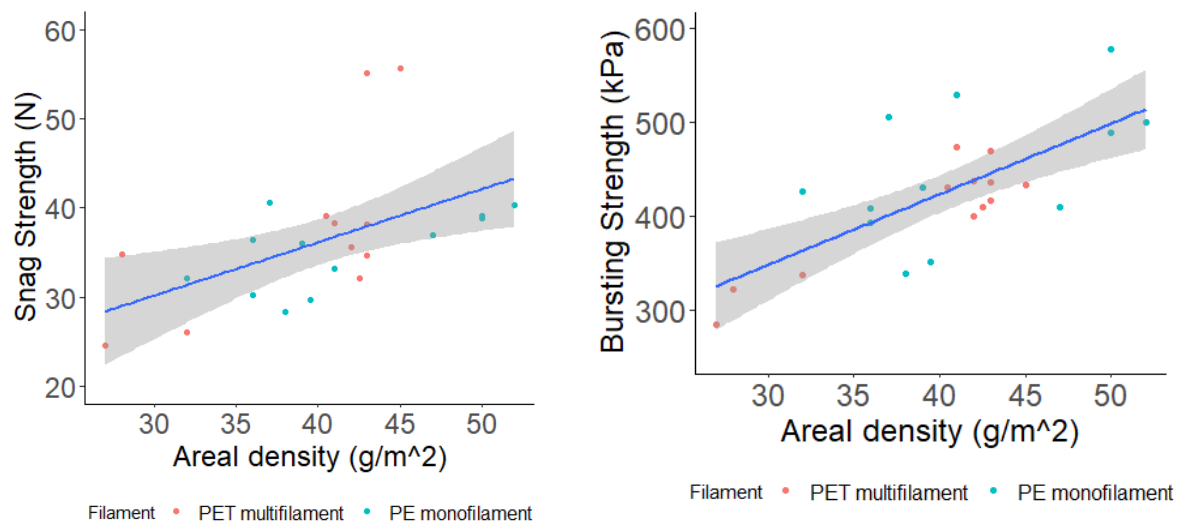3 **each other, with a Spearman correlation of 0.661.**

4
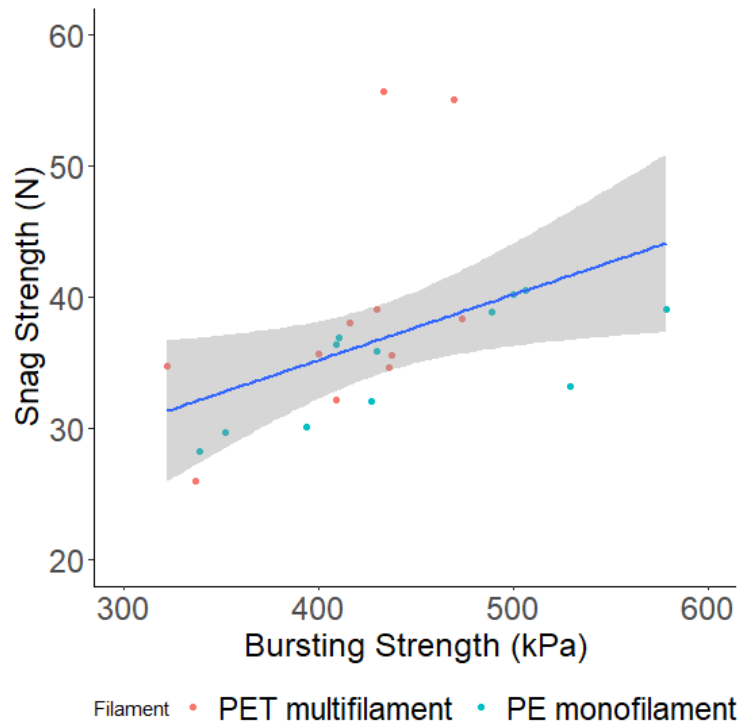
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1   **Supplementary file 5: Relationship between area density and snag/burst strength**

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1   **Supplementary file 6: Relationship between mesh count and hole enlargement**

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