Incorporating spatial dose metrics in machine learning-based normal tissue complication probability (NTCP) models of severe acute dysphagia resulting from head and neck radiotherapy

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Incorporating spatial dose metrics in machine-learning-based normal tissue complication probability (NTCP) models of severe acute dysphagia resulting from head and neck radiotherapy

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\textbf{Abstract}

Severe acute dysphagia commonly results from head and neck radiotherapy (RT). A model enabling prediction of severity of acute dysphagia for individual patients could guide clinical decision-making. Statistical associations between RT dose distributions and dysphagia could inform RT planning protocols aiming to reduce the incidence of severe dysphagia. We aimed to establish such a model and associations incorporating spatial dose metrics. Models of severe acute dysphagia were developed using pharyngeal mucosa (PM) RT dose (dose-volume and spatial dose metrics) and clinical data. Penalized logistic regression (PLR), support vector classification and random forest classification (RFC) models were generated and internally (173 patients) and externally (90 patients) validated. These were compared using area under the receiver operating characteristic curve (AUC) to assess performance. Associations between treatment features and dysphagia were explored using RFC models. The PLR model using dose-volume metrics (PLR\textsubscript{standard}) performed as well as the more complex models and had very good discrimination (AUC = 0.82) on external validation. The features with the highest RFC importance values were the volume, length and circumference of PM receiving 1 Gy/fraction and higher. The volumes of PM receiving 1 Gy/fraction or higher should be minimized to reduce the incidence of severe acute dysphagia.

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\section*{Introduction}

Acute dysphagia is a common toxicity resulting from head and neck (chemo)radiotherapy (RT), having a substantial impact on patients’ quality of life \cite{1} and personal relationships \cite{2}. Around half of patients experience significant acute swallowing dysfunction \cite{3}. Moreover, severe acute reactions have been implicated in the development of “late” radiation toxicities \cite{4,5}, including late dysphagia \cite{6}. Clinicians are unable to accurately predict which patients will experience severe acute dysphagia \cite{7}. A normal tissue complication probability (NTCP) model with good predictive ability would, therefore, represent a highly useful tool for clinical decision-support, treatment plan comparison, treatment modality selection \cite{8} and isotropic dose escalation (as is being evaluated in lung RT \cite{9}). Recently, NTCP models of dysphagia six months following RT \cite{10,11} were successfully validated \cite{12-14}. However, as many patients suffer severe acute dysphagia that resolves by six months following RT, these models do not capture the substantial early toxicity burden. The currently existing NTCP models for severe acute...
dysphagia, whilst promising and providing useful insights, [15–21] possess suboptimal discriminative ability and, hence, are not routinely used to guide clinical decision-making.

In addition to the prediction of individual patient toxicity outcomes, there is substantial interest in determining statistical associations between RT dose metrics and toxicity to inform the optimal design of RT treatment planning techniques attempting to reduce the incidence of toxicity. A large number of studies, summarized in [22,23], with conflicting findings, have sought to establish substructures within the head and neck region that are radiosensitive for late dysphagia. However, the apparent differential radiosensitivity of substructures within the pharyngeal musculature is likely to be an artefact of the positions of the primary disease sites relative to those substructures in these study cohorts [24]. To overcome this bias, we combined multiple spatial dose metrics, which are sensitive to both the extent of the dose distribution and regional variations in radiosensitivity, to “tease apart” these effects. Additionally, we hypothesized that the addition of spatial dose metrics would increase the discriminative performance of NTCP models, compared with dose-volume metrics, as has previously been demonstrated for xerostomia [25] and rectal toxicities [26].

The first aim of this study was to determine whether the addition of novel spatial dose metrics would improve the predictive performance of NTCP models for severe acute dysphagia. The second aim was to establish statistical associations between the RT dose distribution and severe acute dysphagia that could be used to inform RT planning techniques aiming to reduce the incidence of severe dysphagia. This study built upon previous acute dysphagia models [27,28] by introducing novel spatial dose metrics and using machine learning approaches.

**Material and methods**

**Patient data**

Severe acute dysphagia models were generated and internally validated using a training dataset of 335 patients with DICOM RT data available, enrolled in one of six different clinical trials [29–33], with institutional review board approval and signed patient consent (Table 1). Patients for whom clinical data (age, sex, primary disease site, use of chemotherapy) were unavailable (13 patients) were excluded from the analyses. The cohort includes a diverse range of primary disease sites and RT delivery techniques, ensuring a large variation in the dose distributions across the cohort. This increases the generalizability of the models and reduces the chance of introducing biases, for example, due to the primary tumour location. An independent external validation dataset was provided by Washington University School of Medicine in Saint Louis (Table 1). This consisted of 90 patients with a range of head and neck primary tumour sites.

The incidences of severe acute dysphagia were defined as the patient requiring percutaneous endoscopic gastrostomy tube (PEG) insertion. It should be noted that there was a slight difference in the scoring systems due to the data available. All institutions treating patients used in this study, including the training and external validation cohorts, employed a reactive and conservative approach to PEG insertion. After removing patients with missing data, 173 patients were available for training and 90 patients available for external validation. The incidences of severe acute dysphagia were 66% in the

<table>
<thead>
<tr>
<th>Trial</th>
<th>Patients available</th>
<th>Primary disease site</th>
<th>Radiotherapy technique</th>
<th>Radiotherapy dose-fractionation</th>
<th>Concurrent chemotherapy</th>
</tr>
</thead>
<tbody>
<tr>
<td>COSTAR (Phase III, multicentre) [29]</td>
<td>72</td>
<td>Parotid gland</td>
<td>Unilateral; 3D conformal RT, IMRT</td>
<td>65 Gy/30 # (definitive RT), 60 Gy/30 # (post-operative RT)</td>
<td>No</td>
</tr>
<tr>
<td>PARSPORT (Phase III, multicentre) [25]</td>
<td>67</td>
<td>Oropharynx, hypopharynx</td>
<td>Bilateral; 3D conformal RT, IMRT</td>
<td>65 Gy/30 # (definitive RT), 60 Gy/30 # (post-operative RT)</td>
<td>No</td>
</tr>
<tr>
<td>Dose Escalation (Phase II, single centre) [26]</td>
<td>26</td>
<td>Larynx, hypopharynx</td>
<td>Bilateral; IMRT</td>
<td>67.2 Gy/28 #, 63 Gy/28 #</td>
<td>Yes</td>
</tr>
<tr>
<td>Midline (Phase II, single centre) [27]</td>
<td>116</td>
<td>Oropharynx</td>
<td>Bilateral; IMRT</td>
<td>65 Gy/30 # (definitive RT), 60 Gy/30 # (post-operative RT)</td>
<td>Yes</td>
</tr>
<tr>
<td>Nasopharynx (Phase II, single centre) [28]</td>
<td>36</td>
<td>Nasopharynx</td>
<td>Bilateral; IMRT</td>
<td>65 Gy/30 # (definitive RT), 60 Gy/30 # (post-operative RT)</td>
<td>Yes</td>
</tr>
<tr>
<td>Unknown Primary (Phase II, single centre) [29]</td>
<td>18</td>
<td>Unknown primary</td>
<td>Bilateral; IMRT</td>
<td>65 Gy/30 # (definitive RT), 60 Gy/30 # (post-operative RT)</td>
<td>Yes</td>
</tr>
<tr>
<td>Washington University School of Medicine in Saint Louis (Independent external validation)</td>
<td>90</td>
<td>Oral cavity, nasal cavity, nasopharynx, oropharynx, hypopharynx, larynx, parotid gland, unknown primary</td>
<td>Bilateral, unilateral; IMRT</td>
<td>70 Gy/35 #, 66 Gy/33 #, 60 Gy/30 #</td>
<td>Both concurrent and no concurrent chemotherapy</td>
</tr>
</tbody>
</table>

The first six trials were used for model training and internal validation. The last trial was used for independent external validation. IMRT – intensity-modulated radiotherapy; # – fractions; RT – radiotherapy; Unilateral – treatment delivered to ipsilateral parotid bed only; Bilateral – treatment delivered to ipsilateral and contralateral mucosa of relevant subsite (e.g. nasopharynx, oropharynx or larynx). All fractionation regimens used 5 fractions per week with 1 fraction per day from Monday to Friday. Where multiple fractionation schedules are listed for a single trial this means that multiple fractionation schedules were employed in those trials.
training dataset and 48% in the external validation dataset. The training dataset incidence is artificially inflated by the strategy for handling missing toxicity data.

Induction chemotherapy, concurrent chemotherapy regimen (cisplatin, carboplatin, one cycle of cisplatin then one cycle of carboplatin or none), definitive versus post-operative RT, primary disease site (nasopharynx/nasal cavity, oropharynx/oral cavity, hypopharynx/larynx, parotid gland and unknown primary), sex and age were also included as covariates in the models. These clinical covariate data are given in Appendix B.

Calculations

Radiotherapy dose metrics

The pharyngeal mucosa (PM) was considered as the organ-at-risk for acute dysphagia. The PM was delineated, by clinical oncologists, from the roof of the nasopharynx to the level of the suprasternal notch (Appendix C). The physical dose distribution was converted to the fractional dose distribution (physical dose delivered in each fraction), which was described by the dose-volume histogram (DVH) in 20 cGy intervals from 20 (V20) to 260 (V260) cGy per fraction. The use of the fractional DVH is appropriate as nearly all patients who developed severe acute dysphagia developed it before the full course of RT had been delivered (data not shown) and follows recommendations for acute toxicity modelling by Tucker et al. [35]. Using the biologically effective dose in place of the fractional dose made very little difference to the results due to the fractionation regimens employed (data not shown). The dose distribution was also described spatially, using novel dose-length (DLH; L20 – L260) and dose-circumference histograms (DCH; C20 – C260) and 3D moment invariants describing the centre of mass (\(I_{001}, I_{010}, I_{100}, I_{011}, I_{101}, I_{110}, I_{111}\)), spread (\(I_{002}, I_{020}, I_{200}\)) and skewness (\(I_{003}, I_{030}, I_{033}\)) of the dose distribution in the left-right, anterior-posterior and superior-inferior directions [25,36], detailed in Appendix D.

Statistical modelling

Statistical analysis was performed using a machine learning pipeline specifically designed for NTCP modelling [36]. Three types of model were compared, penalised logistic regression (PLR), support vector classification (SVC) and random forest classification (RFC). For each, a version with dose-volume metrics (“standard”) and with the spatial dose metrics (“spatial”) was trained and validated. This is described in Appendix E.

Results

The DVH, DLH and DCH data are summarized in Fig. 1. A correlation matrix of the data is shown in Appendix F. Regarding the first aim, the predictive performances of the models are shown in Table 2.

The discrimination of the PLRstandard model was not outperformed by any of the more complex models, on internal (AUC = 0.76, s.d. = 0.08) or external validation (AUC = 0.82, s.d. = 0.04). The log loss and Brier score were similar between all PLR and RFC models on internal and external validation. SVC models do not provide probability estimates; hence, only discrimination could be assessed. Platt scaling was employed to convert the SVC model outputs to probability estimates [37]. However, this led to substantial reductions in AUC related to the algorithm used (data not shown) so the non-scaled SVC models were preferred. The RFC models had better calibration (calibration slope closer to 1 and intercept closer to 0) than the PLR models on internal and external validation. The discriminative ability of PLRstandard model was good on internal validation and very good on external validation. The calibration curve, of the predicted probabilities of severe dysphagia against the actual toxicity outcomes, for this model applied to the external validation data is displayed in Fig. 2a.

The model calibration assessed on the external validation dataset was modest. However, the limitations of model calibration assessment, particularly on a small dataset, should be considered [38]. Fig. 2b indicates how the predicted probability of severe dysphagia in the external validation is related to the DVH. The regression coefficients, and covariate means and standard deviations

Fig. 1. Summary of the pharyngeal mucosa (a) DVH, (b) DLH and (c) DCH data grouped by severe or non-severe peak dysphagia. The lines represent the group medians and the error bars represent the 95 percentile confidence intervals.
required to standardize the covariates, necessary to use the model are provided in Table 3.

The model is given by: \( NTCP = e^f / (1 + e^f) \) where \( f = \alpha + \sum \beta_i x_i \)
where \( \alpha \) is the intercept, \( \beta_i \) is the regression coefficient for covariate \( i \) and \( x_i \) is the, centred and scaled, value of covariate \( i \). To use the recalibrated version of the model \( f \) is instead given by
\[
F_{\text{recalibrated}} = c_{\text{intercept}} + c_{\text{slope}}(\alpha + \sum \beta_i x_i)
\]
where \( c_{\text{intercept}} \) and \( c_{\text{slope}} \) are the external validation intercept and slope (Table 2).

Concerning the second aim, the feature importance values for the RFC models are displayed in Fig. 3.

These indicate increasing importance of the DVH, DLH and DCH metrics, in terms of predicting severe dysphagia in the models, with increasing dose level up to a fractional dose of 180 cGy, for RFCstandard, or 220 cGy, for RFCspatial. There is a decrease in importance at higher doses in this, data-driven, analysis. In the RFCstandard and RFCspatial models, the V140 and C220 were the covariates most strongly associated with severe dysphagia, respectively. The 3D moment invariant with the highest feature importance was \( \eta_{\text{002}} \), describing the spread of the dose in the superior-inferior direction. For completeness, the RFC feature importance values were calculated for a model including both dose-volume and spatial dose metrics (Appendix C).

In both RFC models, the clinical covariates with the highest feature importance were parotid gland primary disease site, no concurrent chemotherapy and age. Parotid gland primary disease site correlated strongly with the dose metrics (Appendix F) as patients with parotid gland primaries received unilateral irradiation and, hence, a smaller volume of PM irradiated. No concurrent chemotherapy was correlated with parotid gland primary disease site and the dose metrics (Appendix F) as the parotid gland cancer patients, treated in the COSTAR trial, did not receive concurrent chemotherapy. These correlations should be considered when interpreting the results. When interpreting the apparent importance of age it is important to consider that it may have been artificially inflated due to the larger number of possible values than the other clinical covariates [39]. The RFC model feature importance results agreed with the PLRstandard model regression coefficients (Table 3).

Discussion

We met our first aim of determining whether the addition of novel spatial dose metrics could improve the predictive performance of NTCP models of severe acute dysphagia. We suggest that the PLRstandard model should be preferred over the other models, for prediction, on the grounds of at least as good discrimination as the other models, similar log loss and Brier score and greater simplicity. The good discriminative ability of this model, on internal and external validation, makes it a suitable aid for supporting clinical decision-making. The “spatial” models trained in this study did not have better discriminative ability than the “standard” models so we do not recommend their use. This may have been due to the DLH and DCH metrics being highly correlated with the DVH metrics (Appendix F). Hence, the spatial variations in the dose distributions across the cohort were captured by the DVHs. It is important to note that we cannot rule out the possibility that using different spatial dose metrics, combinations of features, models or datasets would improve model performance compared with dose-volume based acute dysphagia models. Potential uses of the model are discussed in Appendix H.

We also achieved our second aim of establishing associations between the RT dose distribution and acute dysphagia. The decrease in feature importance for the highest dose levels was due to a lack of variation in these metrics between patients, as they are either 0 or close to 0 for all patients, rather than indicating reduced biological effects at these dose levels. Our results do not support the existence of regional variations in radiosensitivity of the PM for severe acute dysphagia. The fact that \( \eta_{\text{002}} \) was the 3D moment invariant with the highest feature importance suggests that the length, which is correlated with the volume, of the PM irradiated is more important for toxicity than the irradiation of any sub-region of the structure. Other studies suggested that different pharyngeal muscles were more radiosensitive [19,21–23]. However, this is likely related to the primary disease sites of the patients used in those studies [24]. The inclusion of multiple spatial dose metrics, sensitive to different spatial aspects of the dose distribution, and a cohort with a wide variety of dose distributions allowed us to explore regional variations in radiosensitivity more thoroughly than has previously been performed. However, we cannot exclude the possibility that different spatial dose metrics [19], combinations of features, models or datasets could support the existence of spatially dependent radiosensitivity for severe acute dysphagia. The feature importance measures (Fig. 3) indicate that the volume of PM receiving intermediate and high doses are most strongly associated with severe acute dysphagia. This is in agreement with another study using the same data, but a different approach to statistical mod-
elling [28]. RFC feature importance does not provide information on whether the correlations between features and outcome are positive or negative. However, the regression coefficients for the PLRstandard model (Table 3) indicate that the higher the value of the dose metrics the greater the probability of severe dysphagia. There is a relatively large increase in feature importance between V80 and V100 (Fig. 3A). A pragmatic recommendation for RT planning techniques aimed at reducing the incidence of severe acute dysphagia, based on these findings, would be to reduce the volume of the entire PM receiving greater than 1 Gy/fraction as much as possible without compromising other aspects of the treatment plan.

Fig. 2. (a) Calibration of the probabilities of severe dysphagia, as predicted by the PLRstandard model (x-axis), against the observed fraction of severe dysphagia in the external validation dataset (y-axis). The curve shows a logistic regression model of the predicted probabilities (independent variable) against the observed fraction of patients with severe dysphagia (dependent variable). The inset figure shows the histogram of the predicted probabilities and the observed toxicity outcomes (1 = severe dysphagia; 0 = no severe acute dysphagia). (b) Median dose-volume histograms (error bars show 95% confidence intervals) for external validation patients grouped by probability estimate quintiles using the recalibrated PLRstandard model.
A previous model of severe acute dysphagia, without the novel spatial dose metrics, but with a different statistical modelling approach, functional data analysis, had similar discriminative ability to the models trained in this study, but superior performance in terms of the probability calibration [28]. Hence, we recommend that the model recommended in [28] should be preferred over the models presented here for clinical decision-support. The Groningen group have produced and validated models of dysphagia measured six months following RT [10–13,40,41]. Models of severe dysphagia at earlier time points focused on establishing associations between covariates and outcome and, hence, either did not optimize or measure discrimination [15,18,20], included much smaller numbers of patients [19,21] or had lower discriminative ability than the PLRstandard model [16,17]. In addition, with the exception of one study [42], no external validation has been performed. We did not have access to data pertaining to all the covariates, for example genetic polymorphisms, in those published models and, so, were unable to validate them. Moreover, our study featured a more thorough exploration of RT dose-response associations for severe acute dysphagia, including multiple dose levels and different types of spatial dose metric, than previous studies. This resulted in novel insights that could inform RT planning.

Our study possesses several limitations. Firstly, the scoring systems used to assess dysphagia severity differed between the training data and external validation data. The threshold for “severe” dysphagia in the external validation data is higher than in the training data. Therefore, the models generated using the training data generalized well to the external validation data. Whilst the limitations of the CTCAE dysphagia scoring system, which was almost exclusively used when the trials incorporated in this study were conducted, have been demonstrated [43], it has been shown to correlate well with multiple patient-reported quality of life measures [44]. As CTCAE grade 3 and PEG-dependence indicate clinical interventions these are relevant endpoints. The slight difference in the dysphagia scoring systems between the training and external validation cohorts may have reduced the performances of the models on external validation. However, the models performed at least as well on external validation as internal validation. Moreover, it is believed that severe acute dysphagia is a highly complex, multifactorial toxicity with a range of different factors having been implicated. These include tobacco and alcohol use, a patient’s pain tolerance and genetic predispositions to severe (chemo)radiation-induced toxicity. Tobacco and alcohol use were not collected in the PARSPORT or COSTAR trials. Therefore, these factors could not be included in the analysis. It is also likely that chemotherapy is insufficiently characterized, using binary variables, in our analysis. Finally, like most radiotherapy outcomes modelling studies, the size of the training and validation cohorts are smaller than recommended for clinical decision-support tools [45,46]. We suggest that investigators should strive to collect larger datasets for future development and validation of radiotherapy clinical decision-support tools.

**Conclusions**

In conclusion, we have trained and externally validated a NTCP model of severe acute dysphagia with very good discriminative ability (external validation AUC = 0.82). We suggest that this model may be suitable for clinical decision-support. Additionally, we established that the volumes of the PM receiving intermediate and high doses, greater than 1 Gy/fraction, are most strongly asso-
Fig. 3. Bootstrapped feature importance values for the covariates included in the (a) RFC\text{standard} and (b) RFC\text{spatial} models. The whiskers indicate the 95 percentile confidence intervals (data non-normally distributed). Note that the y-axis scales are different in (a) and (b).
associated with severe acute dysphagia. These should be minimized in RT planning, where possible, to reduce the incidence of severe acute dysphagia. Our data did not support a regional variation in radiosensitivity for the PM.

Conflicts of interest

None.

Acknowledgements

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Appendix A. Strategy for handling missing data

If weekly toxicity data are incomplete this can lead to assignment of an incorrect peak toxicity grade. For example, a patient has grade 1 toxicity for weeks 1 to 3, grade 2 toxicity for weeks 4 and 5, missing toxicity week 6 and 1 week following treatment and grade 2 toxicity from 2 weeks following RT to 8 weeks following RT. They would be assigned a peak grade of 2. However, they may, in fact, have experienced grade 3 toxicity, which was not scored, as they were unable to attend their follow-up appointments. This would introduce an error into the analysis. As this type of error can only lead to peak toxicity being under-scored and not over-scored it could introduce bias. Therefore, to reduce bias at the expense of statistical power, patients with any missing toxicity scores and a peak score below 3 were excluded from the analysis. Missing toxicity data were not imputed as many patients (with full toxicity data) with peak toxicity of grade 3 were only scored as grade 3 for one week. We previously investigated the effects of imputing missing toxicity measurements, where there were non-consecutive missing values and found that this made little difference [36]. Patients with some missing toxicity measurements, but at least one measurement scored as grade 3 were included as they must have a peak grade of 3 or higher. It should be noted that retaining patients with missing data, but having a peak grade of 3 skews the apparent incidences of peak toxicity grades. Unbalanced outcome classes were accounted for in the statistical modelling, as described in the manuscript. It should be noted that our approach to handling missing data might still result in bias. Where there are missing data, there is always a risk of bias, particularly where the data are not missing at random. Ultimately, the performance of the model, including any bias introduced by the missing data handling strategy, is assessed by external validation. The external validation dataset had no missing PEG-dependence data.

Appendix B. Comparison of clinical covariate data between training and external validation datasets

Table B1

<table>
<thead>
<tr>
<th>Covariate</th>
<th>n training (%)</th>
<th>n validation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Definitive RT</td>
<td>148 (86)</td>
<td>44 (49)</td>
</tr>
<tr>
<td>Male</td>
<td>114 (66)</td>
<td>68 (76)</td>
</tr>
<tr>
<td>Induction chemotherapy</td>
<td>94 (54)</td>
<td>21 (23)</td>
</tr>
<tr>
<td>No concurrent chemotherapy</td>
<td>82 (47)</td>
<td>46 (51)</td>
</tr>
<tr>
<td>Cisplatin</td>
<td>66 (38)</td>
<td>28 (31)</td>
</tr>
<tr>
<td>Carboplatin</td>
<td>14 (8)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Cisplatin/Carboplatin</td>
<td>11 (6)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Hypopharynx/Larynx</td>
<td>24 (14)</td>
<td>25 (28)</td>
</tr>
<tr>
<td>Oropharynx/Oral cavity</td>
<td>87 (50)</td>
<td>41 (46)</td>
</tr>
<tr>
<td>Nasopharynx/Nasal cavity</td>
<td>18 (10)</td>
<td>15 (17)</td>
</tr>
<tr>
<td>Unknown primary</td>
<td>10 (6)</td>
<td>3 (3)</td>
</tr>
<tr>
<td>Parotid gland</td>
<td>34 (20)</td>
<td>6 (7)</td>
</tr>
<tr>
<td>Covariate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age</td>
<td>59 (23–88)</td>
<td>58 (21–87)</td>
</tr>
</tbody>
</table>

Concurrent chemotherapy was administered in two cycles, on days 1 and 29 of RT, in the training data cohort and in three cycles on days 1, 22 and 43 of RT for definitive RT for cetuximab in the external validation cohort.

Appendix C. Pharyngeal mucosa contouring

Fig. C.1 displays an example of the pharyngeal mucosa contouring technique employed.

In addition to the pharyngeal mucosa, irradiation of the cervical oesophagus can also cause dysphagia [21,47]. Therefore, the oesophagus, down to the level of the suprasternal notch, is included in the pharyngeal mucosa organ-at-risk structure. The cranial extent of the structure is the roof of the nasopharynx and the caudal extent is the level of the suprasternal notch. Most patients in the training data cohort were treated with extended neck positioning, to reduce oral cavity doses. Patients in the external validation cohort were treated with a neutral neck position. Contouring the structure took approximately 5 min per patient.

Appendix D. Spatial dose metrics

For the “spatial” models, multiple different metrics, encoding different types of spatial information, were used to represent the fractional dose distribution. The longitudinal and circumferential extents of the dose distribution to the pharyngeal mucosa were extracted by transforming the Cartesian co-ordinates of the pharyngeal mucosa structure into cylindrical co-ordinates, with the long axis in the superior-inferior direction. Binary masks were generated with thresholds at each fractional dose level from 20 cGy to 260 cGy in 20 cGy intervals. For each binary mask, the longitudinal extent was calculated by summing the number of axial slices containing a 1 and multiplying this by the slice thickness. The circumferential extent was calculated by determining the maximum angle subtended in the axial plane by the binary mask, with the angle measured from the centre of mass of the pharyngeal mucosa. The absolute longitudinal and circumferential extents were normalized to the entire length (by dividing by the length of the pharyngeal mucosa OAR and converting to a percentage) and
the dose is. Moments describing the centre of mass (the left-right direction describe how lateralized or centralized left-right symmetry is accounted for such that the moments in the spatial description of the dose distribution, compared with our expected to offer any significant improvement in the accuracy of the dose-surface maps would not be expected to offer any significant improvement in the accuracy of the spatial description of the dose distribution, compared with our pragmatic approach. Secondly, the pharynx is not a simple tubular shape, but contains ”internal structure”, such as the uvula and glossopiglottic fold. Hence, it is not trivial to ”unwrap” it into a 2D map.

This approach differed from other methods used to characterize the spatial distribution of the dose to other tubular organs, such as 2D dose-surface maps for the rectum [48,49]. The reasons for this were twofold. Firstly, the pharynx is a straight rigid structure (although there could be some deformation anteriorly), unlike some other tubular organs, like the rectum, which are more tortuous. Therefore, more sophisticated methods that account for this curvature in construction of the dose-surface maps would not be expected to offer any significant improvement in the accuracy of the spatial description of the dose distribution, compared with our pragmatic approach. Secondly, the pharynx is not a simple tubular shape, but contains ”internal structure”, such as the uvula and glossopiglottic fold. Hence, it is not trivial to ”unwrap” it into a 2D map.

3D moment invariants, $\eta_{abc}$ [25] describing the spatial distribution of the dose were calculated using the expression

$$\eta_{abc} = \mu_{abc}/\mu_{000}^{\frac{1}{3}} \tag{1}$$

where

$$\mu_{abc} = \sum_{x} \sum_{y} \sum_{z} [(x-x_0)^a(y-y_0)^b(z-z_0)^c] D(x,y,z) I(x,y,z) \tag{2}$$

where $x$, $y$ and $z$ are the voxel coordinates, $D(x,y,z)$ is the dose delivered to the voxel with coordinates $(x,y,z)$, $I(x,y,z)$ is an identity function, which takes a value of 1 if the voxel belongs to the OAR and 0 if it does not, and $(x_0,y_0,z_0)$ is the centre of gravity of the OAR. The moments are translational and scale invariant. The left-right symmetry is accounted for such that the moments in the left-right direction describe how lateralized or centralized the dose is. Moments describing the centre of mass ($\eta_{000}$, $\eta_{100}$, $\eta_{010}$, $\eta_{110}$, $\eta_{101}$, $\eta_{111}$), spread ($\eta_{020}$, $\eta_{200}$, $\eta_{220}$) and skewness ($\eta_{030}$, $\eta_{300}$, $\eta_{003}$) of the dose distribution in the three orthogonal directions (left-right, anterior-posterior, superior-inferior) within each structure were calculated. These allow for regional variations in radiosensitivity to be probed. These would manifest as differences in one or more of the moment invariants between patients who experienced severe mucositis and those who did not. The dose metrics were used as covariates in the statistical modelling.

The software, to extract the planned dose distributions to the pharyngeal mucosa from the DICOM data and compute the fractional DVHs and spatial dose metrics, was developed using the Python version 2.7.9 programming language [50] and the NumPy version 1.9.2 [51], SciPy version 0.15.1 [51], Matplotlib version 1.4.3 [52], Seaborn version 0.6.0 [53] and PyDicom version 0.9.9 [54] modules.

### Appendix E. Machine learning methods

All features were transformed to standardized scores (mean = 0, standard deviation = 1) to avoid scale-related feature dominance. Three different types of classification model were trained: penalized logistic regression (PLR) [55], support vector classification (SVC) [56] and random forest classification (RFC) [57]. The models all penalize complexity to prevent overfitting due to the high number of covariates per toxicity event. We have previously discussed these techniques and their advantages over “conventional” univariable and multivariable logistic regression models in NTCP modelling [36]. Two different versions of each of the three types of model were generated. One with ”standard” dose covariates, describing the dose-distribution using the DVH, and the other with ”spatial” dose covariates, describing the dose distribution using the DLH, DCH and 3D moment invariants. During model fitting the outcome classes, severe and non-severe dysphagia, were weighted inversely proportional to the class frequencies in the training data to account for the fact that the frequencies of the outcomes were unbalanced. Model hyper-parameter tuning was carried out using a cross-validated grid search with shuffled stratified cross-validation (with 80/20 training/test split) with 100 iterations. The possible hyper-parameters over which the grid-searchers were performed were:

- **PLR**: regularization = [LASSO (L1), ridge (L2)]; inverse regularization strength ($C$) = [0.0001, 0.001, 0.01, 0.1, 1.0, 10.0, 100.0, 1000.0];
- **SVC**: kernel = [linear, radial basis function]; $C$ = [0.0001, 0.001, 0.01, 0.1, 1.0, 10.0, 100.0, 1000.0]; kernel coefficient for radial basis function = [0.0001, 0.001, 0.01, 0.1, 1.0, 10.0, 100.0, 1000.0].

![Fig. C1. Axial (left), sagittal (top right) and coronal (bottom right) views of an example of the pharyngeal mucosa structure used.](image)
RFC: number of estimators = 1000; maximum depth = {5, 10, 15, 20}; maximum features = {number of features, number of features/2, square root of number of features}.

To address the first aim, the generalizability of the models to correctly predict dysphagia severity for “unseen” patients was measured through internal and external validation. Internal validation used a nested shuffled stratified cross-validation, with 80/20 training/test split. Covariate transformation to standardized scores and hyper-parameter tuning with a 5-fold cross-validated grid search with 100 iterations, were nested within the internal validation cross-validation to give unbiased error estimates. For external validation NTCP was calculated for each of the 90 external validation patients, using the models generated with the training data, and compared with the known PEG-insertion data. The external validation was bootstrapped with 2000 replicates.

Predictive performance was assessed, using several metrics, on internal and external validation. The area under the receiver operating characteristic curve (AUC) was used to measure discriminative ability for model training and validation. Log loss [58] was calculated to assess the model probability estimates and the Brier score [59] was calculated to evaluate the overall model performance. Model calibration was assessed, using the slope and intercept of a logistic regression model of the actual toxicity outcomes against the predicted probabilities of severe dysphagia [60,61]. Following external validation, the best model was updated for the Washington University patients with PEG-dependence outcome data by recalibrating it using logistic regression (logistic calibration) [62]. This improves model calibration, but does not affect discrimination. More complex model updating was not attempted due to the relatively small size of the external validation cohort [63].

To address the second aim of establishing associations between the model covariates and severe dysphagia, the feature importance values for each covariate in the RFC models were bootstrapped with 2000 replicates. We have previously determined this

- RFC: number of estimators = 1000; maximum depth = {5, 10, 15, 20}; maximum features = {number of features, number of features/2, square root of number of features}.

Fig. F1. Correlation matrix of the model variables. The colour scale shows the Spearman correlation coefficients between the model covariates. definitiveRT – definitive radiotherapy (versus post-operative radiotherapy); indChemo – induction chemotherapy; noConChemo – no concurrent chemotherapy; cisCarbo – one cycle of cisplatin followed by one cycle of carboplatin; independentValidation – patients included in external validation cohort and not used for model training or internal validation; Cx – normalized circumference of pharyngeal mucosa receiving x cGy of radiation per fraction; Lx – normalized length of pharyngeal mucosa receiving x cGy of radiation per fraction; Vx – normalized volume of pharyngeal mucosa receiving x cGy of radiation per fraction; etax – 3D moment invariants (described in Appendix D); severe acute dysphagia – peak acute dysphagia severity (non-severe = 0, severe = 1).
approach to provide a more interpretable understanding of the relationship between the RT dose distribution and toxicity than, the conventionally used, logistic regression, in the context of correlated dose metrics [36]. The feature importance is the total decrease in node impurity, weighted by the probability of reaching that node, approximated by the proportion of patients reaching that node, averaged over all of the trees in the ensemble [57]. Larger values correspond to more important features. The importance values of all the covariates sum to 1. The Pandas version 0.18.0 [64] and Scikit Learn version 0.17 [65] Python modules and val.prob.ci.2 [66] R package were used for statistical analysis.

Appendix F. Correlation matrix

Fig. F.1 shows the correlation matrix of the covariates and outcome variables included in the study.

Appendix G. Combined dose-volume and spatial dose metrics feature importance

Fig. G.1 displays the feature importance values for a RFC model including both the dose-volume and spatial dose metrics.

For equivalent dose levels the volume of pharyngeal mucosa had higher feature importance than the length or circumference. For completeness, the discriminative ability of this model was measured on internal and external validation in the same manner as for the other models (described in the manuscript). The mean internal validation AUC = 0.73 (s.d. = 0.07) and external validation AUC = 0.75 (95 percentile confidence intervals = 0.64–0.85) for this model.

Appendix H. Potential applications of the model

A potential application, for institutions operating a prophylactic, rather than reactive, approach to PEG insertion, would be to use the model to exclude a subset of patients, at low risk of PEG-dependence, from receiving this prophylactic intervention. This may result in improved long-term swallowing outcomes for these patients, as early reliance on PEG feeding has been associated with poorer long-term swallowing function in some [67,68] studies. Other potential applications include treatment plan or regimen comparison, using the model to calculate and compare the probabilities of a patient experiencing severe acute dysphagia with alternative treatment plans. Alternatively, the model could be directly used in treatment plan optimisation in place of physical dose constraints [69], for informing treatment modality selection [8] and isotoxic dose escalation, in a similar manner to approaches being evaluated in lung RT [9]. We recommend the use of decision curve analysis [70] when determining the utility of a prediction model for individualized clinical decision-making for a specific intervention.

Appendix I. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.ctro.2017.11.009.

References


