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BRIEF COMMUNICATION

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# Use of a Bluetooth tablet-based technology to improve outcomes in lung transplantation: A pilot study

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The impact of remote patient monitoring platforms to support the postoperative care of solid organ transplant recipients is evolving. In an observational pilot study, 28 lung transplant recipients were enrolled in a novel postdischarge home monitoring program and compared to 28 matched controls during a 2-year period. Primary endpoints included hospital readmissions and total days readmitted. Secondary endpoints were survival and inflation-adjusted hospital readmission charges. In univariate analyses, monitoring was associated with reduced readmissions (incidence rate ratio [IRR]: 0.56; 95% confidence interval [CI]: 0.41-0.76; $P < .001$), days readmitted (IRR: 0.46; 95% CI: 0.42-0.51; $P < .001$), and hospital charges (IRR: 0.52; 95% CI: 0.51-0.54; $P < .001$). Multivariate analyses also showed that remote monitoring was associated with lower incidence of readmission (IRR: 0.38; 95% CI: 0.23-0.63; $P < .001$), days readmitted (IRR: 0.14; 95% CI: 0.05-0.37; $P < .001$), and readmission charges (IRR: 0.11; 95% CI: 0.03-0.46; $P = .002$). There were 2 deaths among monitored patients compared to 6 for controls; however, this difference was not significant. This pilot study in lung transplant recipients suggests that supplementing postdischarge care with remote monitoring may be useful in preventing readmissions, reducing subsequent inpatient days, and controlling hospital charges. A multicenter, randomized control trial should be conducted to validate these findings.

**KEYWORDS**

business/management, clinical research/practice, economics, health services and outcomes research, hospital readmission, lung transplantation/pulmonology, monitoring: physiologic, organ transplantation in general, outpatient care, quality of care/care delivery

## 1 | INTRODUCTION

Lung transplantation is now a prevalent treatment option for patients with end-stage lung disease, contributing to longer life expectancy and improved quality of life.[1] Despite clinical advances in the field, lung transplant recipients (LTRs) frequently experience postoperative complications that result in unplanned hospital readmissions and other adverse outcomes.[2] Decreased adherence with

**Abbreviations:** CI, confidence interval; CMS, Centers for Medicare & Medicaid Services; CPT, Current Procedural Terminology; ICU, intensive care unit; IRR, incidence rate ratio; LTRs, lung transplant recipients; SHR, subdistribution hazard ratio.

care has been identified as a key driver of poor outcomes, generating the need for more adherence-enhancing interventions designed specifically for LTRs.[3,4] Daily home spirometry initiatives have made some progress towards the achievement of this goal. They have been shown to improve patient satisfaction, compliance with care, and the detection of bronchiolitis obliterans syndrome.[5-7]

In the past few years, remote monitoring applications that measure patient pulmonary function and other clinical parameters have emerged as potentially useful tools for improving LTR compliance with care and reducing posttransplant complications. A 2015 randomized control trial found that 1 such application improved medication adherence and patient compliance with reporting abnormal indicators, but observed no benefits related to rehospitalizations or mortality after 1 year of follow-up.[8] In 2017, we implemented our own remote patient monitoring initiative to evaluate the potential effects on hospital readmissions, readmission days, mortality, and charges. Unlike other monitoring platforms, the system we deployed (ActiCare Health, Livermore, CA) leveraged Bluetooth technology to transmit patient vital sign measurements and respiratory parameters to transplant coordinators in real time, along with symptoms and activity levels. The platform also allowed for face-to-face communication between patients and providers, included a comprehensive educational library complete with customized video content, tutorials, and self-assessments, and relied on humorous memes, inspirational messages, and incentive badges to encourage patient compliance with daily reporting. Weekly compliance reports were provided to the transplant center as well to maintain patients' long-term engagement with monitoring.

## 2 | METHODS

### 2.1 | Study design

We performed an observational pilot study of 28 contemporary LTRs who were enrolled in a home monitoring program after discharge and compared outcomes for these patients to those for 28 matched controls during a 2-year period. This study was approved by the University of Southern California Health Sciences Campus Institutional Review Board (protocol number HS-18-00097).

### 2.2 | Cohort selection

Twenty-eight sequential patients who were transplanted on or after January 1, 2016, discharged from the hospital after surgery, and who consented to sharing their health information with a third-party provider were enrolled in monitoring. Two additional patients received transplants during this time period but did not consent to sharing their health information and were thus excluded from the analysis. We then selected controls from a list of de-identified patients, matched by transplant type (single vs double) and to the extent possible underlying diagnosis, who received lung transplants between 2013 and 2015 and were discharged from the hospital after surgery. All patients in both cohorts were cared for by the same team of surgeons, physicians, and transplant coordinators. No patients in either cohort were retransplants.

With the exception of remote monitoring, all patients received the same level of care posttransplant, including twice-weekly visits during the first month, weekly visits during the second month, biweekly visits during the third month, and monthly visits for the remainder of the first year. After reaching the 1-year mark, patients were seen in the clinic on a quarterly basis. Bronchoscopies with bronchoalveolar lavage were performed in all patients prior to discharge for the transplant event, then again at 6 weeks, 3 months, 6 months, and 1 year posttransplant. Routine surveillance biopsies were conducted at the same intervals for all patients, and additional biopsies were performed 6 weeks after any treated rejection episode.

### 2.3 | Home monitoring

Prior to discharge, consent was obtained from patients to participate in the home monitoring program. Bluetooth-enabled devices measuring blood pressure, heart rate, weight, blood glucose, oxygen saturation, pulmonary function, and activity levels were delivered directly to patients' homes. Patients were also given Microsoft Surface (Microsoft Inc, Redmond, WA) tablets to report signs and symptoms, track appointments and medication compliance, and access educational videos and other materials. Several members of the transplant coordination team filmed a virtual tour of the clinic and recorded educational videos on such topics as medication management, nutrition, physical therapy, lifestyle changes, coping mechanisms, and caregiver issues.

Patients were trained to use each monitoring device, including the in-home spirometer, during a 1-hour, face-to-face session conducted via the tablet's live video application. They were then instructed to utilize the platform daily to measure vital signs and report symptoms via electronic questionnaire. Patients who exhibited high compliance received incentive badges and humorous memes via the tablet; meanwhile, patients who monitored less frequently received encouraging messages. After 3 months, patients were asked to report 3 times a week, although many preferred to continue with daily reporting.

### 2.4 | Data collection

Demographic data, including age, sex, race, insurance status, education level, diagnosis, smoking history, baseline forced expiratory volume in 1 second (FEV1), lung allocation score, and Stanford Integrated Psychosocial Assessment for Transplant score, were recorded in each patient's pretransplant medical record. Data related to the patient's transplant event (single vs double organ, total ischemic times, total hospital length of stay, ICU days, ventilator days, primary graft dysfunction grades), donor characteristics (age, sex, cause of death, terminal $Po_2$), hospital readmissions, readmitted inpatient days, outpatient visits,

pulmonary function, and mortality were collected through a review of all relevant medical records conducted by an independent, blind research coordinator.[9] Charge data collected were for readmissions only and were extracted from the hospital's billing system. Primary outcomes of interest included hospital readmissions and days readmitted during the first 2 years after transplant. Secondary outcomes included mortality and inflation-adjusted hospital readmission charges.

### 2.5 | Statistical analysis

Descriptive statistics for cohort characteristics were evaluated using Fisher's exact tests for categorical variables and Student *t* tests for continuous variables. Distributions for readmissions, days readmitted, and charges (discounted at a rate of 3.5% to adjust for inflation) were predominantly right-skewed (Appendix S1). Two of 178 readmission events (1.1%) were identified as extreme outliers with respect to days readmitted and charges, so their values were truncated to the mean plus 2.5 times the standard deviation of the relevant variables. Univariate Poisson regressions were performed to compute incidence rate ratios (IRR) for hospital readmissions, days readmitted, and readmission charges. Multivariate Poisson and negative binomial regression models were then compared for goodness of fit. A negative binomial regression model was selected to assess the impact of monitoring on readmission outcomes after controlling for key covariates. Hospital readmissions were subdivided into categories for monitored patients and controls; incidence rates were calculated for both groups by category and compared using 2-sided binomial probability tests. Fine-Gray cumulative incidence curves were constructed to illustrate the timing of hospital readmissions during follow-up, while adjusting for the competing risk of death. The Fine-Gray subdistribution hazard ratio (SHR) and its corresponding test statistic were used to evaluate differences in the cumulative incidence functions. Kaplan-Meier curves were utilized to detect differences in survival between monitored patients and controls. Curves were compared using log rank tests. *P* values < .05 were considered statistically significant. All statistical analyses were performed using Stata, version 15.0 (StataCorp, College Station, TX).

## 3 | RESULTS

### 3.1 | Patient characteristics

The group participating in home monitoring was similar to the control group with respect to the distribution of all observed demographic variables (Table 1). There were also no significant differences between the groups in terms of diagnoses, donor, and other pretransplant clinical characteristics. For the transplant event, no statistically significant differences in means for time spent in the hospital, ICU, and on the ventilator were observed. Mean follow-up time for monitored patients was 1.87 years compared to 1.77 years for controls (*P* = .384). All patients enrolled in monitoring complied with the program, reporting data at least weekly during follow-up, and 53.5% of monitored patients reported data 3 times per week or more.

### 3.2 | Hospital readmissions

Compared to controls, patients enrolled in monitoring experienced lower incidence of readmission (IRR: 0.56; 95% CI: 0.41-0.76; *P* < .001) during follow-up (Table 2). In multivariate analysis, the association between monitoring and lower readmission incidence (IRR: 0.38; 95% CI: 0.23-0.63; *P* < .001) remained statistically significant (Table 3). Race was also a statistically significant predictor of readmission in multivariate analysis, with black patients experiencing higher readmission incidence (IRR: 3.90; 95% CI: 1.56-9.75; *P* = .004).

In total, there were 66 readmissions for monitored patients during follow-up versus 112 for controls (Table 4). Monitored patients had lower incidence of readmission for infection (IRR: 0.37; 95% CI: 0.19-0.68; *P* < .001) and nonrejection/noninfection causes (IRR: 0.24; 95% CI: 0.04-0.88; *P* = .017): residual pulmonary hypertension, metabolic abnormalities, failure to thrive/deconditioning, shortness of breath, renal failure, hemoptysis, and arrhythmia. Monitored patients also had lower incidence of readmission for rejection (IRR: 0.71; 95% CI: 0.45-1.10; *P* = .109) and for dual rejection-infection (IRR: 0.32; 95% CI: 0.01-3.95; *P* = .351), but these results were not statistically significant. Figure 1 demonstrates the difference between the groups with respect to cumulative incidence of readmission during follow-up (SHR: 0.55; 95% CI: 0.37-0.81; *P* = .002) after adjusting for the competing risk of death.

### 3.3 | Days readmitted

Univariate analysis showed that monitored patients spent fewer days readmitted to the hospital (IRR: 0.46; 95% CI: 0.42-0.51; *P* < .001) than controls during follow-up (Table 2). In multivariate analysis (Table 3), monitoring remained associated with fewer readmission days (IRR: 0.14; 95% CI: 0.05-0.37; *P* < .001). Race, sex, donor cause of death, and time on the ventilator after transplant were also statistically significant predictors of readmission time. Female sex (IRR: 0.36; 95% CI: 0.14-0.92; *P* = .033) and 1 additional day spent on the ventilator after transplant (IRR: 0.84; 95% CI: 0.73-0.96; *P* = .011) were associated with fewer days readmitted to the hospital during follow-up, while being black (IRR: 5.55; 95% CI: 1.15-26.58; *P* = .032) and receiving an organ from a donor who experienced a fatal cerebrovascular event (IRR: 4.87; 95% CI: 1.15-20.58; *P* = .031) were associated with longer readmission stays.

### 3.4 | Survival

During the follow-up period, there were 2 deaths among home monitoring patients, compared to 6 for controls. Causes of death

**TABLE 1** Cohort characteristics

| Variable | Monitored (N = 28) | Control (N = 28) | *P* value |
|---|---|---|---|
| Patient demographics | | | |
| Mean age at Tx, y (SD) | 54.4 (12.7) | 55.2 (11.9) | .796 |
| No./% female | 10 (35.7%) | 13 (46.4%) | .587 |
| Race | | | .506 |
| White | 17 (60.7%) | 21 (75.0%) | |
| Black | 4 (14.3%) | 1 (3.6%) | |
| Nonwhite Hispanic | 5 (17.9%) | 4 (14.3%) | |
| Other | 0 (0.0%) | 1 (3.6%) | |
| Asian | 2 (7.1%) | 1 (3.6%) | |
| Insurance | | | .606 |
| Commercial | 7 (25.0%) | 10 (35.7%) | |
| Medicare | 5 (17.9%) | 6 (21.4%) | |
| Medi-Cal | 16 (57.1%) | 12 (42.9%) | |
| Education | | | .251 |
| Less than high school | 4 (14.3%) | 9 (32.1%) | |
| High school graduate | 11 (39.3%) | 5 (17.9%) | |
| Some university | 8 (28.6%) | 10 (35.7%) | |
| University graduate | 3 (10.7%) | 1 (3.6%) | |
| Advanced degree | 2 (7.1%) | 3 (10.7%) | |
| Smoking status | | | .423 |
| Former smoker | 12 (42.9%) | 16 (57.1%) | |
| Never smoker | 16 (57.1%) | 12 (42.9%) | |
| Diagnosis | | | .878 |
| Cystic fibrosis | 4 (14.3%) | 2 (7.1%) | |
| Obstructive lung disease | 12 (42.9%) | 12 (42.9%) | |
| Pulmonary vascular disease | 2 (7.1%) | 2 (7.1%) | |
| Restrictive lung disease | 10 (35.7%) | 12 (42.8%) | |
| No./% double lung transplant | 7 (25.0%) | 7 (25.0%) | 1.000 |
| Mean baseline FEV1 (SD) | 2.01 (0.66) | 1.95 (0.83) | .760 |
| Mean LAS (SD) | 50.4 (20.1) | 49.0 (18.0) | .783 |
| Mean SIPAT (SD) | 9.07 (5.7) | 10.2 (8.9) | .602 |
| Donor characteristics | | | |
| No./% donor age > 50 y | 5 (17.9%) | 7 (25.0%) | .746 |
| No./% donor female | 14 (50.0%) | 12 (42.9%) | .789 |
| Donor causes of death | | | .156 |
| No./% anoxia | 1 (3.6%) | 6 (21.4%) | |
| No./% cerebrovascular/ stroke | 14 (50.0%) | 11 (39.3%) | |
| No./% head trauma | 13 (46.4%) | 11 (39.3%) | |
| Donor mean terminal $Po_2$ (SD) | 488 (67.6) | 474.5 (59.9) | .433 |
| Transplant event characteristics | | | |
| Mean left total ischemic time, (SD) | 262.1 (74.4) | 249.6 (95.1) | .638 |
| Mean right total ischemic time, (SD) | 326.3 (101.9) | 296.2 (94.1) | .437 |
| Mean Tx event inpatient days | 18.7 (12.3) | 19.7 (14.1) | .778 |
| Mean ICU days after Tx event | 6.4 (5.8) | 9.1 (10.9) | .254 |
| Mean days on ventilator after Tx event | 3.8 (5.2) | 3.1 (2.1) | .523 |
| No./% PGD grade 3 within 72 h of Tx | 4 (14.3%) | 4 (14.3%) | 1.000 |
| Outpatient characteristics | | | |
| Mean outpatient visits in 2 y (SD) | 24.0 (4.8) | 24.7 (8.3) | .723 |
| Mean FEV1 (SD) | | | |
| 6 mo after Tx | 1.98 (0.7) | 1.82 (0.9) | .451 |
| 1 y after Tx | 1.99 (0.6) | 1.72 (0.9) | .226 |
| 2 y after Tx | 1.91 (0.7) | 1.69 (1.0) | .427 |
| Mean FVC (SD) | | | |
| 6 mo after Tx | 2.61 (0.7) | 2.50 (1.3) | .717 |
| 1 y after Tx | 2.66 (0.7) | 2.28 (1.1) | 0.134 |
| 2 y after Tx | 2.66 (0.9) | 2.14 (1.0) | 0.094 |
| Mortality and causes of death | | | |
| Mortality at 2 y | 2 (7.1%) | 6 (21.4%) | .252 |
| Acute pancreatitis and GI bleed | 0 | 1 | |
| Metastatic adenocarcinoma | 1 | 0 | |
| Cardiac arrest | 0 | 1 | |
| Cerebrovascular event | 0 | 1 | |
| CMV and bacterial pneumonia | 1 | 0 | |
| Colitis and sepsis | 0 | 1 | |
| Suicide | 0 | 1 | |
| Unknown | 0 | 1 | |

Abbreviations: FEV1, forced expiratory volume in 1 second; FVC, forced vital capacity; GI, gastrointestinal; ICU, intensive care unit; LAS, lung allocation score; PGD, primary graft dysfunction; SD, standard deviation; SIPAT, Stanford Integrated Psychosocial Assessment for Transplant; Tx, transplant.

are listed in Table 1. Differences in survival (Figure 2) between the groups were not statistically significant ($P = .14$).

## 3.5 | Hospital readmission charges

In univariate analysis, monitored patients incurred fewer hospital readmission charges (IRR: 0.52; 95% CI: 0.51-0.54; $P < .001$) than controls during follow-up (Table 2). In multivariate analysis (Table 3), remote monitoring (IRR: 0.11; 95% CI: 0.03-0.46; $P = .002$) continued to be associated with reduced readmission charges. An additional

day spent on the ventilator after transplant (IRR: 0.83; 95% CI: 0.71-0.98; $P = .023$) was also a statistically significant predictor of reduced readmission charges during follow-up.

### 3.6 | Outpatient visits and pulmonary function

There were no statistically significant differences between the groups with respect to outpatient visits during follow-up (Table 1). FEV1 and forced vital capacity measurements (Table 1) were higher for monitored patients at 6 months, 1 year, and 2 years after transplant, but these differences were not statistically significant.

## 4 | DISCUSSION

The results of this pilot study suggest that supplementing the postdischarge care of LTRs with remote monitoring may be useful in preventing readmissions, reducing total readmission days, and controlling hospital readmission charges. Presumably monitoring helps to achieve these outcomes by allowing care providers to react to data sooner and take intervening steps before a patient's condition worsens. The monitoring platform was designed to trigger alerts in accordance with parameters for blood pressure, glucose, spirometry, oxygen saturation, and symptoms set by the transplant program prior to implementation. There are 2 types of alerts: email notifications for noncritical, but slightly out-of-range values and phone alerts for critical values. During work hours, coordinators respond to email notifications by contacting patients to review their self-reported symptoms and Bluetooth-transmitted vital signs. When a critical value occurs, a representative from the monitoring service contacts the patient to confirm the result or repeat the measurement and then makes a follow-up phone call to the patient's coordinator after the result is verified. If critical values occur after hours, phone calls are placed to the coordinator on-call. In the case of all phone alerts, coordinators contact patients to deliver specific clinical guidance. For example, in response to declining home spirometry measurements, coordinators will ask patients to come to the hospital for confirmatory spirometry. Appendix S2 contains a summary of all alert parameters and their corresponding notifications.

During the course of this study, we observed several instances where the ability to react to data in real time helped to prevent hospitalizations or even fatal events. Our follow-up protocols related to diminishing pulmonary function resulted in several unscheduled bronchoscopies with biopsies where rejection was confirmed. A patient who reported severe abdominal pain via the in-home tablet was brought to our emergency department and was diagnosed with a small-bowel obstruction requiring emergency surgery. The platform identified bradycardia in a patient on amiodarone therapy and hospitalization was avoided by modifying treatment. In another case, the platform helped identify a patient with severe hypertension, and therapy was adjusted on an outpatient basis.

The Fine-Gray cumulative incidence functions for hospital readmissions provide support for this hypothesis. The curves showed little difference between the groups for the first 30 days of observation, but subsequently diverged for the remainder of follow-up, with incidence of readmission increasing at a faster rate for controls than monitored patients. Typically, patients do not receive monitoring equipment until 2 weeks after discharge. It then takes another 2 weeks for them to complete training and become comfortable measuring their vital signs independently, which likely accounts for the observed delay in the benefit associated with monitoring. Once comfortable, however, the majority of patients test multiple times a week, if not daily. Because monitored patients are rewarded for measuring their vital signs and encouraged to test if they have not submitted results for more than 2 days, the act of reporting becomes an integral part of their daily routines. Monitored patients see that their care providers respond with near immediacy when they report problematic symptoms or out-of-range parameters, which in turn makes these patients more compliant with reporting as well as the instructions of their care providers. We suspect this feedback loop predicated on compliant reporting, earlier detection on the part of the transplant team, and adherence to care instructions most likely explains why monitored patients experienced fewer readmissions than controls during the follow-up period (Figure 3).

We also postulate that this dynamic accounts for why monitored patients had shorter readmission stays compared to controls. With more data available to them, care providers can identify and respond to problematic trends when they are less severe, which, in cases where hospitalization cannot be avoided, theoretically results in shorter stays.

**TABLE 2** Univariate analysis of remote monitoring and hospital readmissions, readmitted days, and charges

| | Remote monitoring | | Control | | | | |
|---|---|---|---|---|---|---|---|
| **Outcomes of interest** | **Events** | **EPPY** | **Events** | **EPPY** | **IRR** | **95% CI** | ***P*-value** |
| Hospital readmissions | 66 | 1.27 | 112 | 2.26 | 0.56 | 0.41-0.76 | <.001* |
| Readmitted days | 543 | 10.41 | 1116 | 22.50 | 0.46 | 0.42-0.51 | <.001* |
| Readmission charges (in thousands) | 7562 | 145.04 | 13748 | 277.14 | 0.52 | 0.51-0.54 | <.001* |

Abbreviations: CI, confidence interval; EPPY, events per person per year; IRR, incidence rate ratio.

*Denotes statistical significance for *P* values < .05.

**TABLE 3** Multivariate regression model of variables associated with primary and secondary readmission endpoints

| | Readmissions | | | Inpatient days | | | Hospital charges | | |
|---|---|---|---|---|---|---|---|---|---|
| **Variable** | **IRR** | **95% CI** | ***P* value** | **IRR** | **95% CI** | ***P* value** | **IRR** | **95% CI** | ***P* value** |
| Remote monitoring | 0.38 | 0.23-0.63 | <.001* | 0.14 | 0.05-0.37 | <.001* | 0.11 | 0.03-0.46 | .002* |
| Age at Tx | 1.00 | 0.97-1.04 | .795 | 1.02 | 0.96-1.08 | .532 | 1.01 | 0.93-1.11 | .750 |
| Sex: female | 0.72 | 0.42-1.22 | .217 | 0.36 | 0.14-0.92 | .033* | 0.29 | 0.08-1.04 | .060 |
| Race | | | | | | | | | |
| White | Ref | Ref | Ref | Ref | Ref | Ref | Ref | Ref | Ref |
| Black | 3.90 | 1.56-9.75 | .004* | 5.55 | 1.15-26.58 | .032* | 7.14 | 0.83-61.27 | .073 |
| Nonwhite Hispanic | 0.52 | 0.24-1.11 | .092 | 0.36 | 0.10-1.32 | .124 | 0.59 | 0.09-3.64 | .568 |
| Other | 0.42 | 0.09-2.00 | .277 | 0.09 | 0.01-1.10 | .060 | 0.11 | 0.01-2.77 | .182 |
| Asian | 2.83 | 0.73-10.99 | .133 | 6.68 | 0.63-71.09 | .115 | 16.59 | 0.37-744.99 | .148 |
| Insurance | | | | | | | | | |
| Commercial | Ref | Ref | Ref | Ref | Ref | Ref | Ref | Ref | Ref |
| Medicare | 0.65 | 0.33-1.27 | .205 | 0.51 | 0.17-1.55 | .235 | 0.62 | 0.15-2.54 | .504 |
| Medi-Cal | 0.88 | 0.48-1.59 | .665 | 1.09 | 0.36-3.30 | .880 | 1.28 | 0.29-5.86 | .747 |
| High School or less | 1.10 | 0.64-1.87 | .732 | 1.90 | 0.79-4.61 | .154 | 2.24 | 0.61-8.23 | .226 |
| Never smoker | 1.38 | 0.81-2.36 | .238 | 2.44 | 0.93-6.41 | .069 | 2.65 | 0.74-9.48 | .135 |
| Diagnosis | | | | | | | | | |
| Cystic fibrosis | Ref | Ref | Ref | Ref | Ref | Ref | Ref | Ref | Ref |
| Obstructive lung disease | 0.96 | 0.27-3.37 | .948 | 0.74 | 0.07-8.26 | .810 | 1.23 | 0.05-33.09 | .903 |
| Pulmonary vascular disease | 0.31 | 0.06-1.60 | .161 | 0.45 | 0.02-9.09 | .606 | 0.77 | 0.02-38.31 | .894 |
| Restrictive lung disease | 1.31 | 0.36-4.84 | .683 | 0.86 | 0.08-9.52 | .901 | 1.77 | 0.06-47.96 | .734 |
| Donor age | 0.99 | 0.96-1.01 | .351 | 0.96 | 0.92-1.01 | .103 | 0.94 | 0.88-1.01 | .093 |
| Donor sex: female | 0.65 | 0.35-1.22 | .180 | 0.40 | 0.14-1.10 | .076 | 0.34 | 0.09-1.31 | .118 |
| Donor causes of death | | | | | | | | | |
| Anoxia | Ref | Ref | Ref | Ref | Ref | Ref | Ref | Ref | Ref |
| Cerebrovascular/stroke | 1.90 | 0.90-4.01 | .093 | 4.87 | 1.15-20.58 | .031* | 7.71 | 1.00-59.68 | .050 |
| Head trauma | 0.62 | 0.30-1.27 | .192 | 0.63 | 0.19-2.14 | .462 | 0.52 | 0.11-2.52 | .413 |
| Terminal $Po_2$ | 1.00 | 0.99-1.01 | .278 | 1.00 | 0.99-1.01 | .724 | 0.99 | 0.98-1.01 | .835 |
| LAS | 1.01 | 0.99-1.03 | .060 | 1.02 | 0.99-1.05 | .124 | 1.02 | 0.98-1.07 | .258 |
| Inpatient days after Tx event | 0.99 | 0.96-1.03 | .694 | 1.02 | 0.96-1.08 | .467 | 1.03 | 0.95-1.11 | .465 |
| ICU days after Tx event | 1.02 | 0.98-1.07 | .306 | 1.01 | 0.92-1.12 | .802 | 1.02 | 0.88-1.16 | .818 |
| Days on vent after Tx event | 0.92 | 0.82-1.02 | .116 | 0.84 | 0.73-0.96 | .011* | 0.83 | 0.71-0.98 | .023* |

Abbreviations: CI, confidence interval; ICU, intensive care unit; IRR, incidence rate ratio; LAS, lung allocation score; Tx, transplant; vent, ventilator.
*Denotes statistical significance for *P* values < .05.

Since charges reflect patients' time spent in-hospital, these too are lower for monitored patients. Some of the differences in outcomes we observed with respect to sex and race may be explained by differential compliance as well. Women were more likely than men to monitor daily and spent fewer days readmitted to the hospital, while black patients were less compliant with frequent monitoring (50%), were more likely to be readmitted, and experienced longer readmissions.

With regard to mortality, 7 meta-analyses of remote monitoring interventions conducted between 2007 and 2013 reported statistically significant risk reductions ranging from 17% to 51%.[10-16] A 2016 randomized control trial assessing the impact of a telehealth intervention on lung transplant recipients also found, after 5.7 years of follow-up, that self-monitoring reduced the risk of mortality by 55%.[17] Though no such association between monitoring and survival was observed in our study, it still may be possible that remote monitoring offers patients a mortality benefit for the reasons discussed previously, as well as longer-term adherence to prescribed medications and recommended lifestyle changes. We did, for example, observe that during 2 years of follow-up, 2 deaths occurred among monitored patients, compared to 6 for controls, but the size of our sample was likely insufficient to detect a statistically significant difference between the groups.

**TABLE 4** Causes of readmissions and incidence rate comparisons

| | Remote monitoring | | Control | | | | |
|---|---|---|---|---|---|---|---|
| **Readmission reason** | **Events** | **EPPY** | **Events** | **EPPY** | **IRR** | **95% CI** | ***P* value** |
| Infection | 16 | 0.31 | 41 | 0.83 | 0.37 | 0.19–0.68 | <.001* |
| Rejection | 38 | 0.73 | 51 | 1.03 | 0.71 | 0.45–1.10 | .109 |
| Rejection and infection | 1 | 0.02 | 3 | 0.06 | 0.32 | 0.01–3.95 | .351 |
| Nonrejection/nonrejection Tx-related | 3 | 0.06 | 12 | 0.24 | 0.24 | 0.04–0.88 | .017* |
| Other non-Tx–related | 8 | 0.15 | 5 | 0.10 | 1.52 | 0.44–5.91 | .477 |

Abbreviations: CI, confidence interval; EPPY, events per person per year; IRR, incidence rate ratio; Tx, transplant.

*Denotes statistical significance for *P* values < .05.

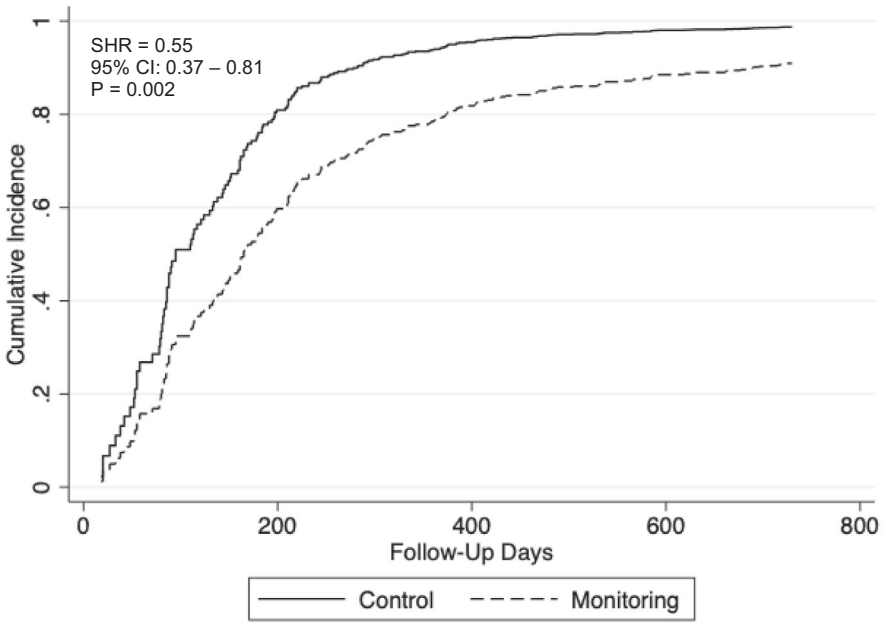


**FIGURE 1** Cumulative incidence of readmission estimated by the Fine-Gray Model with death as the competing risk. CI, confidence interval; SHR, subdistribution hazard ratio

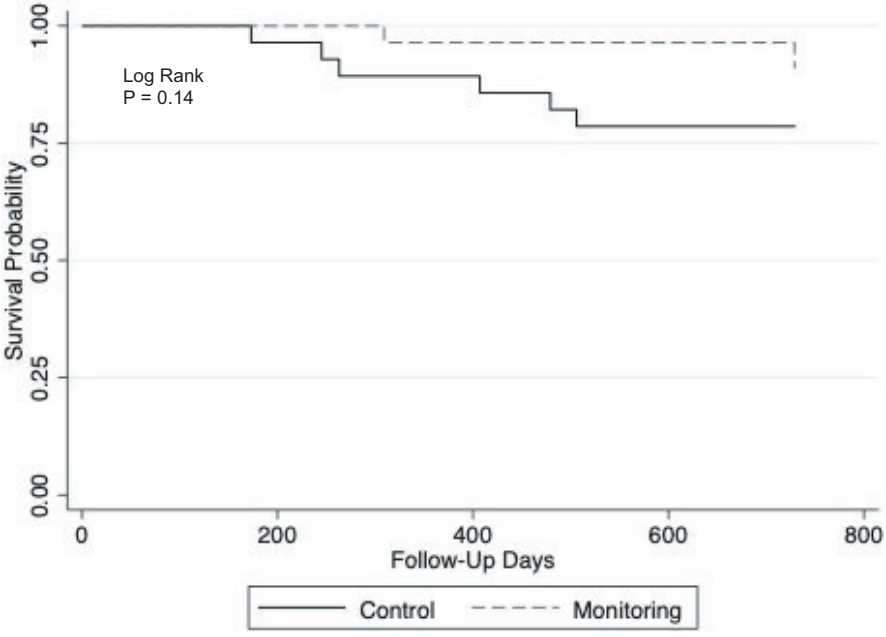


**FIGURE 2** Kaplan-Meier curves comparing survival probabilities for remote monitoring and controls

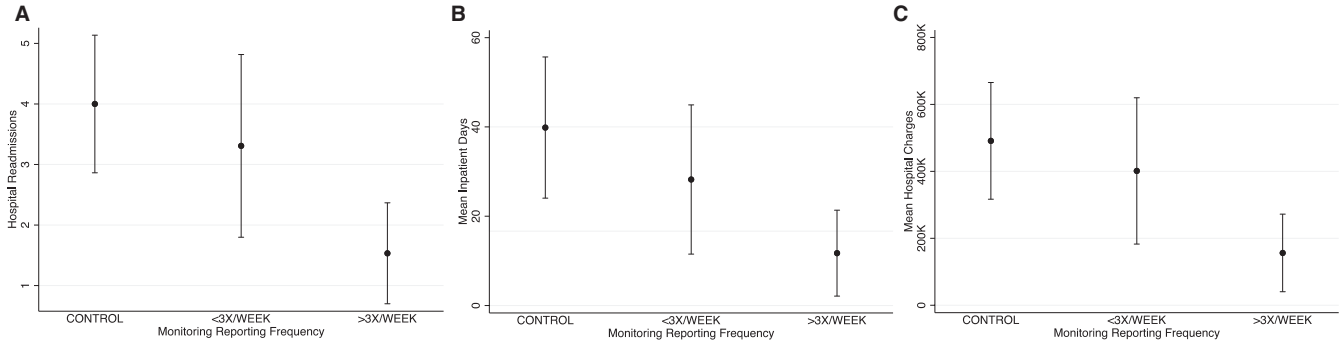


**FIGURE 3** Posttransplant readmission (A), inpatient days (B), and hospital charge (C) means and 95% CI plots by monitoring frequency

Limited reimbursement presents an obstacle to the widespread adoption of remote patient monitoring and very likely contributes to the fact that few studies have been conducted to evaluate its impact on clinical outcomes for transplant recipients. In 2017, the Centers for Medicare & Medicaid Services (CMS) introduced new provisions to expand payment for telehealth services, including the review of remotely generated patient data (with an associated Current Procedural Terminology, CPT, code 99091), remote monitoring of physiologic parameters (CPT codes 99453, 99454, and 99455), and care planning for patients with chronic diseases (with an associated Healthcare Common Procedure Coding System, code G0506). This was an important step forward, especially when one considers the fact that, as recently as 2016, Medicare offered no reimbursement for remote patient monitoring and merely covered telehealth services that were a proxy for in-person consultations. With that said, current policies are not sufficient to promote broad access to remote monitoring services. Reimbursement for data review and remote monitoring of physiologic parameters is only permitted once per patient per month, while payments for chronic care telehealth visits still depend on patients receiving service at originating sites or residing in designated rural areas.[18]

Health economists have argued that federal legislation should focus on expanding telehealth programs broadly, rather than establishing reimbursement in individual cases (eg, live video vs "store and forward" in which information is sent and stored at an intermediate station and sent to a final destination in the future) because doing so could reduce disparities both in terms of access to and quality of care. While policy initiatives are still ongoing, hospitals have started to recognize the benefits of telehealth. Today, 4 of every 10 hospitals in the United States are making some sort of investment in telehealth and remote monitoring programs.[19] Pay-for-performance initiatives, in particular, have led health systems to employ remote monitoring technologies to prevent unplanned events and early readmissions among patients with chronic diseases such as congestive heart failure and diabetes.[20] Transplant centers in the United States have been slower to adopt these technologies, but, as pressure to control costs in the first year after transplant grows, there may be greater incentive to do so.[21] As our data show, remote patient monitoring could help to reduce posttransplant readmissions, and concerns regarding the expense associated with implementing the technology need to be considered in the context of the potential cost savings associated with these outcomes.

There may be staff efficiencies to be gained from implementing remote monitoring for newly transplanted patients as well. Currently, transplant coordinators allocate large portions of time to the review and collection of patient data required for both routine clinical care as well as regulatory (United Network for Organ Sharing and CMS) audit purposes, calling patients to assess their status, answering questions, and providing education posttransplant. Remote monitoring has the potential to streamline communication between patients and their care teams. Appointment and medication reminders can be delivered via in-home mobile devices, rather than phone calls. Additionally, patient education can be administered through live video-conference applications, enabling critical information to be imparted to patients sooner and on an as-needed basis—not just when the opportunity presents itself during an in-person visit. While we observed some of these benefits during the course of this analysis, the scope of our investigation did not include evaluating the impact of monitoring on staff efficiency. Future studies that explore this topic are needed.

Although the results of this analysis are promising, there are several inherent study limitations. First and most importantly, the study is limited by its small sample, comprising patients from a single center. We attempted to control for all variables that might confound the relationship between remote monitoring and our outcomes of interest, but we cannot rule out the effect of unobserved confounders on our results. With that said, when we controlled for all known confounders, we observed even stronger associations between monitoring and our primary outcomes of interest. While we took great care to maintain blindness in selecting our control group, the nature of this study does not eliminate the possibility that a biased design affected our findings. Despite these concerns, this pilot study suggests that remote monitoring could help to promote patient engagement and compliance with care, allow for earlier identification of potential issues, and decrease readmissions and hospital stays, while simultaneously fostering greater patient empowerment and accountability. Ultimately, a multicenter, randomized control trial should be conducted to validate these findings.

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## DISCLOSURE

The authors of this manuscript have conflicts of interest to disclose as described by the *American Journal of Transplantation*. CCM is an employee of ActiCare Health and provided statistical support. The other authors have no conflicts of interest to disclose.

## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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## SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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