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Development and validation of multivariable prediction models of remission, recovery, and quality of life outcomes in people with first episode psychosis: a machine learning approach

Samuel P Leighton, Rachel Uptegrove, Rajeev Krishnadas, Michael E Benros, Matthew R Broome, Georgios V Gkoutos, Peter F Lidde, Swaran P Singh, Linda Everard, Peter B Jones, David Fowler, Vimal Sharma, Nicholas Freemantle, Rune H B Christensen, Nikolai Albert, Merete Nordentoft, Matthias Schwannauer, Jonathan Cavanagh, Andrew I Gumley, Max Birchwood*, Pavan K Mallikarjun*

Summary

Background Outcomes for people with first-episode psychosis are highly heterogeneous. Few reliable validated methods are available to predict the outcome for individual patients in the first clinical contact. In this study, we aimed to build multivariable prediction models of 1-year remission and recovery outcomes using baseline clinical variables in people with first-episode psychosis.

Methods In this machine learning approach, we applied supervised machine learning, using regularised regression and nested leave-one-site-out cross-validation, to baseline clinical data from the English Evaluating the Development and Impact of Early Intervention Services (EDEN) study (n=1027), to develop and internally validate prediction models at 1-year follow-up. We assessed four binary outcomes that were recorded at 1 year: symptom remission, social recovery, vocational recovery, and quality of life (QoL). We externally validated the prediction models by selecting from the top predictor variables identified in the internal validation models the variables shared with the external validation datasets comprised of two Scottish longitudinal cohort studies (n=162) and the OPUS trial, a randomised controlled trial of specialised assertive intervention versus standard treatment (n=578).

Findings The performance of prediction models was robust for the four 1-year outcomes of symptom remission (area under the receiver operating characteristic curve [AUC] 0·703, 95% CI 0·664–0·742), social recovery (0·731, 0·697–0·765), vocational recovery (0·736, 0·702–0·771), and QoL (0·704, 0·667–0·742; p<0·0001 for all outcomes), on internal validation. We externally validated the outcomes of symptom remission (AUC 0·680, 95% CI 0·587–0·773), vocational recovery (0·867, 0·805–0·930), and QoL (0·679, 0·522–0·836) in the Scottish datasets, and symptom remission (0·616, 0·553–0·679), social recovery (0·573, 0·504–0·643), vocational recovery (0·660, 0·610–0·710), and QoL (0·556, 0·481–0·631) in the OPUS dataset.

Interpretation In our machine learning analysis, we showed that prediction models can reliably and prospectively identify poor remission and recovery outcomes at 1 year for patients with first-episode psychosis using baseline clinical variables at first clinical contact.

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Introduction

Psychosis is an illness with an early first onset, occurring usually in young people and with an incidence of 31 per 100 000 person-years.5 Patients with first-episode psychosis have heterogeneity of outcomes, with a 58% prevalence of remission and 38% of recovery.6 The identification of individual-patient outcomes at initial clinical contact might help to personalise treatment and lead to improved use of resources for those most in need or likely to respond to treatment.7 However, few validated tools are available for the accurate early identification of patients with good or poor outcomes.

Previous observational studies have identified predictors of outcomes at the group level, including sociodemographic factors, clinical and treatment response variables, comorbidity, and functional and cognitive deficits,8,9 with inconsistent reliability.4 More clarity is needed on how to apply group-level factors to an individual level of prediction. An approach that can be applied to stratify the individualised risk of a poor outcome at the initial clinical contact is required. One solution is the use of machine learning, in which algorithms can sift through a large array of predictor variables and detect complex high dimensional interactions that can reliably predict individual-patient outcomes.7
Evidence before this study

Evidence before this study

Added value of this study

Methods

Study design and sources of data

In this machine learning approach, we used data from several sources: the National EDEN studies, two Scottish validation datasets, and the OPUS trial. The National EDEN studies are a longitudinal naturalistic study of 1,027 patients with first-episode psychosis recruited from 14 early intervention services across the National Health Service (NHS) in England (2005–10); the methods and baseline characteristics have been outlined previously. The Scottish validation datasets were two longitudinal cohort studies of patients with first-episode psychosis: the Compassionate Recovery: Individualised Support in early Psychosis (CR:ISP) study of 83 patients in NHS Greater Glasgow & Clyde (2011–14), and an earlier study of 79 patients in NHS Glasgow and NHS Edinburgh (2006–09). The methodologies and baseline characteristics of these studies have been outlined previously. The
OPUS trial (NCT00157313) was a randomised controlled trial of 578 patients with first-episode psychosis recruited from all inpatient and outpatient mental health services in Copenhagen (Copenhagen Hospital Corporation) and Aarhus County, Denmark. OPUS assessed standard (n=272) versus specialised assertive intervention integrated treatment (n=275; January, 1998, to December, 2000). The methods and baseline characteristics of OPUS have been outlined previously.12 Local ethics committees approved the studies and the trial. We have adhered to the transparent reporting of a multivariable prediction model for individual prognosis or diagnosis (TRIPOD) statement.13

With data from the EDEN studies, we developed four predictive models for each of the outcomes assessed in our study and internally validated the models by nested leave-one-site-out cross-validation (LOSOCV). Subsequently, we identified shared variables (from the top predictor variables from the internally validated models) between the EDEN studies and the Scottish datasets and between the EDEN studies and OPUS trial. We used these shared variables to build separate prediction models for external validation on the Scottish datasets and OPUS trial.

The key differences between EDEN (development) and Scottish (validation) datasets were the setting (EDEN was done in NHS England, whereas the Scottish datasets were from studies done in NHS Scotland and study period (2005–10 in EDEN, 2011–14 and 2006–09 in the Scottish datasets). Both NHS England and NHS Scotland are free at the point of delivery. The key differences between EDEN and the other validation dataset (OPUS) were the setting (England vs Denmark, but both at the point of delivery), study period (2005–10 vs January, 1998 to December, 2000 in OPUS), study type (naturalistic in EDEN, for which everyone received early intervention, vs randomised clinical trial in OPUS, for which early intervention was compared with treatment as usual), and inclusion criteria (participants were aged 14–35 years with a first presentation of psychotic illness in EDEN, whereas in OPUS, participants were aged 18–45 years with a diagnosis in the schizophrenia spectrum according to the International Classification of Diseases tenth edition codes in the F2 category, and participants in OPUS had not been given antipsychotic drugs for more than 12 weeks of continuous treatment). The inclusion and exclusion criteria for all three studies have been provided in the appendix (p 1).

Outcome variables
For EDEN, Scottish, and OPUS studies, assessments of predictors and outcomes were done by research assistants not directly involved in clinical care. We assessed four binary outcomes that were recorded at 1 year: symptom remission, meeting the Positive and Negative Syndrome Scale in Schizophrenia (PANSS) criteria at both 6 months and 1 year,14 social recovery, achieving a Global Assessment of Functioning (GAF) score (range 0–100) of 65 or higher in EDEN, and a mean GAF symptoms and GAF disability score of 65 or higher in OPUS,15 vocational recovery, assessing whether participants were in employment, education, or training;16 and quality of life (QoL), assessed with the 3-level European QoL 5 Dimensions Index (EQ-5D-3L) time trade-off index based on UK population norms and dichotomised to greater than median (0·848)7 in EDEN, the WHO QoL 26-item instrument with total score dichotomised to greater than median (88) in the 2006–09 Scottish study, and the Lancashire QoL score5 dichotomised at the median (43·5) in OPUS. We chose operationalised criteria for symptom remission16 and included the three outcome measures for recovery to cover a broader patient-centred experience of recovery. Social recovery was not measured in the Scottish studies.

Statistical analysis
The EDEN study was powered for duration of untreated psychosis. OPUS was powered for positive symptoms

![Table](Figure 1 continues on next page)
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### Figure 2: Top prediction variables for each outcome

Top predictor variables selected by elastic net regularisation across all 14 LOSOCV models for each outcome, ordered by their mean rank across the 14 models by absolute coefficient magnitude, along with their direction of effect (red is negative, grey is positive). PANSS=Positive And Negative Symptom Scale. GAF=Global Assessment of Functioning Scale. DUP=Duration of Untreated Psychosis. EQ-5D-3L=3-level European Quality of Life 5 Dimensions Index. UK TTO=time trade-off index.

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Quality of life</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unemployment, education, or training at baseline</td>
<td>EQ-5D-3L anxiety or depression</td>
</tr>
<tr>
<td>PAS client general employment at baseline</td>
<td>PANSS G2—conceptual disorganisation</td>
</tr>
<tr>
<td>Qualification level</td>
<td>PANSS N5—difficulties in abstract thinking</td>
</tr>
<tr>
<td>GAP disability total</td>
<td>PANSS P3—hallucinatory behaviour</td>
</tr>
<tr>
<td>Main income source is salary or wage</td>
<td>PANSS P2—conceptual disorganisation</td>
</tr>
<tr>
<td>Help by friend or relative around the house in last 3 months</td>
<td>PANSS N6—lack of spontaneity</td>
</tr>
<tr>
<td>Main income source is state benefits</td>
<td>PANSS P2—conceptual disorganisation</td>
</tr>
<tr>
<td>Main income source is something other than family, salary, or benefits</td>
<td>PANSS G2—disturbance of volition</td>
</tr>
<tr>
<td>Most serious self-harm is with knife or razor</td>
<td>PANSS G6—depression</td>
</tr>
<tr>
<td>Adjusted DUP in days</td>
<td>GAF total</td>
</tr>
<tr>
<td>PANSS client childhood sociability withdrawal</td>
<td>History of ketamine use</td>
</tr>
<tr>
<td>GAF symptoms total</td>
<td>History of cocaine use</td>
</tr>
<tr>
<td>Ethnicity—Pakistani</td>
<td>PANSS P3—hallucinatory behaviour</td>
</tr>
<tr>
<td>In employment, education, or training at baseline</td>
<td>PANSS P3—hallucinatory behaviour</td>
</tr>
<tr>
<td>Help by friend or relative around the house in last 3 months</td>
<td>PANSS N6—lack of spontaneity</td>
</tr>
<tr>
<td>PANSS G2—poor attention</td>
<td>PANSS G7—poor attention</td>
</tr>
<tr>
<td>PANSS N6—lack of spontaneity</td>
<td>PANSS G2—poor attention</td>
</tr>
<tr>
<td>Help by friend or relative around the house in last 3 months</td>
<td>PANSS G2—poor attention</td>
</tr>
<tr>
<td>PANSS N6—lack of spontaneity</td>
<td>PANSS G2—poor attention</td>
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<tr>
<td>Help by friend or relative around the house in last 3 months</td>
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<tr>
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<td>PANSS G2—poor attention</td>
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<tr>
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</tr>
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<td>PANSS G2—poor attention</td>
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</tr>
</tbody>
</table>

Figure 2: Top prediction variables for each outcome

Top predictor variables selected by elastic net regularisation across all 14 LOSOCV models for each outcome, ordered by their mean rank across the 14 models by absolute coefficient magnitude, along with their direction of effect (red is negative, grey is positive). PANSS=Positive And Negative Symptom Scale. GAF=Global Assessment of Functioning Scale. DUP=Duration of Untreated Psychosis. EQ-5D-3L=3-level European Quality of Life 5 Dimensions Index. UK TTO=time trade-off index.

According to the Scale for Assessment of Positive Symptoms (SAPS). The 2006–09 Scottish study was powerless for the strength of association between duration of untreated psychosis and psychiatric symptomatology. The 2011–14 Scottish study was powered for positive and negative symptoms. Because our study is a post-hoc analysis, a sample size calculation is not applicable.

Studies with missing outcome data were removed from the analysis. Regarding predictor selection, during data pre-processing in EDEN, all 266 baseline social, demographic, and clinical predictor variables were centred and scaled, variables with zero variance and near-zero variance were removed, and variables with more than 20% of missing data were excluded. For the remaining 163 (61%) of predictor variables (appendix pp 2–6), missing data were imputed by use of k-nearest neighbour imputation (k=5) to increase prediction performance. We did not complete any a-priori hypothesis-based feature selection.

We used the EDEN dataset for model development and undertook both internal and external validation with LOSOCV. We fit a logistic regression model by elastic net regularisation with variable selection in the caret package using the glmnet package. Glmnet fits a generalised linear model through penalised maximum likelihood (appendix pp 1–2). All the 163 predictor variables were used simultaneously with the elastic net regularisation model. Each of the 14 EDEN sites was left out once for the validation of a model based on the remaining 13 sites and trained by use of a ten-fold cross-validation (splits balanced by outcome class) over a 10×10 grid of α and λ hyperparameters, with Breiman’s 1 SE rule.

We measured average performance across the resulting 14 best LOSOCV models using receiver operating characteristic (ROC) curve and area under the curve (AUC). AUCs, with 95% CIs, were established on the basis of U-statistic theory, and permutation testing confirmed significance. Representative model accuracy, sensitivity, specificity, positive predictive value (PPV), negative predictive value (NPV), prognostic summary index (PSI), positive likelihood ratio (LR+) and negative likelihood ratio (LR−) are presented on the basis of the point on the ROC curve corresponding to Youden’s index. We assessed the stability (φ) of feature selection in the 14 best LOSOCV models using the approach described by Nogueira and colleagues, where φ lower than 0.4 shows poor agreement between the 14 models, 0.4 to 0.75 shows intermediate to good agreement, and higher than 0.75 shows excellent agreement. We did this model development procedure for each of our four binary outcomes.

We assessed the relatedness of the four models by computing the Yule φ correlation between the four outcomes, computing the Pearson correlation between probability outputs of the four logistic regression models, and assessing the prediction performance when using the probability outputs of one model as predictors of outcome for the other three models with LOSOCV (appendix pp 6–7). We used the shared predictor variables among the top variables for the four models to build generalised linear models for external validation.

For external (geographical and temporal) validation of the prediction models, we used the Scottish and OPUS datasets. For each outcome, we took the shared variables across both the EDEN and the external validation dataset from the top predictor variables determined during model development (those selected in all 14 LOSOCV models; figure 1). We standardised these variables.
separately on each dataset before model fitting; therefore, we were able to assess EDEN model performance on the validation dataset even though some shared variables were measured on different scales. Afterwards, we used the entire EDEN dataset to fit a generalised linear model by maximum likelihood estimation (without regularisation) using these shared top predictor variables (having found no improvement in performance during initial scoping with more complex classifiers, including linear and radial support vector machines, elastic net, and random forest). We confirmed that the internal–external validation performance on the EDEN dataset remained robust with the new model using only the shared top predictor variables. The internally–externally validated EDEN model was then externally validated on the external dataset, with performance reported as already outlined. This process was repeated separately for the Scottish datasets and the OPUS dataset (figure 2).

All statistical analyses were done with R, and the code is available online. The comparison between EDEN, Scottish, and OPUS samples (demographic and social variables) is provided in the appendix (p 2).

Role of the funding source
The funder of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report. The corresponding author had full access to all the data in the study and had final responsibility for the decision to submit for publication.

Results
We included only participants for whom outcome data were available (table 1). In the EDEN studies, 673 (66%) of 1027 patients had complete symptom remission outcome data, 829 (81%) had complete social recovery outcome data, 807 (79%) had complete vocational recovery outcome data, and 729 (71%) had complete QoL outcome data. 15–39% of patients were missing outcomes data on model performance at 1 year for training cohorts

<table>
<thead>
<tr>
<th></th>
<th>Training data (EDEN studies)</th>
<th>Validation data (Scottish studies)</th>
<th>Validation data (OPUS trial)</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Symptom remission</td>
<td>320/673 (48%)</td>
<td>66/131 (50%)</td>
<td>121/338 (36%)</td>
<td>0·0006*</td>
</tr>
<tr>
<td>Social recovery</td>
<td>388/829 (47%)</td>
<td>NA</td>
<td>73/518 (14%)</td>
<td>&lt;0·0001*</td>
</tr>
<tr>
<td>Vocational recovery</td>
<td>436/807 (54%)</td>
<td>59/142 (42%)</td>
<td>173/553 (31%)</td>
<td>&lt;0·0001*</td>
</tr>
<tr>
<td>Quality of life</td>
<td>328/729 (45%)</td>
<td>23/47 (49%)</td>
<td>113/226 (50%)</td>
<td>0·39</td>
</tr>
</tbody>
</table>

Data are n/N (%). NA—not applicable. *Significant differences (determined with Pearson’s χ² test) of rates of positive outcomes between the cohorts, after Holm-Bonferroni correction.

Table 1: Outcome data for training and validation cohorts

For the R code see https://github.com/samleighton87/EDEN_R_Code
During internal cross-validation with all the 163 predictor variables simultaneously, all of our four models had AUCs higher than 0.700, significantly better than chance \(p<0.0001\); figure 3, table 2). The accuracy achieved by the four models was higher than AUC 0.65, and the PSI of the four models was higher than 0.31, indicating a 31% additional gain in prediction certainty. The stability of feature selection in the 14 LOSOCV models was 0.54 for the remission model, 0.67 for the social recovery model, 0.71 for the vocational recovery model, and 0.70 for the QoL model (appendix p 7).

The correlation of the probability outputs of the four models was higher than the correlation of the respective outcomes that they were trained to predict. Each model predicted its outcome best, but they also significantly predicted each of the other three outcomes, with a lower level of performance (appendix pp 6–7).

The top predictors for the four models selected by the elastic net model are provided in figure 1. The four models included predictor variables ranging from demographic...
characteristics, family history, premorbid functioning, baseline education and employment status, social factors, duration of untreated psychosis, and baseline symptoms (appendix pp 2–6). These models had similar performance to the elastic net model built with use of the 163 predictor variables on LOSOCV. The external validation performance of the generalised linear models was significantly better than chance, with AUCs higher than 0·67 for symptom remission and QoL outcomes, and higher than 0·86 for the vocational recovery outcome in the Scottish datasets. The external validation performance of the generalised linear models had AUCs of 0·61 for remission, 0·57 for social recovery, and 0·66 for vocational recovery outcomes in the OPUS dataset. The AUC of the generalised linear model for QoL was not statistically significant (table 2, appendix pp 11–12). We did external validation performance for the two groups of the OPUS trial (appendix pp 9–10). Model performance was better in the standard treatment group for remission and social recovery than for the other outcomes, whereas in the intervention group, performance was better for vocational recovery.

**Discussion**

In this study, we developed outcome prediction models for remission and recovery for people with first-episode psychosis using baseline sociodemographic and clinical variables, and we internally cross-validated the models with a large naturalistic cohort study (EDEN study). We externally validated the prediction models on patients from three studies: two longitudinal cohort studies of patients with first-episode psychosis (Scottish studies) and a randomised control trial of specialised assertive intervention treatment versus standard treatment (OPUS). The predictive performance of the models were in the range of values for established calculators in use for predicting risk of cardiovascular diseases (AUC 0·71–0·76) and cancer (0·57–0·72). The PSIs indicated that our prediction models provided a 31–37% increase in prognostic certainty compared with that of pre-test probabilities at 1 year.

We developed prediction models for multiple outcomes, including remission and recovery (social and vocational recovery and QoL), in recognition of the fact that intervention strategies might be distinct for each outcome, even though each of our models was able to accurately predict other outcomes significantly better than chance, albeit with reduced performance. Our prediction model for social recovery had similar performance (AUC 0·731) to that of Koutsouleris and colleagues' model (balanced accuracy 0·71), though their study was limited by the absence of a true external validation. Our model performance for the remission outcome (AUC 0·703 [95% CI 0·664–0·742]) was better than that of Leighton and colleagues' model (0·635–0·670), whereas their model performance for vocational recovery was better than that of our model. In our study, the stability of feature performance for in-hospital stay, vocational, social, and overall recovery, and quality of life outcomes was validated at 1 year (table 2, appendix pp 11–12).

### Table 2: Performance metrics for internal–external and external validation

<table>
<thead>
<tr>
<th>Outcome</th>
<th>Social recovery</th>
<th>Vocational recovery</th>
<th>Quality of life</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPUS</td>
<td>0·867 ± 0·001</td>
<td>0·660 ± 0·001</td>
<td>0·616 ± 0·001</td>
</tr>
<tr>
<td>OPUS</td>
<td>0·726 ± 0·003</td>
<td>0·618 ± 0·001</td>
<td>0·721 ± 0·001</td>
</tr>
<tr>
<td>OPUS</td>
<td>0·680 ± 0·001</td>
<td>0·617 ± 0·001</td>
<td>0·684 ± 0·001</td>
</tr>
<tr>
<td>OPUS</td>
<td>0·664 ± 0·001</td>
<td>0·616 ± 0·001</td>
<td>0·663 ± 0·001</td>
</tr>
<tr>
<td>OPUS</td>
<td>0·620 ± 0·001</td>
<td>0·616 ± 0·001</td>
<td>0·618 ± 0·001</td>
</tr>
<tr>
<td>OPUS</td>
<td>0·558 ± 0·001</td>
<td>0·616 ± 0·001</td>
<td>0·554 ± 0·001</td>
</tr>
<tr>
<td>OPUS</td>
<td>0·546 ± 0·001</td>
<td>0·616 ± 0·001</td>
<td>0·539 ± 0·001</td>
</tr>
<tr>
<td>OPUS</td>
<td>0·457 ± 0·001</td>
<td>0·616 ± 0·001</td>
<td>0·558 ± 0·001</td>
</tr>
<tr>
<td>OPUS</td>
<td>0·439 ± 0·001</td>
<td>0·616 ± 0·001</td>
<td>0·546 ± 0·001</td>
</tr>
<tr>
<td>OPUS</td>
<td>0·412 ± 0·001</td>
<td>0·616 ± 0·001</td>
<td>0·490 ± 0·001</td>
</tr>
<tr>
<td>OPUS</td>
<td>0·387 ± 0·001</td>
<td>0·616 ± 0·001</td>
<td>0·575 ± 0·001</td>
</tr>
<tr>
<td>OPUS</td>
<td>0·375 ± 0·001</td>
<td>0·616 ± 0·001</td>
<td>0·539 ± 0·001</td>
</tr>
<tr>
<td>OPUS</td>
<td>0·350 ± 0·001</td>
<td>0·616 ± 0·001</td>
<td>0·514 ± 0·001</td>
</tr>
<tr>
<td>OPUS</td>
<td>0·333 ± 0·001</td>
<td>0·616 ± 0·001</td>
<td>0·490 ± 0·001</td>
</tr>
<tr>
<td>OPUS</td>
<td>0·322 ± 0·001</td>
<td>0·616 ± 0·001</td>
<td>0·476 ± 0·001</td>
</tr>
<tr>
<td>OPUS</td>
<td>0·312 ± 0·001</td>
<td>0·616 ± 0·001</td>
<td>0·463 ± 0·001</td>
</tr>
<tr>
<td>OPUS</td>
<td>0·301 ± 0·001</td>
<td>0·616 ± 0·001</td>
<td>0·450 ± 0·001</td>
</tr>
<tr>
<td>OPUS</td>
<td>0·290 ± 0·001</td>
<td>0·616 ± 0·001</td>
<td>0·439 ± 0·001</td>
</tr>
<tr>
<td>OPUS</td>
<td>0·281 ± 0·001</td>
<td>0·616 ± 0·001</td>
<td>0·428 ± 0·001</td>
</tr>
</tbody>
</table>

*Note:* AUC stands for area under the curve. The table shows the performance metrics for external validation (OPUS), internal–external validation (EDEN) and external validation (Scottish).
Articles

within each of the four prediction models.25 indicates an intermediate to good strength of agreement
model, 0·67 for the social recovery model, 0·71 for the selection in the 14 LOSOCV models (0·54 for the remission
indicates an intermediate to good strength of agreement
model, 0·67 for the social recovery model, 0·71 for the multiple outcomes. Each of the individual prediction
models predicted the other three outcomes better than chance, although with reduced performance. An
argument exists for using one prediction model to predict multiple outcomes, although this would come with a
trade-off of marginally reduced performance and needs further testing in prospective clinical trials.

Our study also has several limitations. About 49% of
eligible patients consented to participate in the EDEN
study, which might affect the generalisability of our
prediction models to all patients with first-episode
psychosis. However, participants who did not consent
had characteristics largely similar at baseline to those of
individuals who consented to participate.30 Despite this,
we cannot assume that the models developed with data
from the patients included in the EDEN study would
have a better performance than chance in individuals not
included in the EDEN study sample. The effect of
missing outcomes data on model performance was not
trivial in patients at 1 year for training cohorts (15–39%)
and for validation cohorts (OPUS 4–61%; Scottish studies
19–61%). This effect might introduce bias and affect the
generalisability of our results. Importantly, our models
have not been validated for prediction after baseline as
treatment progresses. Future studies could consider
building models that account for change over time or in
response to treatment (eg, dynamic Bayesian networks
with continuous retraining). We did not collect cognitive
and physical biomarkers of illness, including blood
samples and neuroimaging, which previous studies have
highlighted as potentially important for generating
accurate predictions.31 The duration criteria for recovery
has been proposed to be at least 2 years.33 However, the
criteria used in our analysis for recovery outcomes were
much narrower and, for three of four measures, were
based on point outcomes (GAF; employment, education,
or training status; and QoL) at 1 year. The prevalence of
recovery in our training cohort was similar to that
reported in a large meta-analysis,4 but higher than that
reported in another meta-analysis,5 which might also
affect the generalisability of our model.

The decision making process to determine which
interventions to use and for how long in the treatment of
patients with a first-episode psychosis is based on clinical
intuition. We are not aware of evidence assessing how
accurate clinicians using baseline information are at
predicting 1-year outcomes for psychosis, although it
has been shown that clinicians are poor at predicting
outcomes in depression.4,5 Clinicians working with
patients with first-episode psychosis might benefit from
a reliable and methodologically robust tool to identify
individuals with likelihood of a good or poor outcome
at initial clinical contact, so that the information on

Our analysis has several strengths. The data for the
model development were derived from one of the largest
naturalistic cohort studies in patients with first-episode
psychosis treated in early-intervention services. We used
LOSO CV for model development and internal validation.
We found the stability of the feature selection with
LOSO CV for 14 sites to have intermediate to good level of
agreement. Furthermore, we externally validated the
models in three independent datasets with different time
periods, geographical regions, and recording methods.
We used strict operationalised outcome criteria to define
symptomatic outcomes and developed prediction models
for multiple outcomes. Each of the individual prediction
models predicted the other three outcomes better than
chance, although with reduced performance. An
argument exists for using one prediction model to predict
multiple outcomes, although this would come with a
trade-off of marginally reduced performance and needs
further testing in prospective clinical trials.

Our study also has several limitations. About 49% of
eligible patients consented to participate in the EDEN
study, which might affect the generalisability of our
prediction models to all patients with first-episode
psychosis. However, participants who did not consent
had characteristics largely similar at baseline to those of
individuals who consented to participate.30 Despite this,
we cannot assume that the models developed with data
from the patients included in the EDEN study would
have a better performance than chance in individuals not
included in the EDEN study sample. The effect of
missing outcomes data on model performance was not
trivial in patients at 1 year for training cohorts (15–39%)
and for validation cohorts (OPUS 4–61%; Scottish studies
19–61%). This effect might introduce bias and affect the
generalisability of our results. Importantly, our models
have not been validated for prediction after baseline as
treatment progresses. Future studies could consider
building models that account for change over time or in
response to treatment (eg, dynamic Bayesian networks
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outcome prediction can be used alongside clinical judgment for stratification of treatment.

Patients with good outcomes are likely to need a different set of interventions and duration of treatment compared with patients with poorer outcomes. If outcome prediction models are developed into clinically applicable tools after further rigorous testing of their usefulness in a prospective clinical trial, they could assist in clinical decision making, leading to better use of clinical resources by providing targeted interventions based on individual predictions of patient outcomes. Guidelines could be developed in consultation with stakeholders on how to put such tools into practice to facilitate a stepped model of care. Future work should identify, in a prospective clinical trial, whether one prediction model might accurately predict multiple outcomes and whether it is possible to update the prediction models prospectively over time and in response to different interventions. Whether the addition of other predictors, including biomarkers, will improve prediction accuracy of the models remains to be tested.

In our machine learning analysis of a longitudinal cohort of patients with first-episode psychosis treated in early-intervention services, we were able to show that multiple outcomes can be reliably predicted for patients by use of baseline demographic and clinical variables at 1 year, with external generalisability. Our prediction models have similar discriminatory power to other available predictive models. Our models benefit from being developed with use of a naturalistic cohort study and externally validated in a cohort study and a randomised control trial, together with the use of readily available clinical data and, to our knowledge, the largest sample size used in a machine learning study of first-episode psychosis to date. Furthermore, to our knowledge, our study represents the first published evidence for the use of machine learning models of QoL outcome in patients with a first-episode psychosis.

Contributors
PKM conceptualised the analysis plan. PKM and SPL designed the analysis plan and drafted and revised the paper. SPL did the analysis. RU, MRB, RK, JC, GVG, MS, and PFL contributed to the interpretation of the analysis. RU, MRB, RK, JC, GVG, MS, PFL, SPS, LE, PBJ, DF, VS, NF, AIG, MEB, and RHBC revised the draft. SPS, LE, PBJ, DF, VS, and NF designed the EDEN study. SPS, LE, PBJ, DF, VS, NF, AIG, MEB, and RHBC contributed data. MEB, RHBC, and NF did the validation analysis on OPUS data. MB monitored data collection for the EDEN studies and supervised them. AIG monitored the data collection on OPUS data. MN reviewed the final version of the manuscript.

Declaration of interests
PKM has received honorariums from Sunovion and Sage. RU has received honorariums from Sunovion. JC has received grants from Wellcome Trust and Sackler Trust and honorariums from Johnson & Johnson. SPS and MB are part-funded by the National Institute for Health Research (NIHR) Collaboration for Leadership in Applied Health Research and Care WM (CLAHRC WM). GVG has received support from H2020-EINFRA, the NIHR Birmingham ECRC, NIHR Birmingham SRMRC, the NIHR Birmingham Biomedical Research Centre, and the MRC HDR UK, an initiative funded by UK Research and Innovation, Department of Health and Social Care (England), the devolved administrations, and leading medical research charities. All other authors declare no competing interests.

Data sharing
MB acts as custodian of the EDEN dataset and data sharing and secondary analyses are supported under the auspices of the University of Warwick (Coventry, UK); please contact MB for all requests. AIG acts as custodian of the Scottish datasets and data sharing and secondary analyses are supported under the auspices of the University of Glasgow (Glasgow, UK); please contact AIG for all requests. MN acts as custodian of the OPUS trial dataset and data sharing and secondary analyses are supported under the auspices of the University of Copenhagen (Copenhagen, Denmark); please contact MN for all requests.

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References
10 Birchwood M, Lester H, McCarthy L, et al. The UK national evaluation of the development and impact of Early Intervention Services [the National EDEN studies]: study rationale, design and baseline characteristics. Early Interv Psychiatry 2014; 8: 59–67.


van Nieuwenhuizen Ch, Schene AH, Koeter MWJ, Huxley PJ. The Lancashire Quality of Life Profile: modification and psychometric validation. Soc Psychiatry Psychiatr Epidemiol 2001; 36: 36–44.


