Precision medicine to improve use of bleeding avoidance strategies and reduce bleeding in patients undergoing percutaneous coronary intervention: Prospective cohort study before and after implementation of personalized bleeding risks

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Authors
Precision medicine to improve use of bleeding avoidance strategies and reduce bleeding in patients undergoing percutaneous coronary intervention: prospective cohort study before and after implementation of personalized bleeding risks

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ABSTRACT

OBJECTIVE
To examine whether prospective bleeding risk estimates for patients undergoing percutaneous coronary intervention could improve the use of bleeding avoidance strategies and reduce bleeding.

DESIGN
Prospective cohort study comparing the use of bleeding avoidance strategies and bleeding rates before and after implementation of prospective risk stratification for peri-procedural bleeding.

SETTING
Nine hospitals in the United States.

PARTICIPANTS
All patients undergoing percutaneous coronary intervention for indications other than primary reperfusion for ST elevation myocardial infarction.

MAIN OUTCOME MEASURES
Use of bleeding avoidance strategies, including bivalirudin, radial approach, and vascular closure devices, and peri-procedural bleeding rates, stratified by bleeding risk. Observed changes were adjusted for changes observed in a pool of 1135 hospitals without access to pre-procedural risk stratification.

HOSPITAL LEVEL AND PHYSICIAN LEVEL VARIABILITY
Hospital level and physician level variability in use of bleeding avoidance strategies was examined.

RESULTS
In a comparison of 7408 pre-intervention procedures with 3529 post-intervention procedures, use of bleeding avoidance strategies within intervention sites increased with pre-procedural risk stratification (odds ratio 1.81, 95% confidence interval 1.44 to 2.27), particularly among higher risk patients (2.03, 1.58 to 2.61; 1.41, 1.09 to 1.83 in low risk patients, after adjustment for control sites; P for interaction=0.05). Bleeding rates within intervention sites were significantly lower after implementation of risk stratification (1.0% v 1.7%; odds ratio 0.56, 0.40 to 0.78; 0.62, 0.44 to 0.87, after adjustment); the reduction in bleeding was greatest in high risk patients. Marked variability in use of bleeding avoidance strategies was observed across sites and physicians, both before and after implementation.

CONCLUSIONS
Prospective provision of individualized bleeding risk estimates was associated with increased use of bleeding avoidance strategies and lower bleeding rates. Marked variability between providers highlights an important opportunity to improve the consistency, safety, and quality of care.

STUDY REGISTRATION
Clinicaltrials.gov NCT01383382.

Introduction
Most medical treatments are associated with heterogeneity of benefit; some patients benefit a great deal from treatment, whereas others do not.1 2 Observational studies show many examples of a “risk-treatment paradox,” in which patients at the highest risk (and with the greatest potential to gain from treatment) are treated less often than those at lower risk and with less potential to benefit.3–10 These practice patterns are not patient centered and are intrinsically inefficient in terms of costs, safety, and outcomes. Developing methods to integrate individualized risk stratification within routine clinical care has the potential to remedy this paradoxical practice pattern by alerting clinicians to each patient’s potential benefits from treatment and enabling more patient centered, evidence based, efficient care with safer, better outcomes.11

The use of bleeding avoidance strategies at the time of percutaneous coronary intervention is a prototypical example of the risk-treatment paradox. Bleeding is one of the most common non-cardiac complications of percutaneous coronary intervention and is associated with increased mortality, morbidity, and costs.12–19 It is also modifiable through the use of bleeding avoidance strategies, such as bivalirudin, radial percutaneous coronary...
intervention, and, potentially, vascular closure devices. Importantly, although the magnitude of bleeding reduction and bleeding related mortality are strongly associated with patients’ underlying risk of bleeding, bleeding avoidance strategies are paradoxically used most often in patients at low risk of bleeding and least often in those at high risk.

To improve use of bleeding avoidance strategies, and reduce percutaneous coronary intervention related bleeding, we implemented a novel method for prospectively determining and informing physicians of patients’ bleeding risks by using a validated risk model developed by the American College of Cardiology’s National Cardiovascular Data Registry (NCDR) CathPCI Registry. Patients’ personalized risks were calculated with the Patient Risk Information Services Manager (ePRISM), which was designed to translate multivariable risk models, using each patient’s specific clinical risk factors, at the point of care. As a vehicle to translate models to the clinical setting, ePRISM was designed to be seamlessly integrated within routine clinical workflow. In the setting of percutaneous coronary intervention, ePRISM was used to generate personalized consent forms and replace sites’ traditional consent forms, where it has recently been shown to improve patients’ experience with care. It also created streamlined decision support tools that could be printed and given to physicians before the percutaneous coronary intervention procedure.

We did a pre/post-implementation study at nine large US percutaneous coronary intervention centers and evaluated changes in use of bleeding avoidance strategies and bleeding outcomes, while correcting for contemporary trends among matched NCDB CathPCI hospitals that did not have access to the ePRISM tool. We hypothesized that prospective stratification of bleeding risk could improve the use of bleeding avoidance strategies in higher risk patients and reduce bleeding in patients undergoing percutaneous coronary intervention.

Methods

In this prospective cohort study, individualized bleeding risk estimates were incorporated into the informed consent document for all patients undergoing non-emergent coronary angiography (supplemental figure A) and possible percutaneous coronary intervention at nine US centers (Washington University, Saint Louis, MO; Integris Hospital, Oklahoma, OK; Yale University, New Haven, CT; Henry Ford Hospital, Detroit, MI; Baystate Medical Center, Springfield, MA; The Heart Hospital at Baylor, Plano, TX; Kaiser Hospital, San Francisco, CA; St John’s Hospital, Springfield, IL; Mayo Clinic, Rochester, MN). The pre-procedural risk models were generated using the ePRISM software platform (Health Outcomes Sciences, Overland Park, KS), which was provided through grant funding to each center. We compared use of bleeding avoidance strategies and bleeding rates before and after implementation of the personalized risk estimates. Because the routine process of care was changed at each center to include the new personalized consent forms, randomization of individual patients was not feasible. To overcome the most important bias in pre-/post-intervention comparisons—namely, temporal trends in care that could account for observed changes in treatment and outcomes—we used an additional comparison of non-participating NCDR sites as concurrent controls. This study design (supplemental figure B) was endorsed by two peer reviewed study sections (American Heart Association and the National Heart Lung and Blood Institute), who provided funding for the study.

The implementation of ePRISM has been previously described, and a rolling enrollment of sites led to staggered start dates between March 24, 2010 and May 5, 2011. Before implementation of the new consent process, a study investigator (JAS) provided didactic education about the bleeding risk model and data on the comparative effectiveness of bleeding avoidance strategies in reducing bleeding. Within one to two months of implementation, an interventional cardiologist (ARK) provided additional information on strategies to reduce bleeding as a function of risk. We considered the period between the start of prospective risk stratification and the interventionalist’s visit to be a “break-in” period and excluded it from analysis. We did not provide bleeding avoidance strategy protocols to the sites, and each site was able to implement the tool as fit best within their practice.

Data from all percutaneous coronary interventions performed during the study period were available for analysis through access to each site’s CathPCI Registry data. The CathPCI Registry, sponsored by the American College of Cardiology Foundation and the Society for Cardiovascular Angiography and Interventions, collects detailed clinical characteristics, treatments, and outcomes using standardized definitions (www.ncdr.com/webncdr/cathpci/home/datacollection).

The pre-implementation period consisted of the 12 months before implementation of prospective bleeding risk stratification at each site. The post-implementation period consisted of the time period after system activation and a physician site visit for didactic education on the methods and approach to risk stratification. Data collected in the “break-in” period between implementation and the physician site visit were excluded from analysis.

Study population

During the study period, 218 physicians across the nine sites performed 22066 percutaneous coronary intervention procedures. Patients were excluded from analysis for the following reasons: ST elevation myocardial infarction or other emergent procedures for which insufficient time was available to provide the personalized consent form (n = 3895); repeat percutaneous coronary intervention during the same hospital admission for which attribution of which procedure was associated with bleeding is difficult (n = 268); procedures of unknown status (emergent or other; n = 33); procedures for which the percutaneous coronary intervention operator was not documented (n = 274); procedures during...
the “break-in” period between implementation and the physician site visit (n=1470); and procedures in the post-implementation period for which a personalized consent with bleeding risk was not generated (n=3156; for example, a consent had already been signed at a referring institution, administrative error). We excluded an additional 2033 procedures from analysis owing to non-overlapping propensity scores between pre-implementation and post-implementation groups (see below). This resulted in a final study cohort of 10 937 percutaneous coronary intervention procedures (7408 before implementation and 3529 after implementation) performed by 137 physicians.

Bleeding risk estimates
The previously validated CathPCI Registry bleeding risk model incorporates nine pre-procedural clinical variables (age, sex, previous heart failure, glomerular filtration rate, peripheral vascular disease, previous percutaneous coronary intervention, functional status, ST elevation myocardial infarction/non-ST elevation myocardial infarction, and cardiogenic shock; C statistic=0.72). Patients were classified as having low (<1%), moderate (1–3%), or high (>3%) risk of bleeding. We selected these cut-off values a priori on the basis of previous publications. Because the physicians’ education components of the intervention encouraged use of bleeding avoidance strategies in patients at moderate or high risk for bleeding, the categorical analyses of bleeding outcomes and changes in bleeding avoidance strategy use are between patients with low and moderate/high risk (<1% v ≥1%) for bleeding. We calculated these risk estimates retrospectively for the pre-implementation period by using NCDR data, but they were not available to the physician before percutaneous coronary intervention.

Outcomes
Study outcomes included use of bleeding avoidance strategies and in-hospital, post-procedural bleeding rates. Bleeding avoidance strategies were analyzed individually and by use of any strategy. Use of bivalirudin was considered the most modifiable strategy, as radial approaches are very operator dependent (interventionalists tend to predominantly use or not use this access approach) and the benefits of vascular closure devices to prevent bleeding are controversial. Bleeding events were prospectively collected and defined according to standard NCDR definitions (access site, retroperitoneal, gastrointestinal, genitourinary, or unknown bleeding within 72 hours after percutaneous coronary intervention, associated with a drop in hemoglobin of ≥3 g/dL or requiring transfusion, procedural intervention, or surgery).

Statistical analyses
To account for contemporary trends in use of bleeding avoidance strategies and bleeding incidence, we matched the nine study sites to control hospitals selected from among the 1135 CathPCI Registry sites not participating in this study. Hospitals were matched on annual percutaneous coronary intervention volume, teaching status, and the physicians’ average pre-ePRISM rate for each outcome. Given the number of outcomes, we could not match intervention sites with controls on the pre-procedural rates of all five outcomes (bleeding, bivalirudin use, closure device use, radial access, and any bleeding avoidance strategy use), so we did separate matches for each outcome. To reduce the effects of measurement error and sampling variation among the specific control hospitals selected, we used full optimal matching to match as many controls as possible to each study site. Between 130 and 178 control hospitals were matched, depending on the outcome. We ensured balance between study and matched control hospitals by calculating standardized differences, which were all less than 10% for each variable within each outcome analysis (supplemental table A).

To adjust for differences in patients’ and procedural characteristics before and after ePRISM implementation, as well as between study and control sites, we calculated multiple group propensity scores. This enabled us to adjust simultaneously for a myriad of patients’ characteristics so that the differences in treatment and outcomes were attributable to the intervention rather than to the types of patients treated in the different time periods. To do this, we constructed a multinomial logistic regression model predicting membership in each of the four “treatment” groups (study v control; pre- v post-ePRISM implementation) on the basis of 31 demographic, clinical, and procedural variables (table 1). From this model, we obtained three propensity scores estimating the probability of membership in each of three groups compared with the reference group of study sites before implementation of ePRISM. We assessed covariate balance by comparing propensity adjusted standardized differences between patients in the pre-intervention and post-intervention groups (<10% indicates good balance). Overlap of propensity score distributions among the four groups was good for all scores. We included these scores as covariates in the outcome models.

The primary unit of analysis in this study was the percutaneous coronary intervention physician operator. We used hierarchical logistic regression models to assess the effect of exposure to ePRISM on physicians’ change in use of bleeding avoidance strategies and the incidence of post-procedural bleeding, corrected for concurrent trends among control hospitals. Models included a fixed effect for study phase (before v after ePRISM implementation, centered within physician), physician level random intercepts and random effects for study phase, a fixed effect for study versus control hospital groups, a study phase-by-group interaction term, and adjustment for hospital matched sets and the three logit propensity scores. We quantified the effect of ePRISM as the relative difference in odds ratio for study phase between study and control hospitals. In addition, among the nine study sites, we evaluated variability in use of bleeding avoidance strategies by physician with median odds ratios, which estimate the relative difference in use between two randomly selected physicians or hospitals for “identical” patients with the same covariates.
Finally, we repeated the above analyses, augmenting the models with terms for bleeding risk and ePRISM-by-risk interactions, to examine whether greater changes in treatment or benefit occurred among higher risk patients. We did separate analyses incorporating bleeding risk as a categorical (low v moderate/high) or continuous variable. Among the nine study sites, we derived variability in physicians’ use of bleeding avoidance strategies as a function of bleeding risk both before and after implementation of ePRISM from the estimated random effects from the model incorporating bleeding risk as a continuous variable. We also repeated these approaches for other anticoagulation and antiplatelet regimens, including unfractionated heparin, low molecular weight heparin, glycoprotein IIb/IIIa inhibitors, and thienopyridine use (both clopidogrel and prasugrel). We also did an exploratory descriptive analysis to assess the effect of pre-procedural risk stratification on in-hospital mortality, as recorded in the NCDR registry, among the intervention sites. We used SAS 9.3 and R version 2.15.0 for all analyses.33 All hypothesis tests were two tailed and evaluated at a significance level of 0.05.

Results
The mean “break-in” period between implementation of pre-procedural risk stratification and the physician site visit was 2.1 months, and the mean study duration after the physician site visit was 9.4 months (supplemental table B). The final study cohort consisted of 10937 percutaneous coronary intervention procedures (7408 before implementation and 3529 after implementation) by 137 physicians. Table 1 shows patients’ baseline demographic and clinical characteristics. Estimated bleeding risks were similar between the two groups. After propensity adjustment, all patients’ and procedural characteristics were well balanced (standardized differences 0–28% before adjustment, 0–7% after; supplemental table A).

Processes of care to mitigate bleeding
To understand the effect of pre-procedural risk stratification on the use of bleeding avoidance strategies, we compared the observed changes at the intervention sites overall, and stratified by bleeding risk, and adjusted these observations for changes in bleeding avoidance strategy use at the control sites. Overall bleeding avoidance strategy use (table 2) increased from 81.4% to 88.7% after implementation (odds ratio 1.81, 95% confidence interval 1.44 to 2.27; P<0.001). The increase was significantly greater in patients at high risk of bleeding (odds ratio 2.03 v 1.48 for low risk patients; P=0.05 for interaction). After correction for contemporary trends, the effect of pre-procedural risk stratification on the use of bleeding avoidance strategies was of borderline statistical significance (corrected odds ratio 1.23, 0.98 to 1.56) across all patients but significantly greater in patients at high risk for bleeding (1.41, 1.09 to 1.83; P=0.008). When we examined individual bleeding avoidance strategies, the availability of pre-procedural bleeding risk estimates was associated with similar overall use of bivalirudin (odds ratio 1.18, 0.93 to 1.48) but a change in practice that favored its use in high risk patients (1.36, 1.05 to 1.75) over low risk patients (0.92, 0.69 to 1.24; P value for interaction=0.03). When we adjusted for control hospitals, we found no overall difference in bivalirudin.
Table 2 | Bleeding avoidance strategy use and post-percutaneous coronary intervention (PCI) bleeding by bleeding risk and availability of these risks before PCI

<table>
<thead>
<tr>
<th>Outcomes—peri-procedural bleeding</th>
<th>Study hospitals</th>
<th>Pre-PRISM rate</th>
<th>Post-PRISM rate</th>
<th>Odds ratio (95% CI)</th>
<th>P value</th>
<th>PRISM effect (corrected for controls)</th>
<th>PRISM effect (corrected for controls)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall</td>
<td></td>
<td>1.7%</td>
<td>1.0%</td>
<td>0.56 (0.40 to 0.78)</td>
<td>&lt;0.001</td>
<td>0.71</td>
<td>0.62 (0.44 to 0.87)</td>
</tr>
<tr>
<td>Low bleeding risk</td>
<td></td>
<td>0.7%</td>
<td>0.3%</td>
<td>0.46 (0.20 to 1.06)</td>
<td>0.07</td>
<td>0.91</td>
<td>0.51 (0.21 to 1.20)</td>
</tr>
<tr>
<td>Moderate/high bleeding risk</td>
<td></td>
<td>2.1%</td>
<td>1.3%</td>
<td>0.59 (0.41 to 0.85)</td>
<td>0.004</td>
<td>0.90</td>
<td>0.65 (0.45 to 0.94)</td>
</tr>
<tr>
<td>Low bleeding risk</td>
<td></td>
<td>5.6%</td>
<td>14.2%</td>
<td>0.84 (0.74 to 1.11)</td>
<td>0.12</td>
<td>0.61</td>
<td>0.51 (0.21 to 1.20)</td>
</tr>
<tr>
<td>Moderate/high bleeding risk</td>
<td></td>
<td>5.6%</td>
<td>14.2%</td>
<td>0.84 (0.74 to 1.11)</td>
<td>0.12</td>
<td>0.61</td>
<td>0.51 (0.21 to 1.20)</td>
</tr>
<tr>
<td>Overall</td>
<td></td>
<td>4.7%</td>
<td>10.7%</td>
<td>0.80 (0.62 to 1.0)</td>
<td>&lt;0.001</td>
<td>0.71</td>
<td>0.62 (0.44 to 0.87)</td>
</tr>
<tr>
<td>Processes of care—bleeding avoidance strategies</td>
<td>Any strategy</td>
<td>Overall</td>
<td>81.4%</td>
<td>88.7%</td>
<td>1.81 (1.44 to 2.27)</td>
<td>&lt;0.001</td>
<td>0.05</td>
</tr>
<tr>
<td>Low bleeding risk</td>
<td></td>
<td>85.9%</td>
<td>90.0%</td>
<td>1.48 (1.08 to 2.04)</td>
<td>0.02</td>
<td>1.50 (1.39 to 1.62)</td>
<td>0.99 (0.71 to 1.37)</td>
</tr>
<tr>
<td>Moderate/high bleeding risk</td>
<td></td>
<td>78.7%</td>
<td>88.3%</td>
<td>2.03 (1.58 to 2.61)</td>
<td>&lt;0.001</td>
<td>1.44 (1.35 to 1.53)</td>
<td>1.41 (1.09 to 1.83)</td>
</tr>
<tr>
<td>Bivalirudin:</td>
<td></td>
<td>Overall</td>
<td>48.6%</td>
<td>52.6%</td>
<td>1.38 (0.93 to 1.48)</td>
<td>0.17</td>
<td>0.03</td>
</tr>
<tr>
<td>Low bleeding risk</td>
<td></td>
<td>51.5%</td>
<td>49.6%</td>
<td>0.92 (0.69 to 1.24)</td>
<td>0.61</td>
<td>1.27 (1.18 to 1.36)</td>
<td>0.73 (0.54 to 0.99)</td>
</tr>
<tr>
<td>Moderate/high bleeding risk</td>
<td></td>
<td>47.9%</td>
<td>55.5%</td>
<td>1.36 (1.05 to 1.75)</td>
<td>0.02</td>
<td>1.29 (1.31 to 1.27)</td>
<td>1.05 (0.81 to 1.37)</td>
</tr>
<tr>
<td>Closure device:</td>
<td></td>
<td>Overall</td>
<td>31.2%</td>
<td>28.9%</td>
<td>0.90 (0.73 to 1.10)</td>
<td>0.30</td>
<td>0.16</td>
</tr>
<tr>
<td>Low bleeding risk</td>
<td></td>
<td>37.4%</td>
<td>33.4%</td>
<td>0.84 (0.64 to 1.10)</td>
<td>0.20</td>
<td>0.90 (0.84 to 0.96)</td>
<td>0.94 (0.71 to 1.24)</td>
</tr>
<tr>
<td>Moderate/high bleeding risk</td>
<td></td>
<td>29.4%</td>
<td>28.6%</td>
<td>0.96 (0.77 to 1.20)</td>
<td>0.73</td>
<td>0.95 (0.89 to 1.00)</td>
<td>1.02 (0.81 to 1.28)</td>
</tr>
<tr>
<td>Radial access:</td>
<td></td>
<td>Overall</td>
<td>4.7%</td>
<td>10.7%</td>
<td>2.45 (1.84 to 3.26)</td>
<td>&lt;0.001</td>
<td>0.46</td>
</tr>
<tr>
<td>Low bleeding risk</td>
<td></td>
<td>5.6%</td>
<td>14.2%</td>
<td>2.77 (1.90 to 4.02)</td>
<td>&lt;0.001</td>
<td>2.54 (2.22 to 2.91)</td>
<td>1.09 (0.73 to 1.62)</td>
</tr>
<tr>
<td>Moderate/high bleeding risk</td>
<td></td>
<td>4.5%</td>
<td>9.8%</td>
<td>2.32 (1.72 to 3.16)</td>
<td>&lt;0.001</td>
<td>2.36 (2.11 to 2.63)</td>
<td>0.99 (0.72 to 1.36)</td>
</tr>
</tbody>
</table>

*Among physicians performing at least one radial procedure before implementation of PRISM.

use in high risk patients but decreased use in lower risk patients (odds ratio 0.73, 0.54 to 0.99; P=0.04). We found no significant changes in use of vascular closure devices within intervention sites or between intervention and control sites. Although use of radial access increased within the intervention sites, these changes were similar to those at control sites and did not vary by bleeding risk categories.

Analyses incorporating risk of bleeding as a continuous variable (supplemental figure C) showed significant increases in use of bleeding avoidance strategies after the availability of pre-procedural bleeding risk estimates, although interactions between bleeding avoidance strategy use and bleeding risk were not statistically significant. Other anticoagulation strategies (supplemental table C) also varied after the intervention, including less use of low molecular weight heparin (overall odds ratio 0.62, 0.52 to 0.75; adjusted odds ratio 0.71, 0.59 to 0.86, with no significant interaction by bleeding risk group) and less use of glycoprotein IIb/IIIa inhibitors (0.66, 0.55 to 0.79, with no interaction by bleeding risk group and no difference after adjustment for contemporary practice in control sites: 0.91, 0.75 to 1.10). We observed no significant differences in the use of unfractionated heparin or thienopyridines (either clopidogrel or prasugrel) after pre-procedural risk stratification once we adjusted for changes in hospitals without access to pre-procedural bleeding risk estimates.

**Bleeding outcomes**

Table 2 summarizes the effect of pre-procedural bleeding risk estimates on bleeding. Bleeding complications decreased from 1.7% to 1.0% after implementation (odds ratio 0.56, 0.40 to 0.78; P<0.001), and this effect persisted after correction for contemporary trends (difference between differences 0.56 v 0.91, P<0.001; corrected odds ratio 0.62, 0.64 to 0.87, P=0.006). Bleeding complications decreased significantly at intervention sites, compared with control sites, for patients at high risk of bleeding (odds ratio 0.65, 0.45 to 0.94; P=0.02) but not among patients at low risk of bleeding (0.51, 0.21 to 1.20; P=0.12). Analyses incorporating risk of bleeding as a continuous variable (fig 1) suggested a greater absolute decrease in bleeding rate as bleeding risk increased. In contrast to the beneficial effects of pre-procedural risk stratification on bleeding, we observed no differences in in-hospital mortality among the intervention sites (0.37% pre-ePRISM v 0.41% post-ePRISM; P=0.62).

**Hospital and physician variability**

Significant hospital and physician level variability in BAS use was present. In the post-intervention period, use of bleeding avoidance strategies ranged from 31% to 98%, bivalirudin use ranged from 1% to 96%, vascular closure device use ranged from 3% to 70%, and radial access ranged from 1% to 51% across hospitals. The effect of pre-procedural bleeding risk estimates on bleeding avoidance strategy use varied widely across hospitals (table 3), with hospital specific odds ratios for the use of any strategy ranging from 0.49 to 2.65 (P=0.006 for differences by hospital), although the effect of ePRISM on bleeding avoidance strategy use was greater than 1.0 in seven of nine
hospitals, suggesting that all but two hospitals increased their use of such strategies after being provided with pre-procedural estimates of patients’ bleeding risk. Within hospitals, we also saw substantial variability in bleeding avoidance strategy use by physicians at each hospital (table 4). The median odds ratio for any use of any strategy, after adjustment for between hospital differences, was 4.1 when the personalized consents were used, indicating a fourfold difference in the probability of any bleeding avoidance strategy use between two randomly selected physicians at the same hospital treating patients with identical bleeding risk and other clinical characteristics. We observed similar variation for each individual strategy, with bivalirudin use showing the greatest variability. Figure 2 shows the use of bivalirudin as a function of patients’ bleeding risks, before and after pre-procedural risk stratification. This figure emphasizes the wide variability across physicians, even after personalized estimates of bleeding were provided. Some physicians never used bivalirudin, even among the patients at highest risk for bleeding, whereas others used it in all of their high risk patients. Physician level performance for other strategies are shown in supplemental figure D.

Discussion
To our knowledge, this is the first demonstration that precision medicine, delivered through pre-procedural risk stratification, can improve the safety of medical care by supporting tailored treatment in patients at the greatest risk for adverse outcomes. In this before/after study at nine US percutaneous coronary intervention centers, we sought to overcome a well documented risk-treatment paradox in healthcare delivery by prospectively providing personalized estimates of bleeding risk for patients undergoing percutaneous coronary intervention. This intervention was associated with increased use of bleeding avoidance strategies overall, with a greater use in high risk patients (odds ratio 1.41) after adjustment for contemporary trends in bleeding management. The only other change in anticoagulation regimens observed at the intervention sites, compared with control sites, was a lower use of low molecular weight heparins, which have been associated with less bleeding and may have diminished the observed differences in bleeding between intervention and control sites. Most importantly, the overall bleeding rates improved significantly more at the intervention sites after prospective risk stratification than was observed at other matched hospitals participating in the NCDR registry (reduction in odds of bleeding at intervention sites 44% v 9% at control sites). These findings extend our previous experience at a single institution to support the generalizability of this approach.34

Implications of findings
This study highlights the potential value of risk models to improve care. Although risk adjusted benchmarking of performance can enable hospitals to identify whether they are performing favorably compared with their

Table 3 | Variation in bleeding avoidance strategy (BAS) use and effect of personalized bleeding risk estimates across hospitals

<table>
<thead>
<tr>
<th>Bleeding avoidance strategy</th>
<th>Range in BAS use</th>
<th>Range in effect of PRISM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre-PRISM</td>
<td>Post-PRISM</td>
</tr>
<tr>
<td>Any strategy</td>
<td>13–98%</td>
<td>31–98%</td>
</tr>
<tr>
<td>Bivalirudin</td>
<td>1–95%</td>
<td>1–96%</td>
</tr>
<tr>
<td>Closure device</td>
<td>0.2–80%</td>
<td>3–70%</td>
</tr>
<tr>
<td>Radial access</td>
<td>1–14%</td>
<td>1–51%</td>
</tr>
</tbody>
</table>

Table 4 | Variation in bleeding avoidance strategy use and effect of personalized bleeding risk estimates across physicians

<table>
<thead>
<tr>
<th>Bleeding avoidance strategy</th>
<th>Median odds ratios across hospitals</th>
<th>Median odds ratios within hospitals</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre-PRISM</td>
<td>Post-PRISM</td>
</tr>
<tr>
<td>Any strategy</td>
<td>9.4</td>
<td>7.8</td>
</tr>
<tr>
<td>Bivalirudin</td>
<td>11.0</td>
<td>11.3</td>
</tr>
<tr>
<td>Closure device</td>
<td>7.9</td>
<td>6.3</td>
</tr>
<tr>
<td>Radial access</td>
<td>3.2</td>
<td>3.3</td>
</tr>
</tbody>
</table>

Fig 1 | Unadjusted rates of bleeding before and after ePRISM implementation, as a function of bleeding risk. PCI=percutaneous coronary intervention

Fig 2 | Individual physicians’ variability in use of bivalirudin, as a function of bleeding risk, before and after PRISM. Each line represents a physician in the study
emergency cases were excluded from our study.

myocardial infarction or emergent patients, as these
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Secondly, the inclusion of nine sites limits the general-
similar to those in the post-intervention time period.
reduction in bleeding compared with contemporary
leverage the same data collection infrastructure at more
randomized study design would have more definitively
we could not randomize individual patients. A cluster
implementation of clear protocols for optimal use of
individualized bleeding risk estimates had little effect on
the observed variability in care, we believe that future
efforts to support more consistent care may require
implementation of clear protocols for optimal use of
bleeding avoidance strategies as a function of bleeding
risk, feedback reports on protocol adherence, and hold-
ing physicians accountable for their practice patterns.

Limitations of study
Our findings should be interpreted in the context of sev-
eral potential limitations. Firstly, this was a non-ran-
domized study with a before/after design. Because we
changed the processes of obtaining informed consent,
we could not randomize individual patients. A cluster
randomized study design would have more definitively
compared the effect of pre-procedural risk stratification
on care and outcomes. Nevertheless, we were able to
leverage the same data collection infrastructure at more
than 1100 hospitals to document a significantly greater
reduction in bleeding compared with contemporary
trends. We were also able to use propensity models to
ensure that patients in the pre-intervention phase were
similar to those in the post-intervention time period.
Secondly, the inclusion of nine sites limits the general-
izability of the findings to other institutions. Our find-
ings are also not generalizable to ST elevation
myocardial infarction or emergent patients, as these
emergency cases were excluded from our study.

However, the lessons learnt from this effort, particularly
our belief in the importance of having established pro-
tocols and feedback, could potentially lead to more suc-
cessful future implementations.

A third limitation is that the optimal management of
anticoagulation and antiplatelet treatment at the time of
percutaneous coronary intervention is complex, with
both oral (for example, clopidogrel, aspirin) and intra-
venous (glycoprotein IIb/IIIa) antiplatelet agents and a
range of anticoagulants (bivalirudin, unfractionated and
low molecular weight heparin) used in various combi-
nations by different operators. We were unable to attri-
but the reduction in bleeding solely to the observed
changes in use of bleeding avoidance strategies. How-
ever, this does not detract from the importance of our
finding that prospective risk stratification was associ-
ated with improved bleeding outcomes for patients
undergoing percutaneous coronary intervention, how-
ever it was achieved. An additional concern might be the
recently announced results of the HEAT PPCI study, in
which bivalirudin did not result in less bleeding than
heparin alone. We excluded primary percutaneous cor-
ony intervention from our analyses, and our results
should not be affected by this new information. A fur-
ther potential concern is the short time of observation
after pre-procedural risk stratification was introduced
and that physicians might take a longer time to incorpo-
rate such information into their practice patterns, some-
thing that would have led to underestimation of the
potential benefits of this approach. Finally, the bleeding
events were not independently adjudicated, with relia-
ance on the NCDR data collection infrastructure, and we
were not able to adjudicate ischemic complications that
may have been affected by changes in antithrombotic
treatment. We also did not have long term outcomes
available, and nor were we able to compare the accuracy
of bleeding events in NCDR between our nine centers
and the rest of the NCDR. Future work should attempt
to assess these outcomes more definitely.

The Institute of Medicine has challenged US healthcare
to be more patient centered, evidence based, and effi-
cient, as well as safer. We have previously reported that
the enhanced informed consent documents generated by
the personalized consents improved patients’ experi-
ences with consent to percutaneous coronary interven-
ton. In this study, we have shown that prospective,
individualized bleeding risk estimates were associated
with more appropriate use of bleeding avoidance strate-
gies and significantly lower bleeding rates. Nevertheless,
the variability of care observed in this study suggests an
important opportunity to further improve the safety and
quality of percutaneous coronary intervention care.

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School and Harvard School of Public Health, Boston, MA, for
guidance in the conceptualization of the analytic approach for
this study. Because JAS has a potential competing interest with
Health Outcomes Sciences (Oberland Park, KS), the entity
supporting ePRISMA, a complete set of data was provided to
Theodora Cohen, executive director of biometrics at the Harvard
Clinical Research Institute, for independent analysis and verification
of the study results.

Contributors: JAS, PGJ, CD, and AKC designed the study. JAS obtained
funding. PGJ did the data analysis. JAS, PGJ, and AKC interpreted the
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