Preoperative blood typing and screening for benign prostatic hyperplasia surgery: A retrospective analysis and real-world validation of a machine learning model for predicting intraoperative and immediate postoperative blood transfusion

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ABSTRACT

Introduction: Routine preoperative blood type and screen (T&S) testing is commonly performed prior to benign prostatic hyperplasia (BPH) surgery, despite the low transfusion risk associated with endoscopic procedures such as transurethral resection of the prostate (TURP) and holmium laser enucleation of the prostate (HoLEP). In contrast, open simple prostatectomy (OP) remains a high-bleeding-risk procedure. Nevertheless, current guidelines do not provide clear recommendations regarding selective T&S use. This study aimed to identify objective predictors of perioperative transfusion, determine evidence-based cutoffs, and prospectively validate a risk-based testing protocol.

Methods: We analyzed 1232 consecutive BPH surgeries (2017–2022) performed at a tertiary center: 173 OP, 740 TURP, and 319 HoLEP. Demographic, comorbidity, and perioperative data were retrieved and cross-referenced with transfusion records, categorized as intraoperative or within 24 hours postoperatively. First, receiver operating characteristic (ROC) analysis was used to define optimal transfusion risk thresholds for each variable. Second, all predictors were entered into a logistic regression model, achieving an area under the curve (AUC) of 0.81,

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followed by a machine learning gradient boosting (XGBoost) algorithm to address the low transfusion event rate. Third, based on six final risk factors, a multidisciplinary team (urology, anesthesiology, hematology) developed a selective T&S protocol, which was prospectively implemented in 309 patients undergoing BPH surgery in 2023.
Results: The final XGBoost model identified age ≥80 years, hemoglobin ≤11 g/dL, platelets ≤100 × 10^9/L, international normalized ratio (INR) ≥1.3, prostate volume ≥100 mL, and Charlson Comorbidity Index >4 as high-risk criteria. In the retrospective cohort, transfusions occurred intraoperatively in 4.9% (OP 24%, TURP 1.9%, HoLEP 0.9%) and postoperatively in 8% (OP), 1.1% (TURP), and 1.5% (HoLEP). Due to the high transfusion rate observed in OP, preoperative T&S testing was maintained for open procedures, while omission was applied only to low-risk endoscopic surgeries. Among the 309 validation patients, intraoperative transfusions occurred in 0% of TURPs and 2.3% (n=5) of HoLEPs. Of these, three were correctly screened, one was a protocol deviation, and one had an undiagnosed coagulopathy. Overall, 35% of patients met none of the risk criteria and safely underwent surgery without T&S.
Conclusions: Our findings support shifting away from universal preoperative T&S testing toward a protocol emphasizing individualized risk. Based on our findings, routine preoperative T&S testing can be safely omitted in low-risk patients undergoing TURP or HoLEP, while it should be maintained for open procedures and for patients with predefined high-risk features. Future studies may further validate these criteria and the model.

INTRODUCTION

Surgery performed for the treatment of benign prostatic hyperplasia (BPH) may carry a risk of intraoperative and postoperative bleeding due to the vascularity of prostatic tissue. Reported transfusion rates vary markedly by surgical approach, from approximately 0.8–2.9% for endoscopic procedures such as transurethral resection of the prostate (TURP) and holmium laser enucleation of the prostate (HoLEP)[1-3], to over 20% for open simple prostatectomy[4]. Despite these differences, there is no consensus on recommendations for preoperative blood typing and screening (T&S) in BPH surgery.

The Maximum Surgical Blood Order Schedule (MSBOS), first introduced in 1976[5], was based on expert consensus between surgical specialties and hospital blood banks. While it standardized pre-transfusion testing, it did not account for evolving surgical techniques or real-world transfusion rates. Frank et al. (2013)[6] demonstrated that institutional transfusion data from an anesthesia information management system could be used to create a data-driven MSBOS (dMSBOS), aligning blood preparation with actual utilization. In their model, procedures with a transfusion probability below 5%—including TURP—were classified as low risk, for which

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routine T&S testing is unnecessary. Woodrum et al. (2017)[7] expanded this approach by applying department-specific utilization data from anesthesia and laboratory systems to update institutional guidelines, significantly reducing unnecessary T&S orders while maintaining patient safety.

In contrast to these data-driven recommendations, the 2018 NHS Maximum Surgical Blood Ordering Schedule (MSBOS) assigns TURP to the same transfusion risk category as radical and retropubic prostatectomy, requiring both T&S and crossmatch testing. These tests are to be performed during the preoperative assessment clinic (POAC) and repeated upon admission or immediately prior to surgery[8]. Although less intensive than full crossmatching for all patients, this protocol still requires substantial staff resources and imposes a notable logistical and financial burden.

At our institution, T&S testing have been routinely performed before all BPH surgeries in accordance with the aforementioned guidelines. The primary aim of this study was to evaluate the bleeding risk associated with different BPH procedures and to determine whether preoperative T&S testing can be safely omitted in selected patients. A secondary objective was to identify patient-level risk factors to guide targeted preoperative testing.

METHODS

Study design

The internal review board approved the study at TLVMC (TLV No. 0317-22). The first stage of our study was a retrospective cohort study of all BPH cases between 2017 and 2022 in a single academic medical center. Cases were performed by a mix of experienced surgeons and residents; Data were extracted from the institutional electronic medical record using the MDClone data-sharing platform (www.mdclone.com), which enables automated retrieval of real-world clinical data based on predefined queries. The cohort comprised real patients, identified by defining BPH surgery as the reference event. We queried the database for each patient's demographic characteristics, prostate size, ASA score, Must score, Charlson Comorbidity Index (CCI), procedure length, preoperative hemoglobin level, and postoperative hemoglobin level.

To ensure data accuracy and reliability, several validation steps were performed. Blood transfusion events identified through the MDClone extraction were cross-referenced with institutional blood bank issuance records. For each blood transfusion event, we retrieved the timing of the transfusion: intraoperative or in the periopertive setting and the number of units transfused.

In addition, a random sample of 10% of cases was manually reviewed by the investigators, and all extracted variables were compared with the original electronic medical records. All manually reviewed parameters were found to be accurate, and no discrepancies requiring correction were identified.

Patients who underwent any surgical procedure for the treatment of BPH were included. BPH procedures were classified into open prostatectomy (OP), TURP, and HoLEP (Lumenis

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Pulse 120H Holmium Laser System). The exclusion criteria included prostate surgeries performed for known cases of prostate malignancy.
In addition, we queried the database for each patient's demographic characteristics, prostate size, ASA score, Must score, Charlson Comorbidity Index (CCI), procedure length, preoperative hemoglobin level, and postoperative hemoglobin level.

The second stage of our study was a prospective observational study. After collecting and analyzing our retrospective data, in collaboration with our Anesthesiology and Hematology departments, the pre-operative algorithm was modified. In lieu of performing a pre-operative T&S for all patients, we stopped performing routine T&S prior to all endoscopic BPH procedures. We continued to take T&S prior to all open surgical procedures for BPH as well as for patients undergoing endoscopic surgery for BPH who met any of the following criteria: Age over 80, known anemia with preoperative hemoglobin levels of 11 ng/dL or lower, platelet count under 100,000 per mcL, INR > 1.3, Prostate volume over 100 mL, CCI > 4 (Figure 1).
This decision was implemented on January 1st, 2023. We then defined a one-year period to test and analyze our new policy.

Statical analysis

Descriptive analysis was performed on the full retrospective cohort to summarize patient demographics, comorbidities, and baseline laboratory values. Categorical variables were reported as counts and percentages, while continuous variables were summarized using means and standard deviations or medians and interquartile ranges, as appropriate. The distribution of surgical approaches (open, monopolar TURP, HoLEP) was recorded, along with relevant preoperative variables.

Prediction model for blood transfusion

Continuous preoperative variables were dichotomized using optimal thresholds derived from receiver operating characteristic (ROC) curve analysis. For composite categorical variables such as the Charlson Comorbidity Index and MUST score, we first evaluated the predictive performance of each component individually. Subsequently, we applied a unified binary cutoff for simplicity. Multivariable logistic regression analysis was performed to identify independent predictors of intraoperative and early postoperative blood transfusions (within 24 hours). Patients receiving both intraoperative and postoperative transfusions were counted once as positive in the combined binary outcome. Due to the cohort's low event rate of intraoperative transfusion, we employed a Gradient Boosting classifier (XGBoost algorithm)[9] to enhance predictive accuracy and account for class imbalance. Data preprocessing was conducted using Microsoft Excel (Microsoft Corporation, Redmond, WA), and statistical analyses were performed using R version 4.3.1 (R Foundation for Statistical Computing, Vienna, Austria).

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RESULTS

During the retrospective period (2017-2022), 1431 surgical procedures for BPH were performed in our institution. 112 were excluded due to undergoing channeling TURP/HoLEP, and 87 were excluded because of substantially incomplete datasets that were not suitable for analysis. The final analysis therefore included 1,232 cases. Table 1 summarizes the key findings.

Cases were distributed among open surgery (n=173, 14%), TURP (n=740, 60%), and HoLEP (n=319, 26%). The overall mean age at surgery was 73.8 ± 8.6 years, with slight variations across groups ($p = 0.12$). The Charlson Comorbidity Index showed that 47% of patients had a score of 3 or 4, while 34% had a score of 5 or higher. Patients undergoing open surgery had a lower proportion of high comorbidity scores (27%) compared to those undergoing TURP (40%) and HoLEP (48%) ($p < 0.001$). The majority of patients were classified as low risk according to the MUST score, with open surgery patients having the highest proportion of low-risk cases (89%) compared to TURP (82%) and HoLEP (85%) ($p = 0.03$). The ASA score was consistent across procedures, with a median of 2. However, TURP patients were more likely to have a mode ASA score of 3.0 compared to those undergoing open surgery and HoLEP ($p = 0.02$). Patients undergoing open surgery had the largest prostate volumes, with a median of 120 mL (±58 SD), followed by HoLEP at 100 mL (±42 SD). TURP had the smallest prostates, at 50 mL (±29 SD). The median prostate size across all procedures was 69 ml (±47 SD). Preoperative indwelling catheter use was most common in open surgery (44%, n = 76), followed by HoLEP (35%, n = 112) and TURP (30%, n = 223)

The mean surgery duration varied significantly, with open surgery lasting the longest (180 ± 90 minutes), followed by TURP (80 ± 50 minutes) and HoLEP (120 ± 70 minutes) ($p < 0.001$). Preoperative hemoglobin levels averaged 12.4 ± 2.0 g/dL across all procedures, with no statistically significant differences between groups ($p = 0.24$). Platelet counts before surgery, within 24 hours, and 30 days post-surgery were similar across all procedures ($p = 0.15$). Intraoperatively, packed red blood cell (RBC) transfusion was administered in 4.9% of patients overall, with the highest rate in open surgery (24%) compared to TURP (1.9%) and HoLEP (0.9%) ($p < 0.001$). Postoperatively, packed RBC administration within 24 hours was more frequent in open surgery (8%) than in TURP (1.08%) and HoLEP (1.5%) ($p = 0.04$).

Building the prediction model

Excluding open surgery

Given a 24% intraoperative transfusion rate for open surgery, we decided to continue pre-operative blood type and cross-match prior to surgery. Hence, open cases were excluded from this point on in the analysis.

Individual parameters as predictors

Receiver operating characteristic (ROC) curve analysis was performed to evaluate various prostate volume thresholds for predicting intraoperative and immediate (within 24 hours)

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postoperative blood transfusions. For prostate volume, a cutoff of ≥100 cc was selected as optimal, offering a tradeoff between sensitivity (33%) and specificity (86%) compared to other thresholds. Similar ROC analyses were conducted on the other preoperative variables. Variables were considered reasonably accurate if they achieved an AUC ≥ 0.60 and either a sensitivity ≥ 0.40 or a specificity ≥ 0.80. Based on this criterion, the most accurate individual predictors were hemoglobin levels lower than 11 /dl, age at surgery over 80 years, ASA score over 2, CCI over 4 points, and a prostate volume of more than 100 mL.

Additionally, we performed the ROC analysis for TURP and HoLEP separately and found no significant differences in optimal cutoffs between the two groups. We therefore proceeded with modal building as a unified cohort. The full results of the ROC analyses for all preoperative variables are presented in Table 2.

Logistic regression analysis

Logistic regression analysis was performed using all predictors as continuous variables in the combined TURP and HoLEP cohort. The following variables were statistically significant: ASA score, age at surgery, CCI, prostate volume, hemoglobin level, and platelet count (all $p < 0.01$). In this model, the odds ratio (OR) for each variable represents the effect of a one-unit increase on the odds of receiving a transfusion. For example, each additional year of age (OR = 1.02, 95% CI 1.01–1.03) or each additional milliliter in prostate volume (OR = 1.02, 95% CI 1.01–1.02) was associated with a modest but statistically significant increase in transfusion risk. Conversely, higher hemoglobin (per 1 g/dL increase, OR = 0.67, 95% CI 0.64–0.69) and platelet count (per $1 \times 10^3/\mu L$ increase, OR = 0.99, 95% CI 0.99–0.99) were protective. INR, MUST score, and presence of an indwelling catheter were not statistically significant in this model. When CCI components were added to the multivariable logistic regression model, Chronic pulmonary obstructive disorder (OR = 0.28), history of peripheral vascular disease (OR = 0.4), and renal disease (OR = 0.49) were associated with significantly increased odds of transfusion. Despite the inclusion of individual components, the total Charlson Comorbidity Index score ≥4 remained an independent predictor (OR = 0.6). Only the total CCI score was retained in the final model to reduce redundancy and improve model interpretability.

The overall predictive performance of the continuous variables logistic regression model yielded an accuracy of 0.76, a sensitivity of 0.77, a specificity of 0.76, and an ROC-AUC of 0.82. For clinical interpretability, we also examined the risk of transfusion using the cutoffs for individual predictors in individual predictor analyses. The dichotomized variable model demonstrated strong discriminatory ability, with a sensitivity of 0.77, a specificity of 0.76, and an area under the ROC curve (AUC) of 0.82 (Table 3).

Machine learning model: Gradient Boosting (XGBoost) model

The model was trained using all preoperative predictors. In XGBoost, “Importance” refers to the variable's frequency of selection in the model; a higher importance value indicates a more influential predictor. Two XGBoost models were developed to predict the risk of perioperative

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blood transfusion in patients undergoing TURP or HoLEP: one model incorporated dichotomized clinical predictors based on same cutoff used for the logistic regression model, and the second model used continuous values for prostate volume, age, hemoglobin, platelet count, and INR, while maintaining categorical predictors (CCI, MUST, ASA, and preoperative catheter) in binary form. For each model, stratified 5-fold cross-validation was used to maximize robustness and account for the low event rate.

The dichotomized-variable model achieved an area under the receiver operating characteristic curve (AUC) of 0.75, with a sensitivity of 59% and specificity of 90% at the optimal threshold. In this model, the most important predictors were CCI ≥ 4, age ≥ 80 years, and MUST score ≥ 1, whereas prostate volume ≥ 100 mL showed the lowest importance.

When all available clinical predictors were entered as continuous variables, model performance improved, with an AUC of 0.81, sensitivity of 67%, and specificity of 91%. In this configuration, prostate volume emerged as the most important variable by a large margin, followed by hemoglobin and platelet count, while categorical comorbidity and risk scores played a lesser role. Both models maintained a high negative predictive value (>99%), but positive predictive values remained low due to the rarity of transfusion events in the cohort. Full importance rankings are presented in Table 4.

Prospective study period

Based on our analysis, in collaboration with our hematology and anesthesiology teams, we identified the following high-risk factors: open surgery, age ≥ 80, hemoglobin ≤ 11 g/dL, platelet count ≤ 100 × 10^9/L, INR ≥ 1.3, prostate volume ≥ 100 mL, and Charlson Comorbidity Index > 4. Among patients in the retrospective cohort undergoing non-open surgery, 41% had none of these high-risk features and may have potentially safely avoided routine T&S testing

Real-world risk stratification implementation

Following the introduction of our new criteria, 309 patients underwent surgical procedures for BPH during 2023, comprising 91 TURP procedures and 218 HoLEP procedures. Supplementary Table 1 shows the comparison of the cohorts' parameters. A significant difference in mean prostate volume was noted between the two cohorts (78.7 mL in the retrospective cohort vs. 93.0 mL in the 2023 cohort, $p < 0.001$).

This discrepancy may be explained by differences in imaging modalities used to assess prostate size. Ultrasound and CT were used at similar rates in both cohorts (US: 77% vs. 66%; CT: 13% vs. 11%). In contrast, MRI use was markedly higher in the prospective cohort (27% vs. 10%). As MRI generally provides more accurate measurements and tends to report slightly larger prostate volumes than ultrasound or CT[10-11], the observed increase in mean prostate volume in 2023 likely reflects methodological differences rather than a true clinical change.

Additionally, INR values before surgery differed statistically between cohorts (mean INR: 1.06 in the retrospective cohort vs. 1.02 in the prospective cohort, p=0.001); the clinical

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relevance of this minor numerical difference appears negligible. All other parameters were not found to differ between the cohorts.

The intraoperative blood transfusion rate in the prospective cohort was 0% (n=0) for TURP, and 2.3% (n=5) for HoLEP. 35% (n=109) of the patients had no high-risk predictive factors, and blood T&S were not obtained. Postoperatively, the transfusion rate was 2.2% for TURP and 0.9% for HoLEP.

Of the five HoLEP procedures in which transfusion was required, three had blood T&S prepared based on our criteria, and two did not. Of these two cases, one was a human error in which the blood T&S should have been prepared, and the second was a patient who was later diagnosed with a previously unknown blood-clotting disorder. Accordingly, only one of the five cases represents a true failure of the predictive model, corresponding to 1 out of 5 patients (20%).

DISCUSSION

We evaluated whether routine preoperative blood T&S testing can be safely omitted for patients undergoing surgery for BPH. Our data demonstrate significant differences in bleeding risk across surgical approaches. Open simple prostatectomy was associated with a 24% intraoperative transfusion rate—consistent with prior reports[4]. In contrast, endoscopic techniques such as TURP and HoLEP showed markedly lower transfusion rates of 1.9% and 0.9%, respectively. These findings are in line with previous large-scale studies and meta-analyses evaluating intraoperative transfusion rates[1,2,12-14]. Our data represents a mix of experienced surgeons and residents at different stages in the learning curve of HoLEP.

Despite the well-established low hemorrhagic risk associated with endoscopic BPH procedures, international guidelines remain inconsistent in their recommendations regarding preoperative blood testing. The data-driven MSBOS (dMSBOS)[6], classifies TURP as a low-risk procedure for which routine T&S testing is unnecessary. In contrast, the 2018 NHS MSBOS includes TURP in a high-risk transfusion category, alongside radical and open prostatectomy[8]. This discrepancy reflects a broader uncertainty in how to stratify transfusion risk in the context of evolving surgical practice.

Given this lack of consensus and the limitations of guideline-based categorizations, we sought to identify specific patient-level risk factors for perioperative transfusion using real-world institutional data. Multivariable logistic regression revealed six independent predictors: age ≥80 years, hemoglobin ≤11 g/dL, platelet count ≤100 $\times 10^9$/L, INR ≥1.3, prostate volume ≥100 mL, and Charlson Comorbidity Index (CCI) >4. These findings provided the foundation for our selective testing protocol.

To further refine risk prediction and enhance accuracy in this low-event-rate setting, we applied a supervised machine learning approach using gradient boosting (XGBoost). This model allowed us to address the low event rate of blood transfusion. When using continuous input variables, the XGBoost model achieved high specificity (91%) and excellent negative predictive

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value, with an AUC of 0.81. Prostate volume, hemoglobin, and platelet count were the most influential variables in this model[9].

We validated our approach prospectively in 2023, applying the new protocol to 309 patients. Among them, 35% did not meet any high-risk criteria and therefore did not undergo T&S testing. None of these patients required intraoperative transfusion. Of the five HoLEP patients who ultimately required transfusion, three were appropriately flagged and screened in advance. Of the two who were not, one was due to human error, not following the suggested criteria, and the other was later found to have an undiagnosed coagulopathy. These rare exceptions underscore the importance of maintaining clinical oversight and auditing mechanisms alongside algorithmic risk stratification.

These findings are particularly relevant in light of ongoing shifts in surgical practice. In recent years, open simple prostatectomy has declined sharply[15-17] in favor of minimally invasive techniques such as HoLEP, which offers both efficacy and superior hemostatic control[13,18]. Robotic simple prostatectomy is also gaining traction[19,20], with transfusion rates lower than those of traditional open surgery. These surgical trends call for updated perioperative protocols that align with contemporary practice, rather than persisting with blood preparation strategies designed for open procedures.

In addition to improving clinical relevance, tailoring preoperative testing has important logistical and economic benefits. Prior studies have shown that omitting unnecessary testing in low-risk surgeries can reduce hospital charges by 9–12% per patient[6,21]. Similar overuse has been reported by Morberg et al.[22], who found that T&S was performed in over half of surgeries despite very low transfusion rates. At our institution, eliminating routine T&S testing for patients not meeting high-risk criteria allowed patients to arrive directly to the operating room without preoperative admission, streamlining care and conserving staff time and institutional resources. In the prospective cohort of Moussaoui et al. [23], applying prostate volume >80 mL and baseline hemoglobin <10 g/dL led to T&S testing in approximately 70% of HoLEP cases, with no use of unmatched blood products; similarly, in our cohort, 65% of patients classified as high risk and required preoperative T&S testing. Our work further expands on this concept by applying a machine learning-based, data-driven approach with real-world prospective validation to identify a broader set of predictors of perioperative bleeding risk.

This study has several limitations. First, although our protocol aimed to reduce unnecessary preoperative blood T&S testing, only 35% of patients were ultimately deemed low-risk and did not undergo testing. This proportion was lower than initially anticipated. Nevertheless, even a 35% reduction in routine preoperative type and screen represents a meaningful decrease in unnecessary testing and associated costs. Importantly, identifying patients at high risk for transfusion requires minimal additional effort, as it relies on readily available clinical and laboratory parameters. The conservative nature of our protocol reflects a deliberate prioritization of patient safety over reduction in testing burden. Second, the primary outcome - perioperative blood transfusion - is a rare event, which inherently limits statistical

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power and model calibration, even when using advanced machine learning techniques. Third, the study was conducted at a single tertiary academic center with a high volume of endoscopic procedures and experienced surgical teams. The generalizability of our findings may therefore be limited in settings with differing parameters.

Despite these limitations, our study provides a framework for selective preoperative testing in BPH surgery and lays the groundwork for future refinement through prospective, multicenter research.

CONCLUSIONS

Our findings support a transition away from universal preoperative T&S testing toward a targeted, data-driven protocol that emphasizes individualized risk. In clinical practice, we recommend maintaining routine preoperative T&S testing for open BPH procedures. For endoscopic procedures such as TURP and HoLEP, T&S testing can be safely omitted in patients without high-risk features, including advanced age, anemia, coagulopathy, significant comorbidity burden, or large prostate volume. Adoption of this selective approach may reduce unnecessary testing while preserving patient safety. Future studies may further validate these criteria and extend the model to additional surgical populations with similarly low transfusion risk.

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FIGURES AND TABLES

Figure 1. Flow chart of the study design. BPH: benign prostatic hyperplasia.

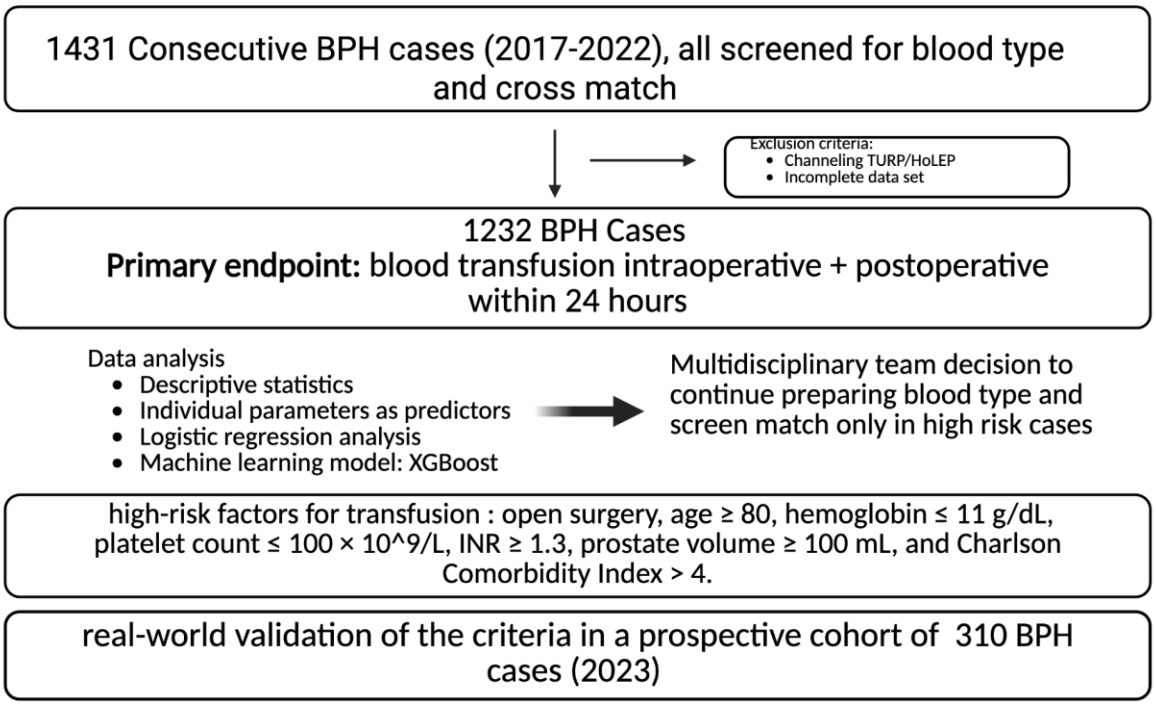

Table 1. Patient characteristics by surgical procedure, 2017–2022

Variable	Overall (n=1232)	Open Surgery (n=173)	TURP (n=740)	HoLEP (n=319)	p*
Age at surgery (years) (n=1232)					
Mean ± SD	73.8±8.6	73.9±7.1	74.1±9.1	73.1±8.2	0.12
Range	47.7–101.7	50–90	48–100	49–99	
Charlson comorbidity index (n=1232)					
0–2	19% (n=230)	19% (n=33)	20% (n=150)	14% (n=46)	<0.001
3–4	47% (n=585)	54% (n=93)	50% (n=371)	38% (n=120)	<0.001
5+	34% (n=413)	27% (n=46)	40% (n=297)	48% (n=68)	<0.001
MUST score (n=1013)					
Low risk	83% (n=841)	89% (n=131)	82% (n=563)	85% (n=144)	0.03

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Medium risk	12% (n=125)	8% (n=12)	13% (n=91)	12% (n=21)	
High risk	5% (n=47)	3% (n=5)	5% (n=37)	3% (n=5)	
ASA score (n=1232)					
Median	2.0 (n=1205)	2.0 (n=171)	3.0 (n=735)	2.0 (n=299)	0.02
Prostate volume, ml					
Median ± SD	69±47	120±58	50 ±29	100±42	<0.001
Indwelling catheter (n=1229)					
Yes	33% (n=411)	44% (n=76)	30% (n=223)	35% (n=112)	0.07
Surgery duration (minutes)					
Mean ± SD	139±86	180±90	80±50	120±70	<0.001
Range	15−445	60−300	20−400	30−210	
Non-invasive blood pressure during surgery (mmHg)					
Systolic (mean ± SD)	123±30	120±27	123±30	129±31	0.49
Diastolic (mean ± SD)	71±16	70±12	71±16	76±16	0.08
Hemoglobin levels before surgery - within 30 days (≤30 days) (mmHg)					
Mean ± SD	12.4±2.0 (n=754)	13.1±2.0 (n=101)	12.4±2.0 (n=596)	11.9±1.8 (n=57)	0.1
Range	6.0−18.5	6.5−18.3	6.2−18.5	8.0−16.5	
Platelet count before surgery - within 30 days (≤ 30 days) (10^3/microliter)					
Mean ± SD	225±80 (n=570)	225±69 (n=91)	225±83 (n=389)	221±84 (n=90)	0.99
Range	29−721	106−450	40−721	29−461	
Hemoglobin levels after surgery - 24 hours after surgery (mmHg)					
Mean ± SD	12.3±1.9 (n=724)	11.5±1.8 (n=110)	12.4±1.9 (n=502)	12.5±1.9 (n=112)	< 0.001
Range	2.0−17.8	6.9−15.4	2.0−17.7	7.4−17.8	
Platelet count after surgery - 24 hours after surgery (10^3/microliter)					
Mean ± SD	19 ±68 (n=724)	196±66 (n=110)	198±70 (n=502)	194±65 (n=112)	0.79
Range	30−639	48−591	30−639	60−424	
Intraoperative packed RBC administered (count)					
Yes	4.9% (n=60)	24% (n=43)	1.9% (n=14)	0.9% (n=3)	<0.001

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Postoperative packed RBC administered (<24 hours) (count)					
Yes	2.2% (n=27)	8% (n=14)	1.08 % (n=8)	1.5% (n=5)	<0.001

ASA: American Society of Anesthesiologists; HoLEP: holmium laser enucleation of the prostate; MUST: Malnutrition Universal Screening Tool; RBD: red blood cells; SD: standard deviation; TURP: transurethral resection of the prostate. *P-values represent global comparisons across surgical approach (open surgery, TURP, HoLEP) using one-way ANOVA or Kruskal-Wallis tests for continuous variables and χ^2 tests for categorical variables.

Table 2. Predictive performance of preoperative variables for blood transfusion in TURP and HoLEP cohort (N=1059)

Variable	Optimal cutoff	AUC	Sensitivity	Specificity
Hemoglobin	<11 g/dL	0.81	0.71	0.90
Age at surgery	>80 years	0.65	0.55	0.76
ASA score	>2	0.63	0.73	0.53
CCI	>4	0.62	0.59	0.66
Prostate volume	>100 mL	0.60	0.33	0.86
Platelets	<100 ×10c³/µL	0.54	0.10	0.98
INR	>1.3	0.52	0.05	0.98
MUST Score	>1	0.50	0.05	0.95

ASA: American Society of Anesthesiologists; CCI: Charlson Comorbidity Index; HoLEP: holmium laser enucleation of the prostate; INR: international normalized ratio; MUST: Malnutrition Universal Screening Tool; TURP: transurethral resection of the prostate.

Table 3. Logistic regression model of preoperative transfusion risk

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Predictor (cutoff)	**B coefficient**	**Odds ratio**	**95% CI lower**	**95% CI upper**	**p**
ASA score ≥2	0.38	1.47	1.14	1.89	0.003
Age at surgery ≥80 years	0.08	1.08	1.06	1.10	<0.001
INR ≥1.3	0.05	1.05	0.29	3.90	0.936
Prostate volume ≥100 mL	0.02	1.02	1.01	1.02	<0.001
MUST score result ≥1	-0.10	0.91	0.73	1.14	0.419
Indwelling catheter present	-0.05	0.95	0.78	1.17	0.642
Charlson score ≥4	-0.46	0.63	0.58	0.69	<0.001
Hemoglobin ≤11 g/dL	-0.51	0.60	0.57	0.64	<0.001
Platelets ≤100 $\times 10^3/\mu L$	-0.01	0.99	0.99	0.99	<0.001

ASA: American Society of Anesthesiologists; CI: confidence interval; INR: international normalized ratio; MUST: Malnutrition Universal Screening Tool.

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Table 4. XGBoost feature importance

Rank	Predictor	Importance (dichotomized)	Importance (continuous)
1	Prostate volume / ≥100 mL	2	183
2	Hemoglobin / <11 g/dL	10	79
3	Platelet / <100	5	45
4	Age / ≥80	27	31
5	INR / ≥1.3	19	17
6	ASA score ≥2	8	12
7	CCI ≥ 4	38	7
8	MUST score ≥1	24	6
9	Preoperative catheter	14	4

ASA: American Society of Anesthesiologists; CCI: Charlson Comorbidity Index. INR: international normalized ratio; MUST: Malnutrition Universal Screening Tool.

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