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Investigating the impact of non-pharmaceutical interventions (NPIs) on post-pandemic Respiratory Syncytial Virus (RSV) hospitalisations and seasonality in Wales, UK

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ABSTRACT

Introduction: Respiratory Syncytial Virus (RSV) is a single-stranded RNA virus and a major cause of hospitalisations in paediatric and geriatric populations. In the Northern Hemisphere, the RSV season is typically between October and March. Following the introduction of Non-pharmaceutical Interventions (NPIs), in response to the COVID-19 pandemic, disruptions in seasonality have been observed.

Methods: We used an age-structured, deterministic SE_2I_2R model with time-dependent contact rates to study RSV hospitalisations and seasonality in the context of specific NPIs in Wales. The transmission process was linked to a clinical events model, to allow comparison to paediatric admissions data from Public Health Wales. The model was calibrated using Welsh demographics, social contact surveys and a severity index of Welsh NPI impact.

Results: Admissions data revealed three out-of-season outbreaks (Autumn 2020, Autumn 2021 and Summer 2022). A surge of admissions in Winter 2022-23 and Winter 2023-24 were forecasted, with peak timings correctly predicted, despite a more protracted outbreak observed in the data. Approximately, 90% of RSV admissions in Wales from 2016-22 were in infants under 1 year old; with the greatest shift in admissions age-structure in 2-4 year olds (quintupling in 2021). The model predicted a rapid return to pre-pandemic patterns after disruptions.

Discussion/Conclusions: Out-of-season peaks chiefly coincided with NPI relaxation. The post-pandemic response of RSV, in terms of timings, magnitude and age-structure shift, were all broadly consistent with simple interruptions in population exposure during the pandemic and the build up of immune naïve cohorts. Our model forms the basis of medium-term projections for paediatric RSV admissions in Wales.

1. Introduction

Respiratory Syncytial Virus (RSV) is a commonly acquired, single-stranded RNA virus that causes cold- and flu-like symptoms (Huang and Wertz, 1982). RSV accounts for 67% of lower respiratory tract infections in infants and is the most common cause of bronchiolitis in all age groups and pneumonia in this age group (ECDC, 2022).

According to the World Health Organization, RSV-related acute lower respiratory tract infection is a leading cause of paediatric hospitalisation globally (WHO, 2024). Indeed, 33 million cases and 66,000 to 199,000 deaths occur annually in children under 5 years old (Shi et al., 2017; Suh et al., 2022). In the United Kingdom, 92% of RSV-related hospitalisations occur in the paediatric population, with ~1400 per year in Wales (total population of 3.2 million individuals, with ~150,000 children 0–4) and infants <1 year old most likely to require

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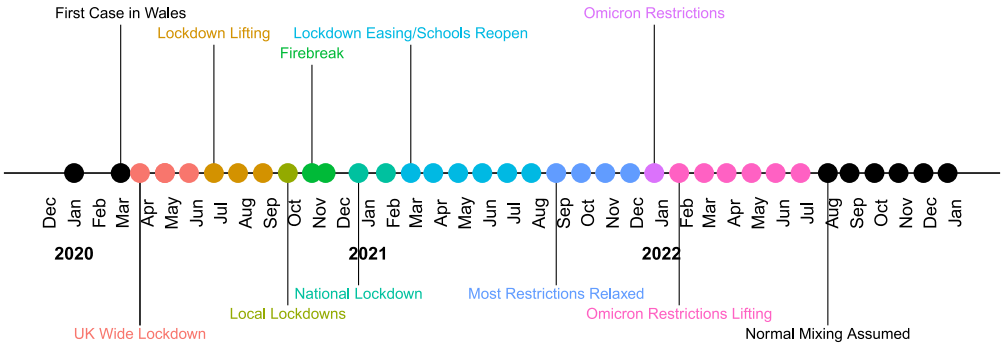

Fig. 1. NPI timeline for Welsh Government pandemic response 2020–22. The first national lockdown (coral) was introduced at the end of the 2019–20 RSV season. It continued into the Summer (June) with restrictions eased before the expected start of the 2020–21 season. Two national lockdowns were introduced during the expected 2020–21 season, the firebreak (green) and a longer lockdown (turquoise). Restrictions continued to ease until further NPI measures were implemented in December 2021 (the expected 2021–22 season), in response to Omicron (lilac and pink). These were lifted before the start of the 2022–23 season (black). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

hospitalisation (Taylor et al., 2016). Many of these hospitalisations are for a short period of time. To reduce hospitalisations, at risk infants may be immunised with Pavilizumab (a programme initiated in 2010, with no major changes over the period of study) (NHS Wales, 2020; JCVI, 2010; Atherton and Evans, 2022). Additionally, Nirsevimab was approved by the Medicines and Healthcare products Regulatory Agency in 2021; with a programme of Abrysvo being rolled out for >75 years old and pregnant women from 1st September 2024 (MHRA, 2022; JCVI, 2023; UKHSA, 2024). Modelling of a maternal vaccine, prior to the characteristics of Abrysvo being known, indicated a predicted reduction in hospitalisations in <6 months (Hogan et al., 2017).

In the Northern hemisphere the RSV season typically spans October to March (EMHA, 2022a,b), with the greatest burden of hospitalisations observed in December in the UK (UKHSA, 2023). RSV transmission was greatly reduced by non-pharmaceutical interventions (NPIs) implemented in response to the COVID-19 pandemic (ECDC, 2022; Welsh Government, 2022a). NPIs affected RSV seasonality in Europe with lack of or out-of-season outbreaks observed in the 2020–21 season (ECDC, 2022).

In Wales, the Welsh Government introduced NPIs between 18th March 2020 and 27th May 2022 (see Fig. 1). Examples include (but are not limited to): national lockdowns, internal and international travel restrictions, school closures, shielding of the elderly and the use of face coverings in indoor settings (Welsh Parliament, 2022). In total, three national lockdowns were employed; the first in response to the first-wave of COVID-19 (23rd March 2020 – 1st June 2020), the second (a 'firebreak') to control hospital admissions in the 2020 Winter period (23rd October 2020–9th November 2020) and the third in response to high prevalence and the emergence of new variants, including alpha (28th December 2020–22nd February 2021).

Cases rebounded rapidly after the return of near-normal contact rates, resulting in more hospitalisations in the 2022–23 season, with the observance of a larger peak, and concerns over a 'tridemic' between RSV, COVID-19 and Influenza (Welsh Government, 2022a).

Two hypotheses may explain the rebound; (a) the emergence of novel genotypes and (b) a prolonged lack of virus exposure and decrease of RSV-specific immunity at the population level. In the case of the former, bioinformatic analysis revealed UK RSV samples taken in 2021 were diverse (clade J) and also seen in Australia in 2022 (Majaz et al., 2023). Additionally, whole genome sequencing of Austrian samples revealed pre-COVID-19 lineages were responsible for the 2022 surge in Austria (Redlberger-Fritz et al., 2023).

In the case of the latter, biochemical analysis revealed a decline of RSV-specific antibodies in the Dutch population (den Hartog et al., 2023). The second hypothesis is consistent with the evidence and supports the view that prolonged lack of exposure and decreased specific immunity, during the NPI period, would result in a larger susceptible population and a rapid rebound of RSV cases in Wales (Welsh Government, 2022a).

Here, we developed an age-structured, deterministic SE_2I_2R model with time-dependent contact rates to study RSV susceptibility and seasonality in the context of the pandemic in Wales. Due to data availability, we used RSV hospitalisations to investigate the disrupted/altered RSV dynamics between 2020 and 2024; we sought to determine and explain out-of-season peaks in admissions, with a secondary aim of projecting future seasonal patterns (for the 2022–23 and 2023–24 seasons). To do this we compared model projections to paediatric admissions data.

2. Methods

2.1. Data

Data were collected by the National Health Service, on behalf of Public Health Wales, and provided by Digital Health and Care Wales. We received hospitalisation records collected from each of the seven health boards in Wales between January 1st 2016 and May 24th 2024 for patients between the ages of 0 and 17 years old. Each patient was admitted with either a primary or secondary diagnosis of bronchiolitis (coded as J20 or J21). Given that RSV is the predominant cause of bronchiolitis (ECDC, 2022), we assumed all bronchiolitis admissions were RSV admissions. In the Results section, we describe the trends in admission cycles pre- and post-pandemic, both in terms of the cycle timings and admissions age-structure.

2.2. Model

We developed an age-structured, deterministic SE_2I_2R model with time-dependent contact rates to reflect the dates and impact of NPIs. In our model, susceptible, exposed, infected and recovered are represented respectively by S, E, I and R. E_a represents the first half of the exposed period, E_b the second half, I_a represents the first half of the infected period and I_b the second half. B indicates the "born immune" population, i.e. a subset of infants who have passively received maternal antibodies to RSV *in utero* and through breastfeeding, conferring approximately 6 months of immunity ($a = 1/182.5$ days). We assumed the proportion of "born immune" infants at time (t) was equal to the fraction of the (working age) adult population immune at that time, with the daily birth rate (Z) set to 100/day (Welsh Government, 2022b).

Each compartment was expanded to encompass seven age groups (0–6 months, 7–12 months, 13–24 months, 2–4 years, 5–15 years, 16–64 years and 65–90 years). A stable population of 3.2 million was

assumed (consistent with the most recent census) (ONS, 2022). The full model is defined by the following equations:

$$\frac{dB}{dt} = Z\left(\sum_{k=r_{min}}^{r_{max}} \frac{R_k}{N_k}\right) - aB \ ;$$

$$\frac{dS_1}{dt} = Z\left(1 - \sum_{k=r_{min}}^{r_{max}} \frac{R_k}{N_k}\right) + aB - \beta_1(t)\left(\sum_{i=1}^{n} c_{1,i}\frac{I_{a,i}+I_{b,i}}{N_i}\right)S_1 - \left(\mu_1+\lambda_1\right)S_1 + \omega R_1 \ ;$$

$$\frac{dS_j}{dt} = \lambda_{j-1}S_{j-1} - \beta_j(t)\left(\sum_{i=1}^{n} c_{j,i}\frac{I_{a,i}+I_{b,i}}{N_i}\right)S_j - \mu_j S_j - (\lambda_j S_j)_{j\neq n} + \omega R_j \ , \ j = 2:n \ ;$$

$$\frac{dE_{a,j}}{dt} = (\lambda_{j-1}E_{a,j-1})_{j\neq n} + \beta_j(t)\left(\sum_{i=1}^{n} c_{j,i}\frac{I_{a,i}+I_{b,i}}{N_i}\right)S_j - (\delta+\mu_j)E_{a,j} - (\lambda_j E_{a,j})_{j\neq n} \ , \ j = 1:n \ ;$$

$$\frac{dE_{b,j}}{dt} = \delta E_{a,j} + (\lambda_{j-1}E_{b,j-1})_{j\neq n} - (\delta+\mu_j)E_{b,j} - (\lambda_j E_{b,j})_{j\neq n} \ , \ j = 1:n \ ;$$

$$\frac{dI_{a,j}}{dt} = \delta E_{b,j} + (\lambda_{j-1}I_{a,j-1})_{j\neq n} - (\gamma+\mu_j)I_{a,j} - (\lambda_j I_{a,j})_{j\neq n} \ , \ j = 1:n \ ;$$

$$\frac{dI_{b,j}}{dt} = \gamma I_{a,j} + (\lambda_{j-1}I_{b,j-1})_{j\neq n} - (\gamma+\mu_j)I_{b,j} - (\lambda_j I_{b,j})_{j\neq n} \ , \ j = 1:n \ ;$$

$$\frac{dR_j}{dt} = \gamma I_{b,j} + (\lambda_{j-1}R_{j-1})_{j\neq n} - (\omega+\mu_j)R_j - (\lambda_j R_j)_{j\neq n} \ , \ j = 1:n \ .$$

With the indices i and j labelling the age categories, the notation for the parameters appearing in the equations is as follows: μ_i represents the death rate; β_i is the (seasonally varying) transmission coefficient; δ the incubation period; γ_i the rate of recovery; λ_i the maturation/cohort aging rate; ω_i the rate of waning immunity; $c_{i,j}$ the entries in the contact matrix (of age category i with age category j); n is the number of age groups and $[r_{\min}, r_{max}]$ is a subset of $[1,n]$ covering the working age population in which most births are produced. (For further details, see Table 1 of the Supplementary Materials.) The model equations are described schematically in Fig. 2.

We assumed an incubation period of 5 days (Wright and Piedimonte, 2011), an infectious period also of 5 days (CDC, 2024) and waning immunity following infection of 2 years. Pre-pandemic contact rates were extracted from Welsh data collected from social contact surveys (Mossong et al., 2008) (see Table 3 in the Supplementary Materials). The transmission model was linked to a post-processed clinical events counting model (see Fig. 2), for comparison to admissions data. An age-dependent proportion of exposed individuals become cases, cases can be hospitalised, die or be admitted to the intensive care unit (ICU), and a proportion of individuals hospitalised or in the ICU die. Distributions for lengths of stay were assumed, allowing occupancy measures to be calculated. Only the hospital (non-ICU) admissions rates were used (due to very small numbers of ICU events or deaths) (see Table 2 in the Supplementary Materials).

The model was fitted to age-structured paediatric hospitalisations since 2016, by estimating the time-dependent β from a grid-search minimal least squares fit to the data. β was assumed constant during the pre-pandemic period, then the relative change in β due to NPIs was estimated separately for each time period corresponding to the key NPI periods in Wales (see Fig. 2) (see full dates and values in Table 4 in the Supplementary Materials). We assumed that NPIs reduced social contacts equally across age compartments. The model is available at bit.ly/3Hsmfxr.

2.3. Model projections

The model was fitted up until the end of the NPI restrictions (mid-2022), after which it was assumed that population mixing returned to pre-pandemic levels. This allowed a projection of the expected re-emergence of RSV over two Winter periods. Admissions data showing the post-pandemic patterns of RSV were collected, described and compared to model projections.

3. Results

3.1. Out-of-season outbreaks in Wales following NPIs

The very regular admissions patterns prior to the pandemic were well captured by the simple seasonally-forced model (see Fig. 3). Simulated admissions peaks were of a similar timing and magnitude to peaks in the data; with troughs (particularly during the summer periods) not well captured.

Following the introduction of NPIs in Wales in March 2020, RSV transmission was disrupted. The first lockdown in Wales (implemented between March 2020 and June 2020) enabled the short-term suppression of RSV transmission (see Figs. 1 and 3). NPIs were relaxed over the Summer and school returns began in Autumn; triggering a small out-of-season peak in admissions in Autumn 2020. The timing and magnitude of the modelled peak echo the observed peak. The peaks differ in terms of peak width (the outbreak is more protracted in the observed peak than the model peak) and the shoulder of the observed peak is absent in the modelled peak.

NPIs were bolstered in the Winter of 2020–21, first in the form of local lockdowns, followed by school closures, the October 'firebreak' and a national lockdown was implemented in December. By August 2021, most restrictions had been relaxed and in Autumn 2021 schools returned and a second out-of-season outbreak was observed. The model fit is similar to that of the first out-of-season outbreak, with the peak and magnitude appearing well matched and the narrower, modelled peak width showing a failure to capture the duration of the outbreak.

The final out-of-season outbreak was observed in the Summer of 2022 when the final Omicron restrictions were lifted, and it is assumed normal contact/mixing patterns resumed. These patterns were well reproduced by the model, with the timing, magnitude and peak width similar to those seen in the data, with time-dependent contact rates coincident with major NPI events (Fig. 3).

3.2. Projections of Winter 2022–23 and 2023–24 outbreaks

Model projections were made from August 2022. The subsequent Winter 2022 outbreak spanned August 2022 to February 2023, peaking in December 2022, with the greatest burden of daily admissions observed on December 7th in the data and January 14th in the model, respectively (see Fig. 3). The model peak is of a similar timing and magnitude with a slightly narrower peak width, suggesting a shorter modelled outbreak compared to the one observed. This is consistent with model behaviour during the fitted period.

Similar patterns were observed for the 2023–24 period, with a peak observed in November 2023 (the greatest burden of daily admissions was observed on November 1st in the data and November 26th in the model, respectively). The timing and size of this peak were less well captured than that of the 2022–23 Winter peak. Overall, our model captured the approximate timing of the outbreaks' peaks (see Fig. 3). The model peaks simulated tended to be sharper, slightly larger and exhibit a more restricted seasonality (i.e. have a narrower peak width).

3.3. Age-structure shift

In a typical pre-pandemic RSV season in Wales, 89%–97% of admissions occur in infants <1 year old, with the majority of admissions in <6 months (see Fig. 4). This is reflective of the 92% average observed across the UK (Taylor et al., 2016). Winter admissions were predominantly comprised of infants under 1 year old, with 62%–67% of admissions in <6 months and 27%–30% in 7–12 months (see Fig. 4). A smaller percentage of admissions in 1–2 years old (5%–8%) and <1% of admissions in 2–15 years old were recorded.

Interestingly, the proportion of admissions in 0–6 months and 7–12 months differed between Winter and Spring peaks; with ~10% el-

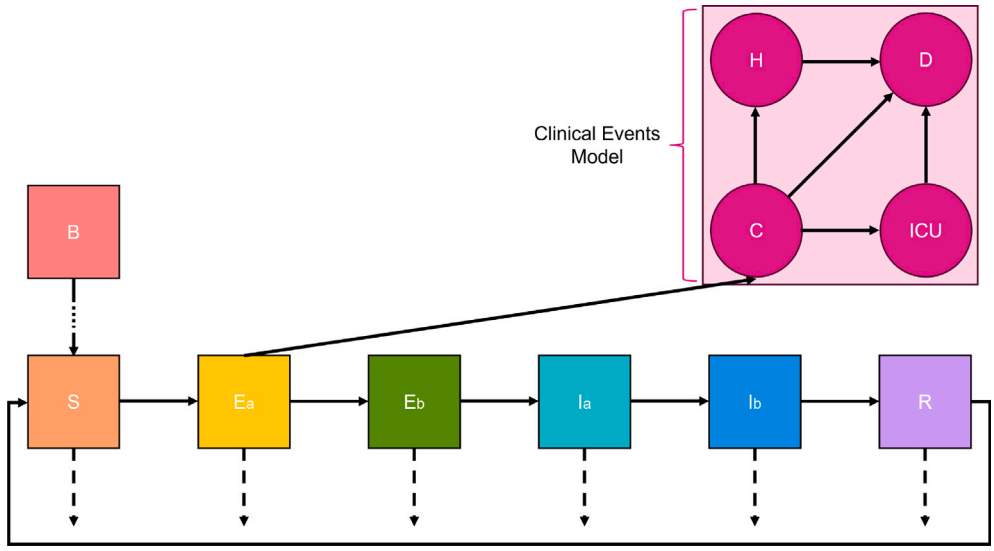

Fig. 2. Schematic representation of our transmission model paired with our clinical events model. Individuals in B ("born immune") transition to S_1 (Susceptible, age category 1). Dashed lines represent λ_i (cohort maturation), and link each compartment within an age group i with the same compartment in age group $i+1$ for $i < n$. The disease has two exposed compartments, E_a and E_b, and two infectious compartments, I_a and I_b. All compartments bar B ("born immune") are replicated across age groups. A proportion of the individuals in the E_a compartment become cases, cases can be hospitalised or admitted to the ICU. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

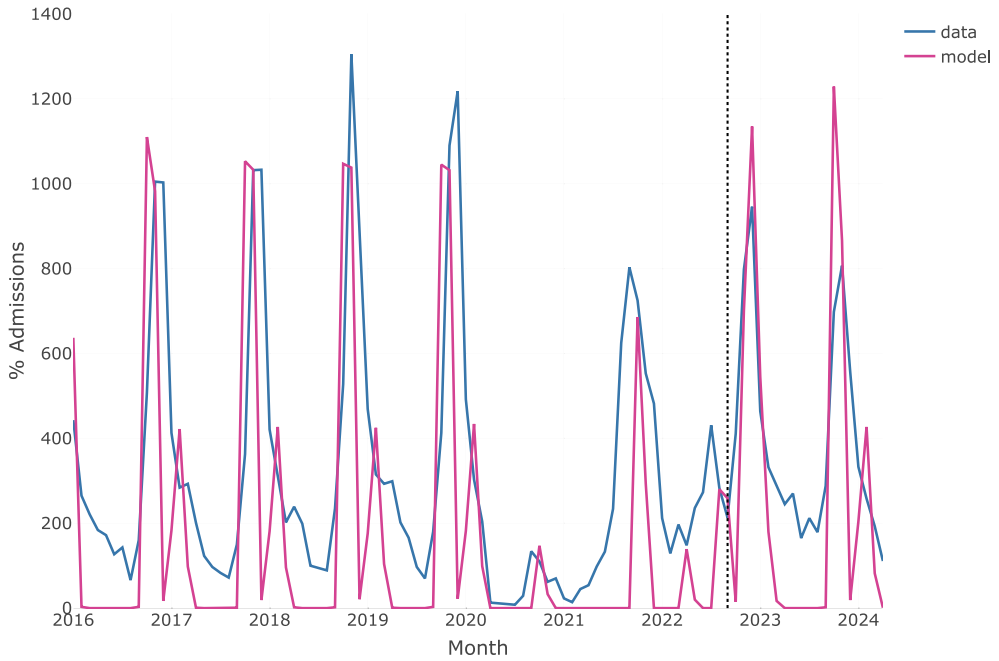

Fig. 3. Paediatric Admissions in Wales 2016–24. Monthly paediatric admissions from PHW surveillance (blue) and monthly model output (pink). The black dotted line represents the end of model fitting in August 2022. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

evation in the proportion of 7–12 months hospitalised during the Spring compared to the Winter offset by a similar sized decrease in 0–6 months. Spring admissions were also predominantly comprised of infants under 1 year old; with 54%–58% of admissions in <6 months and 35%–40% in 7–12 months. With a smaller percentage of admissions in 1–2 years old (6%–8%) and <1% of admissions in 2–15 years old. It is not clear how this pattern reflects suggestions that infants >6 months are better protected from severe infection due to aging-related lung maturation or protective immunity (Ohuma et al., 2012; Pedraza-Bernal et al., 2016; Ruckwardt et al., 2016).

Following the introduction of NPIs, changes were observed in the admissions age-structure, these were not homogeneous across age categories (see Fig. 4). Indeed, a comparison of pre-pandemic average annual admissions with admissions in 2021 revealed similar admissions rates in infants <1 year old and children/adolescents 5–15 years old (these were not statistically significant). During the NPI period, higher rates of hospitalisation were observed in 1–2 years old; they formed 18% of hospitalisations in Autumn 2020 and 15.5% in Autumn 2021, respectively. Higher rates of hospitalisation were also observed in 2–4 years old in Autumn 2021 (3%, approximately a quintupling of

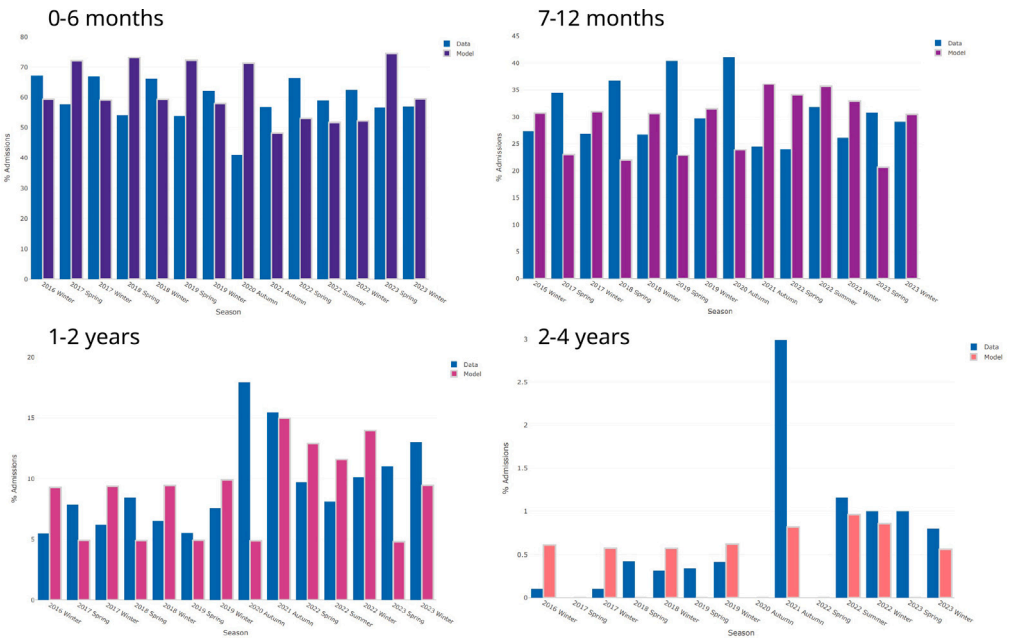

Fig. 4. Comparison of the admissions age-structure between surveillance data and model. Top left 0–6 months, top right 7–12 months, bottom left 1–2 years and bottom right 2–4 years. Most admissions were in <12 months (top row), with the greatest shift in age-structure observed in 1–2 and 2–4 years old (bottom row) in Autumn 2021. Due to differences in admissions between age groups, the scale of each bar plot differs (0%–80% for 0–6 months, 0%–45% for 7–12 months, 0%–20% for 1–2 years and 0%–3% for 2–4 years), to provide a clearer visualisation of the admissions age-structure. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

admissions). Changes observed in 2021 were statistically significant for both 1–2 years old and 2–4 years old (Chi-squared test, $p = 0.002$). A greater burden of hospitalisations has been observed in 1–4 years old since final NPI relaxation, (typically >10% in 1–2 years old and 1% in 2–4 years old, respectively).

Given the fine detail of the data, the model replicated the age-structured admissions in <12 months reasonably well, along with the trends in the shift in age-structure. However, absolute admissions in 1–2 years old and 2–4 years old appear to be harder to capture and the admissions age-structure in the model returned more rapidly to normal in the post-NPI period than found in the data.

4. Discussion

To study the impact of NPIs on typical, seasonal RSV transmission patterns, we have developed an age-structured transmission model and fitted it to 8 years of Welsh hospitalisation data. Following the lockdown response to the COVID-19 pandemic, and the significant reduction in transmission for all seasonal respiratory viruses, RSV returned with three out-of-season peaks; Autumn 2020 (coincident with COVID-19 first-wave NPI relaxation and children returning to school after summer holidays), Autumn 2021 (coincident with schools opening after the summer holidays and following the road map out of NPIs) and Summer 2022 (two months after the relaxation of final restrictions and resumption of, likely, normal contact/mixing patterns) (see Figs. 1 and 3). These dynamics are consistent with those expected from a reduction in exposure rates and a build-up of susceptible cohorts following reduced transmission over the pandemic.

Given the close geographical proximity and shared UK Parliament of England and Wales, NPIs introduced between Spring 2020 and Summer 2021 were similar. During the 2020–21 season, RSV-related paediatric hospital admissions in England were 73.7% lower than pre-pandemic levels, with an out-of-season outbreak observed in Autumn 2021 (Bardsley et al., 2023). Whilst, we successfully captured the magnitude and timing of the Autumn 2021 peak in Wales, we were unsuccessful in our capture of the extended season duration. By contrast, another SIRS-type age-structured modelling effort (in England and Wales) more successfully captured the extended season length but overestimated the peak's magnitude (making findings similar to pre-pandemic patterns) (Koltai et al., 2022. Discrepancies in season length modelling may stem from differences in assumptions about contact rate reduction, whilst we assumed that contact rates were reduced until final NPI removal in May 2022, Koltai et al. (2022) assumed that normal mixing resumed in the Summer of 2021. The latter assumption reflects the removal of most NPIs in England on July 18th 2021 (Brown and Kirk-Wade, 2021).

Findings from England and Wales are consistent with changes in seasonality and out-of-season outbreaks observed across the Northern and Southern hemispheres during the 2020–21, 2021–22 and 2022–23 seasons (ECDC, 2022; Kyriakides et al.; Casalegno et al., 2023; Meslé et al., 2023; Olsen et al., 2021; Monoi et al., 2023; Jia et al., 2022). Additionally, analogous findings have been reported from Australia and South Africa (Eden et al., 2022; Bents et al., 2023).

Using the fitted model as a forecasting tool for the 2023 and 2024 seasons, the model accurately captured the magnitude of the overall waves and the timing of their central peaks. Again, suggesting simple SEIR dynamics capture the key RSV patterns as they settled back to near-normality. However, some seasonal disruption patterns persisted in Wales in the 2022–23 and 2023–24 seasons, with the "Winter" outbreaks spanning longer periods (for example: August 2023 to February 2024, see Fig. 3). As projected by the model, cumulative admissions in 2023 were similar to cumulative admissions in 2018 (4505 and 4605, respectively). The data suggests that the burden of RSV hospitalisations did not increase, rather the distribution of admissions was somewhat altered. This is contrary to previous suggestions that RSV would revert back to pre-pandemic patterns during the 2022–23 season (Koltai et al., 2022).

Post-NPI admission age-structure shifts appear to differ between countries. We report that admissions trends were reasonably conserved in infants <1 year old and children/adolescents 5–15 years old in 2021 and 2022 in Wales. This contrasts with previous findings from South Africa (for the same time period) which showed a decrease in hospitalisations in 3–5 months despite robustness in 0–2 months

and 6–11 months (Bents et al., 2023). Conversely, in China in 2021 the median age of hospitalised patients increased from 2 months to 4 months; with the greatest changes seen in <1 month (10.3% decrease in admissions) and 5–18 years old (2.7% increase in admissions) (Jia et al., 2022).

Additionally, in 2021 we observed statistically significant changes in both 1–2 years old and 2–4 years old but these were not replicated in 2022. By contrast, in South Africa trends remained consistent in 12–23 months but nearly doubled in >2 years old; with the most pronounced changes reported for 3–4 years old for both 2021 and 2022. It is possible fewer 2–4 years old were susceptible in Wales in 2022 given the quintupling of admissions in 2021.

More broadly, the age-structure shift is likely to have been driven by the birth of three immune naïve cohorts having delayed exposure to RSV leading to larger outbreaks of RSV (Eden et al., 2022). Given the preponderance of admissions in <6 months, it would be logical for increasing the age of first infection to coincide with reduced hospitalisations. However, admissions data from Europe, the US, Japan, China, Australia and South Africa have shown that this was not necessarily the case (ECDC, 2022; Kyriakides et al.; Casalegno et al., 2023; Olsen et al., 2021; Monoi et al., 2023; Jia et al., 2022; Eden et al., 2022; Bents et al., 2023).

One possible explanation is that the 'honeymoon effect' observed (large transmission reduction in response to NPIs then out-of-season outbreaks following relaxation) resulted in a larger pool of susceptibles, plus an increase in the mean age of infection, with older cohorts being less likely to be admitted as a severe case. Although we were not able to directly estimate individual age-class hospitalisation rates, we briefly explored the sensitivity of the model output to these parameters and noted that the data was only consistent with considerably higher rates in the lowest age-classes. Additionally, a comparison of total admissions for the two 5-year periods before and after NPI implementation (March 2016 to February 2020 and March 2020 to February 2024) showed that there were 4079 more admissions in the pre-NPI period compared to the post-NPI period (17,895 and 13,819, respectively) suggesting we did not see a worsening 'divorce effect' (Hollingsworth et al., 2020).

It is possible the change in age-structure was not driven solely biologically but that social factors also played a role. In the UK, unscheduled short stay admissions and emergency department attendances were elevated in 2018-19 (Public Health Scotland, 2024). In the context of RSV admissions in Wales, the Winter 2019 peak was larger than in previous years (see Fig. 3). There are several behavioural factors associated with non-urgent attendance of paediatric emergency departments; parental worry, perceived advantages (i.e. care from a paediatrician), perception of unsuitability of other healthcare services, social network influence and lack of confidence due to low health literacy (Holden et al., 2017). The impact of parental stress is exacerbated if the child is younger (Zdun-Ryzewska et al., 2021). It is also important to note, a high proportion of infants <1 year old are admitted, yet quickly discharged after assessment whereas, older children may be assessed in Accident & Emergency (not formally admitted) and sent home thus, not featuring in admissions records.

Whilst our model captures the timing and magnitude of admissions peaks well, it underestimates peak width (assuming a more restricted seasonality than the data) and struggles to capture troughs assuming zero values during these periods (leading to an underestimation of admissions during lower admission periods). These unrealistic transitions between epidemic and inter-season periods could stem from a lack of smoothing in $\beta(t)$ or overfitting to discrete hospitalisation events. It is likely the latter given how challenging it was to fit the Summer 2022 admissions peak. If used prospectively, this could lead to difficulty projecting season start and end dates and underestimate the number of admissions outside of the pre-pandemic RSV season. In terms of the admissions age-structure, although the model broadly replicated this well (particularly in <12 months), the fit was imperfect (particularly in 2–4 years old). This may be explained by the assumption of uniform contact rates and uniform scaling (i.e. the same $\beta(t)$) in individuals under 4 years old. A Markov Chain Monte Carlo could be used in future studies to estimate a smoother function for $\beta(t)$ and improve the transitions seen.

Prior to the COVID-19 pandemic, the RSV season had a predictable, annual cycle. Our present study has shown that, by changing age-specific susceptibility of the population and projecting rebound timings, modelling can predict the main patterns (i.e. impact) of transmission interruptions. Although our model is calibrated for Welsh demographics and interventions, the consistency with classic SEIR-type transmission dynamics suggests it could be widely applicable. Subtle extended-season and age effects do however remain to be explained. Projection of timings of rebounds, and especially their impact on age-structure, is particularly useful for healthcare policymakers and planners. Given the dynamicity of RSV seasonality and changes to the admissions age-structure, seasonal patterns should continue to be observed and age-specific changes should be documented. Additionally, alternative methodologies for fitting β should be trialled in the future, with an aim to improve predictions during transitional periods. We aim to monitor the evolving situation, using our model as the basis of medium-term (6–8 week) projections to assist with admissions planning of RSV vaccines introduced in Autumn 2024, for pregnant women and older people in Wales.

CRediT authorship contribution statement

Gabriella Santiago: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Carla White:** Writing – review & editing, Methodology, Investigation. **Brendan Collins:** Writing – review & editing. **Simon Cottrell:** Writing – review & editing, Investigation, Data curation. **Chris Williams:** Writing – review & editing, Investigation, Date curation. **Biagio Lucini:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Mike B. Gravenor:** Writing – review & editing, Supervision, Methodology, Project administration, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.epidem.2025.100860.

Data availability

Data will be made available on request.

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