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Development of a predictive model for estimation of postoperative risk following brachycephalic obstructive airway syndrome surgery

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Objective
To identify risk factors for postoperative death and complications in dogs undergoing brachycephalic obstructive airway syndrome (BOAS) surgery and utilize this information to develop a predictive model for risk estimation.

Methods
Records of dogs undergoing BOAS surgery at a veterinary teaching hospital between 2012 and 2023 were reviewed. Predictor variables were categorized into domains, including signalment, history, clinical signs, underlying pathology, acuity status, and surgeries performed. Outcomes were categorized as death, major complications, or minor complications. The association between outcomes and predictors was modeled by logistic regression. Results were reported as ORs and regression coefficients with 95% CIs. A predictive model was created to estimate risk of mortality and complications following BOAS surgery.

Results
297 cases were included. Twelve dogs (4%) died prior to discharge. Major complications (airway interventions and pneumonia) were reported for 29 dogs (10%). Major complications were strongly associated with emergent presentation (OR, 7.45; 95% CI, 2.70 to 20.59), female sex (OR, 2.78; 95% CI, 1.11 to 6.67), high-grade laryngeal collapse (OR, 4.28; 95% CI, 1.56 to 11.79), and history of regurgitation/vomiting (OR, 2.16; 95% CI, 0.87 to 5.38).

Conclusions
Risk factors for postoperative death and complications were identified. A predictive model was developed, allowing estimation of postoperative risk based on individual patient factors.

Clinical Relevance
A multivariable predictive model may be useful in clinical practice to obtain individualized postoperative risk predictions to contribute to prognostication, decision-making, and triage. However, as this model has not been externally validated, calculated risk should be utilized with caution and consideration for the clinical picture of each patient.

Keywords: brachycephalic, BOAS, predictive model, emergent, postoperative complications

Brachycephalic obstructive airway syndrome (BOAS) is a condition affecting brachycephalic dogs resulting from innate and acquired anatomic anomalies that occur secondary to brachycephalic conformation.[1,2] There are many surgical strategies used to address BOAS, with techniques tailored to individual patient anatomy and surgeon preferences.

Reported risk factors associated with complications following BOAS surgery include increasing age, body condition score (BCS), high-grade laryngeal collapse, increasing length of general anesthesia, the presence of concurrent airway pathology, postoperative vomiting or regurgitation, breed (English Bulldogs), staphylectomy, and emergent presentation.[3–8] However, several of these risk factors remain controversial, with contradictory results presented among various studies.

Dogs that receive surgery for BOAS present with a spectrum of clinical signs, including minimally affected dogs receiving elective surgery versus dogs presenting in respiratory distress and requiring emergent intervention.[9] Emergent interventions may include sedation, oxygen administration, corticosteroid administration, intubation, temporary tracheostomy, and temporary palatopexy.[10] Patients failing to recover from BOAS crisis despite medical or temporary

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surgical interventions may undergo emergent definitive BOAS surgery.

Predictive modeling refers to the use of mathematical and computational methods to develop models to estimate the likelihood of future events. Predictive modeling has multiple applications, including use in weather forecasting, targeted advertising, and the prediction of health events in human clinical medicine and epidemiology.[11] For example, predictive modeling has been used to predict the spread of the SARS-CoV-2 virus, estimate individual 10-year risk for atherosclerotic cardiovascular disease, and predict 2-year risk of opioid overdose among patients prescribed opioid therapy.[12–14] The use of predictive modeling in veterinary clinical medicine is more limited, with examples including the Acute Patient Physiologic and Laboratory Evaluation or "APPLE" score and brachycephalic (BRisk) score.[15,16] While the BRisk score allows identification of patients at high risk for postoperative death and complications following BOAS surgery, it does not allow for specific, individualized percent risk prediction, which was a goal of the present study.

This study was primarily exploratory and descriptive, with the objective of identifying important predictors for postoperative death and major complications following BOAS surgery, as well as to develop a preliminary prediction model and quantify its predictive performance for this patient sample. We hypothesized that a combination of identifiable preoperative patient characteristics and upper airway abnormalities can successfully separate high-risk from low-risk dogs in the sample. We proposed a preliminary clinical prediction model as a basis for future patient-specific risk estimation.

Methods

Ethical oversight statement

Informed consent was not required for this retrospective study.

Participants and data source

This retrospective cohort medical records review included a single tertiary-level academic veterinary hospital. A single investigator (EAR) searched the University of Florida Veterinary Hospital small animal surgery case database (Cornerstone; Idexx Veterinary Software) for all records of client-owned brachycephalic dogs presenting with BOAS between July 2012 and December 2023, using the search terms *BOAS* and *BAS*. Of 312 eligible cases located, 7 were excluded during screening. Cases were excluded if the animal did not undergo BOAS surgery, a major proportion of postoperative data were missing, the surgical techniques were modified for BOAS (ie, bilateral cuneiformectomy or arytenoid biopsy), or there was severe concurrent disease necessitating euthanasia. Two hundred ninety-seven cases were available for analysis. Dogs that had received prior BOAS surgery were included among these cases. The minimum period of follow-up necessary for case inclusion was to the time of postoperative discharge or death prior to hospital discharge.

Preoperative diagnostic imaging findings from CT and/or thoracic radiographs were reviewed to determine the presence of abnormalities (aspiration pneumonia, hiatal hernia, hypoplastic trachea, and aberrant turbinates). Clinical pathologic data were also recorded, including preoperative PCV and total solids as well as any available arterial blood gas data, though these data did not ultimately contribute to the predictive model.

The surgical procedures performed were recorded and included rhinoplasty (alar wedge resection, alar fold amputation, and ala-vestibuloplasty), staphylectomy or folded flap palatoplasty, tonsillectomy, and laryngeal sacculectomy. Any concurrent nonairway procedures (such as castration or spay) were recorded. All procedures were performed or supervised by American College of Veterinary Surgeons board-certified small animal surgeons.

Protocols for anesthesia premedication, induction, and maintenance were determined and supervised by a board-certified veterinary anesthesiologist. Postoperative treatments, including analgesia, oxygen supplementation, and other supportive medications, were determined on the basis of clinician discretion.

Postoperative complications recorded were increased respiratory effort, oxygen supplementation, emergent intubation, temporary tracheostomy, mechanical ventilation, development of pneumonia, and vomiting or regurgitation. Data including increased respiratory effort and supplemental oxygen administration were obtained from written or digital treatment sheets (Instinct LLC). Follow-up data collected included date of first follow-up (including phone follow-up if in-person follow-up was not available) and description of any complications noted at the time of follow-up. Persistent clinical signs were recorded if reported by owners or noted on the physical examination. Patient disposition and duration of postoperative hospitalization were recorded.

Outcomes

Primary outcomes were death (euthanasia or death prior to hospital discharge), major postsurgical complications (airway interventions [intubation, tracheostomy, and mechanical ventilation] and aspiration pneumonia), and minor complications (postsurgical regurgitation, vomiting, incisional complications, and increased respiratory effort).

Predictors

Predictor variables were classified in 6 domains: signalment, prior BOAS history, clinical signs at presentation, underlying pathology, acuity status, and surgeries performed. Signalment variables were age (years), sex (male or female), intact status (1 = intact, 0 = neutered/spayed), body mass (kilograms), breed (English Bulldog, French Bulldog, Pug, or other), and the 9-point BCS. History variables referred to history of prior BOAS-related hospitalization at this institution and/or a history of prior BOAS surgery, whether performed by the patient's primary care veterinarian or the author's institution. Case acuity at admission was designated as emergent or elective, with emergent presentation defined as presentation

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through the emergency service or incidence of respiratory distress following presentation. Chief complaints and symptoms at presentation (present or absent) were airway noise, noise quality (stertor, stridor, both, or neither), history of exercise intolerance, heat intolerance, syncopal episodes, and/or regurgitation or vomiting. Identification of preexisting pathology (elongated soft palate, enlarged tonsils, everted saccules, laryngeal collapse, and collapse grade) was determined via airway examination at the time of anesthetic induction. No objective measurements of the soft palate or other upper airway anatomy were obtained. Soft palate elongation was defined as extension of the caudal edge of the soft palate beyond the caudal edge of the palatine tonsils or the cranial tip of the epiglottis. Three stages of laryngeal collapse were defined: stage 1, eversion of the laryngeal saccules; stage 2, medial displacement of the cuneiform processes of the arytenoid cartilages; and stage 3, medial collapse of the corniculate processes of the arytenoid cartilages and loss of the dorsal arch of the rima glottidis.[17]

Data screening

A standardized collection template was piloted and refined before use by 2 investigators (EAR and KMH). Data were collected by 3 investigators (EAR, ZM, and JS) and screened independently by the other investigators (PAR and KMH) for outliers, typographical errors, and entry errors. Formal data screening was performed in SAS version 9.4 and SAS JMP Pro 15 (SAS Institute Inc). Univariate visualization of distributions was performed for all variables and assessed for remaining outliers and missing values. Discrepancies were flagged and corrected with reference to the original patient records.

Overweight and obesity have been identified as clinically important risk factors for BOAS and BOAS-related complications.[18] In this study, a minority of cases had missing BCS data, so substitute values were constructed by multiple imputation on the variables age, breed, sex, intact status, and body mass (*proc MI* package; SAS Institute Inc). A new binary indicator variable was obtained by dichotomizing BCS score as not overweight (BCS < 5) or overweight (BCS ≥ 5).[18] To simplify calculations with all binary predictors, the continuous variable age was also dichotomized, with age < 3 years ("younger" = 0) versus age ≥ 3 years ("older" = 1). Regarding the choice of cut points, values were based on perceived clinical relevance.

Statistical analyses

All calculations were performed in SAS version 9.4 (SAS Institute Inc). Signalment and clinical data were summarized by descriptive statistics. Continuous data were summarized by medians (IQR, minimum, and maximum) and categorical data by counts (n) and percentages (%).

Association between primary outcomes and binary predictor variables was modeled by logistic regression (*proc logistic* package; SAS Institute Inc). To minimize overfitting bias, variable reduction was performed in 3 steps. First, the maximum number of predictor variables that the available sample size of 297 cases could reliably support without producing an overfitted, unstable model was estimated with the methods of Riley et al.[19] Assuming shrinkage of 0.9, R^2 of 0.2 to 0.3, and margin of error of 5%, approximately 8 predictors could be supported with this number of cases. Next, a priori variable reduction was performed by collapsing sparse or missing categories of a given nominal variable to a binary condition (eg, laryngeal collapse grade > 2 = 1 vs grade < 2 = 0) or combining several sparse nominal variables into a new binary variable (eg, "prior history" combined cases with a history of prior emergency admission or hospitalization or surgery for BOAS). Third, backward variable selection on the predictors in each logistic regression model was performed with $P = .15$ to retain the variable in the model. The higher P value is used for variable retention and exclusion in prediction modeling because the objective is optimization of predictive performance rather than formal hypothesis testing (when the familiar $\alpha = .05$ threshold is used). The .15 threshold balances the risk between model overfitting and underfitting. An overfitted model retains too many predictors, making the model overly complex; captures noise rather than identifying underlying systematic patterns; and fails to generalize to new datasets. An underfitted model occurs when the threshold is too strict, leading to the omission of otherwise weak variables that may nevertheless have important joint predictive power with other variables in the model.[20]

Internal model validity and stability was assessed by bootstrapping validation,[21] which uses the source data to develop the prediction model. Internal validity refers to model performance (discrimination and calibration). Model stability is the frequency of retention of each variable in the bootstrapped samples. The full logistic regression model was replicated 1,000 times by unrestricted random sampling with replacement (*proc surveyselect* package; SAS Institute Inc). Backward selection with $P = .15$ to retain a predictor in the model was performed on each bootstrap replicate (*proc logistic* package; SAS Institute Inc).[20]

To quantify the ability of the model to discriminate between patients with and without the outcome, C statistics were calculated for each bootstrap replicate, with 95% CIs for the point estimate obtained from the 2.5 and 97.5 percentiles of the bootstrapped samples. The C statistic is equivalent to the area under the receiver operating curve and quantifies the ability of the model to discriminate between patients with and without the outcome.[21] Any remaining overfitting bias was estimated with bootstrap validation and by calculating the average optimism-corrected C statistic (*proc sql* package; SAS Institute Inc). Optimism is the difference between the bootstrap performance and the performance of the prediction model using the original sample.[22]

Model calibration was assessed by visual inspection of calibration plots for agreement between observed outcomes and predictions (calibration slope, approx 1), and nonsignificance of the Spiegelhalter z statistic and Hosmer-Lemeshow χ^2 statistic (*proc logistic* package; SAS Institute Inc).[23] Overall performance of the final model was assessed by maximum

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adjusted Nagelkerke R^2, which quantifies how much of the variability in the outcome is explained by the predictors in the final model. The maximum R^2 that reflects a realistic and acceptable level of predictive signal in clinical prediction models is approximately 0.2 to 0.3.[19,20]

Results are reported as ORs and regression coefficients β (OR is the exponentiated form of the regression coefficient, e) with associated 95% CIs. Each outcome (death, major postsurgical complications, and postsurgical regurgitation/vomiting) was modeled separately. The predicted probabilities for each outcome were estimated from the regression coefficients for predictor variables in each model with the following equation:

$$\text{Prob}(\text{Outcome} = 1) = \frac{1}{1 + exp[-(\beta_0 + \beta_1 X_1 + \cdots + \beta_k X_k)]}$$

where β_i are the regression coefficients for each predictor X_k. Because predictors are binary, they take the value 0 (absent) or 1 (present). The estimates of effect (*proc logistic* and *estimate* packages; SAS Institute Inc) were converted to probabilities with the inverse link transformation, and CIs were obtained from the 2.5 and 97.5 percentiles of the bootstrapped reduced model.[24,25]

Results

Signalment and case summaries for 297 brachycephalic dogs admitted for BOAS-related surgery are reported in **Table 1**. Eighteen breeds were represented: over half were French Bulldogs (162 of 297 [55%]), 26% (77 of 297) were English Bulldogs, and 7% (22 of 297) were Pugs. Median patient age was 2 years (IQR, 1 to 4 years), and median body mass was 12 kg (IQR, 10 to 19 kg). Dogs were predominantly male (177 of 297 [60%]). Thirty-three dogs (11%) underwent BOAS surgery on an emergent basis, while 264 (89%) received elective surgery.

The most common presenting complaints were airway noise (258 of 297 [87%]), regurgitation/vomiting (150 of 297 [55%]), and exercise intolerance (114 of 297 [38%]). The most common BOAS airway components were elongated soft palate (289 of 297 [97%]) and stenotic nares (273 of 297 [91%]; **Table 2**). Most cases (181 of 297 [61%]) presented with 4 or more airway abnormalities, 34% (100 of 297) with 2 or 3, and only 16 (5%) with 1.

Twelve dogs (4%) died or were euthanized, 29 (10%) exhibited major complications, 103 (35%) exhibited postoperative regurgitation/vomiting, and 104 (35%) exhibited postoperative increased respiratory effort. Median time to follow-up was 13 days (IQR, 4 to 15 days). Results of the performance of the 3 clinical prediction models for death/euthanasia, major postsurgical complications, and postsurgical regurgitation/vomiting are presented in **Tables 3 to 5**. An estimate of the risk of postoperative death, major complications, or minor complications was determined by applying the regression coefficients obtained from the models for each outcome to the equation shown in the Methods; details of the calculations are given in **Supplementary Material S1**.

Table 1—Summary of signalment, presenting complaints, presentation, and outcomes for 297 dogs undergoing brachycephalic obstructive airway syndrome (BOAS) surgery between 2012 and 2023. Data were obtained from retrospectively reviewed records. These data were used to identify risk factors for postoperative complications and mortality following BOAS surgery and to develop a predictive model.

Variable	n (%)
Signalment	
Breed	
English Bulldog	77 (26)
French Bulldog	162 (55)
Pug	22 (7)
Other brachycephalic breeds	36 (12)
Sex	
Intact male	99 (33)
Neutered male	78 (26)
Intact female	45 (15)
Spayed female	77 (26)
Overweight (BCS ≥ 5)	212 (71)
Prior history	
Prior hospitalization	17 (6)
Prior BOAS surgery	17 (6)
Complaint at presentation	
Exercise intolerance	114 (38)
Syncopal episodes	24 (8)
Heat intolerance	49 (16)
Regurgitation, vomiting	150 (51)
Airway noise	258 (87)
Stertor	193 (65)
Stridor	79 (27)
Both stertor and stridor	21 (7)
Presentation	
Emergent	33 (11)
Outcomes	
Death, euthanasia prior to discharge	12 (4)
Dyspnea	148 (50)
Postsurgical complications	
All major complications	35 (12)
Major airway intervention	16 (5)
Pneumonia	19 (6)
Regurgitation, vomiting	103 (35)
Infection, dehiscence	6 (2)
Revision	23 (7)

BCS = Body condition score.

Table 2—Prevalence of anatomic abnormalities among 297 dogs undergoing BOAS surgery.

BOAS component	No. (%) of dogs
Stenotic nares	273 (91)
Elongated soft palate	289 (97)
Everted saccules	167 (56)
Hyperplastic tonsillar tissue	99 (33)
Macroglossia	87 (29)
Laryngeal collapse (grade ≥ 2)	161 (54)

Increased risk of death (12 [4%]) was positively associated with emergent presentation, English Bulldog breed, female sex, history of preoperative vomiting or regurgitation, and laryngeal collapse grade ≥ 2 (Table 3). The number of cases with exercise intolerance reported at admission was much higher for survivors (113 of 285 [38%]) than nonsurvivors (1 of 12 [8%]). The maximum adjusted R^2 of 0.324 was typical and acceptable for a clinical prediction model.

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Table 3—Regression coefficients and ORs for logistic regression model for death or euthanasia based on case records for 297 dogs undergoing BOAS surgery. Associated CIs are presented for each predictor.

Predictor	Regression coefficient[a]	95% CI	*P* value[b]	OR (95% CI)
Intercept (β_0)	−2.85	−3.979 to −1.719	< .001	
Emergent	1.112	0.423 to 1.799	.0016	9.23 (2.33 to 36.53)
Exercise intolerance	−1.118	−2.214 to −0.021	.046	0.12 (0.01 to 0.96)
English Bulldog	0.559	−0.108 to 1.224	.100	3.06 (0.81 to 11.58)
Sex (male)[c]	−0.624	−1.307 to 0.061	.074	0.29 (0.07 to 1.13)
Laryngeal collapse grade ≥ 2	0.839	0.099 to 1.579	.026	5.36 (1.22 to 23.54)
Prior regurgitation, vomiting	0.577	−0.138 to 1.290	0.114	3.17 (0.759 to 13.20)

[a]Regression coefficient values for logistic regression model. Values for regression coefficient are expressed as "condition present" X = 1 for dichotomous variables. The intercept is the log-odds of the outcome occurring when all predictor variables X are equal to 0. [b]Threshold for variable retention in the final model was set at *P* = .15. [c]"Female" was the reference category for sex (X = 0).

Table 4—Regression coefficients and ORs for logistic regression model of major postsurgical complications based on case records for 297 dogs undergoing BOAS surgery.

Predictor	Regression coefficient[a]	95% CI	*P* value[b]	OR (95% CI)
Intercept (β_0)	−2.511	−3.408 to −1.614	< .001	
Emergent	1.004	0.496 to 1.512	< .001	7.45 (2.70 to 20.59)
Exercise intolerance	−0.451	−0.933 to 0.030	.066	0.41 (0.16 to 1.06)
Sex (male)[c]	−0.509	−0.963 to −0.055	.028	0.36 (0.15 to 0.90)
Prior BOAS history (hospitalization/surgery)	−0.713	−1.494 to 0.068	.074	0.24 (0.05 to 1.15)
Laryngeal collapse grade ≥ 2	0.727	0.221 to 1.234	.005	4.28 (1.56 to 11.79)
Prior regurgitation/vomiting	0.385	−0.072 to 0.841	.099	2.16 (0.87 to 5.38)
Enlarged tonsils	0.455	−0.006 to 0.916	.053	2.486 (0.99 to 6.25)
Non–airway-related surgery	−0.417	−0.896 to 0.061	.087	0.43 (0.17 to 1.13)

[a]Regression coefficient values for logistic regression model. Values for regression coefficient are expressed as "condition present" X = 1 for dichotomous variables. The intercept is the log-odds of the outcome occurring when all predictor variables X are equal to 0. [b]Threshold for variable retention in the final model was set at *P* = .15. [c]"Female" was the reference category for sex (X = 0).

Table 5—Regression coefficients and ORs for logistic regression model of postsurgical regurgitation and vomiting based on case records for 297 dogs undergoing BOAS surgery.

Predictor	Regression coefficient[a]	95% CI	*P* value[b]	OR (95% CI)
Intercept (β_0)	−0.500	−0.855 to −0.146	.006	
Sex (male)[c]	0.411	0.136 to 0.686	.003	2.28 (1.31 to 3.94)
Prior regurgitation/vomiting	0.462	0.194 to 0.731	.001	2.52 (1.47 to 4.32)
Everted laryngeal saccules	−0.733	−1.305 to −0.162	.012	0.23 (0.07 to 0.72)
Laryngeal collapse grade ≥ 2	0.623	0.049 to 1.197	.034	3.48 (1.10 to 10.95)
Enlarged tonsils	0.230	−0.047 to 0.507	.104	1.58 (0.91 to 2.75)
Heat intolerance	0.256	−0.082 to 0.594	.137	1.67 (0.85 to 3.28)

[a]Regression coefficient values for logistic regression model. Values for regression coefficient are expressed as "condition present" X = 1 for dichotomous variables. The intercept is the log-odds of the outcome occurring when all predictor variables X are equal to 0. [b]Threshold for variable retention in the final model was set at *P* = .15. [c]"Female" was the reference category for sex (X = 0).

Discrimination was good (0.86; 95% CI, 0.74 to 0.95). However, the estimated optimism was 0.16, indicating the model was overfitted, even with only 6 predictors in the model. Despite nonsignificant calibration tests (Spiegelhalter z = 0.185; P = .85; Hosmer-Lemeshow χ^2 = 2.31; P = .97), the calibration plot deviated from the 1:1 line, again indicating miscalibration and overfitting. Of the 6 identified risk factors for death, only emergent presentation, high-grade laryngeal collapse, and a history of exercise intolerance met the 70% threshold for model stability, while the English Bulldog breed, female sex, and a history of preoperative vomiting or regurgitation did not. A revised model with only 3 predictors (maximum adjusted R^2 = 0.226), good discrimination (C statistic, 0.83; 95% CI, 0.74 to 0.92) and robust calibration (z = −0.371; P = .711; intercept = −0.005; slope = 1.055; optimism < 0.02). However, absolute calibration error was 16% as a consequence of the relatively few deaths in the sample (low overall event rate).

Major postsurgical airway and respiratory complications (pneumonia, airway interventions; n = 29 [10%]) were associated with emergent presentation and laryngeal collapse grade ≥ 2, sex, prior history of regurgitation and vomiting, enlarged tonsils at presentation and additional non–airway-related surgery, and negatively associated with history of exercise intolerance and prior BOAS-related admission (Table 4). Again, despite good calibration (Spiegelhalter z = 0.005; P = .92) and discrimination (C statistic, 0.84; 95% CI, 0.74 to 0.91), the estimated optimism of 0.05 indicated overfitting. Of the identified variables, emergent presentation, sex, and high-grade laryngeal collapse met the 70% threshold for model

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stability. A reduced model again provided good discrimination (C statistic, 0.74; 95% CI, 0.63 to 0.83) and robust calibration (z = –0.21; P = .83; intercept = –0.02; slope = 0.01) with maximum absolute calibration error of 4%.

Risk of postoperative regurgitation and vomiting (n = 103 [35%]) was most strongly associated with prior history of regurgitation and vomiting and more severe airway compromise at admission (enlarged tonsils, everted laryngeal saccules, and laryngeal collapse grade ≥ 2), prior history of heat intolerance, and sex (Table 5). Calibration plots were satisfactory (slope = 1.02; Spiegelhalter z = 0.006; P = .94; Hosmer-Lemeshow χ^2 = 7.46). Discrimination was acceptable (C statistic, 0.72; 95% CI, 0.65 to 0.80), with acceptable maximum adjusted R^2 of 0.205. Of the identified variables, history of heat intolerance and high-grade laryngeal collapse did not meet the 70% threshold for model stability.

Discussion

This study developed an internally validated predictive model that may be used to estimate the risk of mortality and complications in dogs undergoing BOAS surgery on the basis of individual risk factors. This model was developed with the use of a large database including a variety of patient characteristics and outcomes. This model may be useful to clinicians in providing an individualized estimate of postoperative risk based on patient-specific factors. The majority of these risk factors (ie, breed, sex, history, and acuity of presentation) can be identified without advanced diagnostics. This model may help to triage patients at a higher risk for a complicated postoperative recovery, prompting surgeons to preemptively plan for airway intervention and more aggressive postoperative monitoring and respiratory management. It may also help primary care veterinarians determine which cases are higher risk and should be seen at a referral center with a boarded surgeon. This use of predictive modeling may be particularly valuable to clinicians when providing prognostic information to clients and when molding their postoperative plans to accommodate for various outcomes.

One prior study by Tarricone et al[16] developed a predictive risk score (BRisk) for postoperative major complications and death among dogs undergoing BOAS surgery. While the study did develop a score that has value in categorizing dogs as medium-to-high or high risk based on BRisk scores of > 3 or > 4, respectively, it does not allow a specific individual risk prediction to be generated. The goal of our study was to create a more specific, individualized model for risk prediction. The model developed allows patient-specific percent risk estimates to be calculated. Additionally, our model allows estimation of risk of major postoperative complications, postoperative death, and postoperative regurgitation and vomiting, while the BRisk score is only in reference to a composite endpoint of death and major complications.

In addition to developing a predictive model, this study identified several risk factors for death or complications among dogs undergoing BOAS surgery. Risk factors identified included surgery performed on an emergent basis, high-grade laryngeal collapse, English Bulldog breed, and female sex. Interestingly, factors associated with a lower risk of postoperative complications included dogs with a prior history of BOAS-related presentation, surgery, or hospitalization and dogs that underwent concurrent nonairway surgery (Table 4). However, retention of the variables English Bulldog breed, concurrent nonairway surgery, and prior BOAS-related medical history as predictors for death or major complications may have been in part a consequence of model overfitting. Though these variables are discussed herein as potential predictors, they should be considered in the context of each patient's entire clinical picture.

Dogs presenting emergently in respiratory crisis due to BOAS had a significantly greater risk for mortality or major complications than dogs presenting for elective surgery, supporting previous findings.[3] It has been speculated that dogs presenting emergently for BOAS may be predisposed to a poorer outcome owing to the presence of more advanced upper airway pathology and a greater degree of upper airway inflammation compared to dogs presenting electively.[8] Some of these dogs were presented to the emergency room, while others were presented to specialty services and developed a crisis event during the visit.

Laryngeal collapse grade ≥ 2 of 3 was identified as a clinically significant risk factor for postoperative complications and mortality following BOAS surgery. Previous studies[5,6] have found higher-grade laryngeal collapse to be a risk factor for complicated recovery or poor prognosis. The presence of higher-grade laryngeal collapse, which is theorized to be a secondary change associated with chronically increased negative inspiratory pressure generated in the upper airway,[2,26–28] may also correspond to the presence of more advanced disease pathology and thus poorer postoperative outcomes.

English Bulldogs, which made up 26% of the study sample, were found to be at greater risk for mortality following BOAS surgery, corresponding to prior studies in which English Bulldogs experienced higher rates of postoperative and perianesthetic mortality[29] and aspiration pneumonia as compared to other brachycephalic breeds.[4] Possible reasons for poorer postoperative outcomes among English Bulldogs may include breed predisposition to tracheal hypoplasia, pharyngeal myopathy, and obesity. [4,29–32]

In the present study, female sex was identified as a risk factor for major postoperative complications. Though not directly related to postoperative complications, a prior study[33] did indicate that female Pugs were at an increased risk for developing BOAS compared to males. That study also identified neck girth ratio as a significant predictor of BOAS in Bulldogs, with male Bulldogs found to have a significantly higher neck girth ratio than females.[33] Therefore, it is possible that underlying conformational factors play a role in the difference in risk between sexes, though further investigation is required. Population and breed characteristics may also vary between studies explaining differences in risk among sexes.

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Patients with prior history of airway surgery for BOAS or BOAS-related hospitalization had a lower risk of major postoperative complications. To speculate, as these patients had been evaluated for BOAS prior to surgery, this finding may reflect the effect of medical and lifestyle management instituted prior to surgery. Preoperative medical management of dogs undergoing BOAS surgery with antiemetic, antacid, prokinetic, and sedative medications has been shown to reduce the risk of respiratory distress in postoperative BOAS patients.[34] Additionally, patients with a prior surgical history undergoing a revision procedure for BOAS may have benefited from initial airway procedures, as a prior study indicated that the odds of postanesthetic complications were decreased by 79% in dogs that underwent prior surgical intervention for BOAS.[35]

Dogs undergoing nonairway surgery (ie, neuter or ovariectomy) concurrently with their BOAS procedure were at a lower risk of major postoperative complications. This finding may reflect patient selection given the generally elective nature of these procedures, as elective procedures would likely not be pursued in patients for which respiratory stability was a concern. One prior study[5] did identify a longer length of general anesthesia as a risk factor for complicated recovery, potentially indicating that elective procedures should not be pursued in patients at a higher risk of postoperative complications.

Interestingly, in this study, the ORs for death and major complications were < 1 for dogs with a history of exercise intolerance, mirroring a similar finding in a study by Tarricone et al,[16] which identified an OR of 0.52 for major complications or nonsurvival following BOAS surgery associated with a history of exercise intolerance. This does not necessarily indicate a protective effect. More surviving dogs were reported with exercise intolerance (38%) compared to nonsurvivors (8%), indicating underlying baseline risk differences between the groups. This may be an artifact of owner attentiveness and reporting. It is possible that greater owner attentiveness may result in earlier, elective management of BOAS prior to precipitation of a respiratory crisis.

In the present study, elongated soft palate was identified as the most common anatomic abnormality associated with BOAS, followed by stenotic nares. Eighty-four percent of the included dogs had more than 1 upper airway anomaly present, with most dogs (61%) having 4 or more concurrent upper airway anomalies. This is consistent with prior studies[36,37] identifying elongated soft palate as the most common BOAS-associated anomaly and the presence of multiple upper airway abnormalities in up to 69% of dogs with BOAS. These findings support BOAS being a multifactorial syndrome with several associated primary and secondary anatomic anomalies present in affected dogs. They further emphasize the importance of multilevel surgery to simultaneously address multiple anatomic components of BOAS.[6]

One consideration of the risk of pre- and postoperative vomiting and regurgitation in patients undergoing surgery for BOAS is the increased risk for aspiration pneumonia. Preoperative vomiting and regurgitation were reported in approximately half of the dogs in this study. This finding supports other reports of prevalence of GI signs in dogs affected by BOAS.[38] This study found that a history of preoperative vomiting or regurgitation was a significant predictor for postoperative mortality, major complications (including pneumonia) and postoperative vomiting and regurgitation.

A major limitation of this study was that it was a retrospective observational study with patient cases obtained from a single institution. Variation in the completeness and interpretation of medical records may have contributed to data inaccuracies, and other clinically relevant risk factors may have been missed in data collection. Pre- and postoperative protocols and anesthetic protocols were not standardized, likely contributing to variation in the recording of outcomes. Although the sample size was large compared to similar studies, the incidence of mortality in this study was still low (12 cases or 4% of the sample). The low number of events contributed to model overfitting. Although reduced models showed improved discrimination, calibration, and prediction error metrics, omitting variables contributed to selection bias, loss of information, and reduced clinical utility. For example, while excluding the English Bulldog breed, female sex, and prior regurgitation or vomiting improved statistical fit in the short-term mortality model, it also narrowed the clinical context by removing potentially relevant patient characteristics that may enhance diagnostic assessment, risk stratification, and triage decision-making. External validation studies will require multicenter participation with more diverse patient mix cohorts, higher event density, and standardized records to both rigorously quantify performance heterogeneity and ensure sufficiently large sample sizes.

A second limitation was the requirement of airway examination for determination of laryngeal collapse grade to provide a risk prediction. Most predictors can be determined on the basis of physical examination and history without the need for advanced diagnostics, aside from laryngeal collapse grade. Though knowledge of laryngeal collapse grade would allow specific risk prediction for a patient, without airway examination, an estimated risk range could be calculated. To obtain the low end of the risk range, a factor of 0 for laryngeal collapse grade ≥ 2 could be entered into the equation for the predictor. To obtain the high end of the risk range, a factor of 1 could be inserted into the equation for the predictor. This would provide a range of estimated risk that may remain valuable in risk estimation and clinical counseling.

A third limitation of this study was that the predictive model presented has not been prospectively externally validated. We performed extensive internal validation as a nonnegotiable step in model development, with the purpose of verifying accuracy on simulated patients using data sourced from the same institution. External validation evaluates how generalizable (or "transportable") models would be in a different location or clinical setting. The calculated risk probabilities should be interpreted with caution, and the entire clinical picture should be considered for each patient. Discrepancies in risk predictions for outcomes such as death or major complications may exist and may confuse prognostication. For example, the different statistical models may

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suggest a higher risk of death but lower risk of major complications for a particular patient. As a larger volume of data was available for prediction of major complications among our study population, the risk prediction generated for major complications may be more reliable in this circumstance. Clinicians should rely on their clinical judgment in such circumstances and consider the clinical picture with which they are confronted. In the absence of external validation data, we do not recommend using the exact probabilities generated by the risk calculators in this study for definitive medical decision-making on other populations of dogs. Rather, use the calculations along with the clinical picture when evaluating each individual patient.

In conclusion, this study developed a preliminary predictive model that has promise as a tool for clinicians to estimate the risk of complications and mortality following BOAS surgery based on individual patient risk factors. This study provides valuable risk information as well as a potentially useful model to aid clinicians in judging postoperative prognosis among dogs undergoing BOAS surgery. The clinical value in this predictive model lies in its potential to translate individual patient data into actionable probabilities, which may inform point-of-care prognostication and decision-making. Although the risk calculators are preliminary, they can be used with certain restrictions; for example, as the basis of an institutional pilot trial to evaluate feasibility and to direct data collection for local external validation studies and, more immediately, as an educational or secondary checklist tool to ensure broad risk factors are not overlooked. Further investigation and validation of predictive models with multicenter participation may indicate an avenue for future research.

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