


ORIGINAL RESEARCH

Leveraging the Electronic Health Records for Population Health: A Case Study of Patients With Markedly Elevated Blood Pressure

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BACKGROUND: The digital transformation of medical data provides opportunities to perform digital population health surveillance and identify people inadequately managed in usual care. We leveraged the electronic health records of a large health system to identify patients with markedly elevated blood pressure and characterize their follow-up care pattern.

METHODS AND RESULTS: We included 373 861 patients aged 18 to 85 years, who had at least 1 outpatient encounter in the Yale New Haven Health System between January 2013 and December 2017. We described the prevalence and follow-up pattern of patients with at least 1 systolic blood pressure (SBP) ≥ 160 mm Hg or diastolic blood pressure (DBP) ≥ 100 mm Hg and patients with at least 1 SBP ≥ 180 mm Hg or DBP ≥ 120 mm Hg. Of 373 861 patients included, 56 909 (15.2%) had at least 1 SBP ≥ 160 mm Hg or DBP ≥ 100 mm Hg, and 10 476 (2.8%) had at least 1 SBP ≥ 180 mm Hg or DBP ≥ 120 mm Hg. Among patients with SBP ≥ 160 mm Hg or DBP ≥ 100 mm Hg, only 28.3% had a follow visit within 1 month (time window of follow-up recommended by the guideline) and 19.9% subsequently achieved control targets (SBP < 130 mm Hg and DBP < 80 mm Hg) within 6 months. Follow-up rate at 1 month and control rate at 6 months for patients with SBP ≥ 180 mm Hg or DBP ≥ 120 mm Hg was 31.9% and 17.2%.

CONCLUSIONS: Digital population health surveillance with an electronic health record identified a large number of patients with markedly elevated blood pressure and inadequate follow-up. Many of these patients subsequently failed to achieve control targets.

Key Words: electronic health records ■ high blood pressure ■ hypertension ■ quality of care ■ risk factor ■ surveillance

High blood pressure is one of the most potent and actionable risk factors contributing to cardiovascular disease morbidity and mortality in the United States and globally.^{1,2} Health systems have a major role to play in prioritizing blood pressure control and ensuring proper treatment. However, many people who are seen in health systems with high blood pressure do not receive adequate treatment, support, or assistance to control their blood pressure.^{3–6} These patients with persistent high blood pressure, regardless of diagnosis

and treatment of hypertension, have a high risk of adverse outcomes and need attention to control blood pressure.

Electronic health record (EHR) data from large health systems have the potential for being a rich source of information that can identify patients who have high blood pressure along with gaps in care, that may inform opportunities to improve blood pressure control.^{7–9} However, few studies to date have systematically identified individuals who have high blood pressure,

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Supplementary material for this article is available at <https://www.ahajournals.org/doi/suppl/10.1161/JAHA.119.015033>

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CLINICAL PERSPECTIVE

What Is New?

- We provided proof of concept for the use of a large, integrated, clinical data repository in performing digital population health surveillance.
- We showed a significant proportion of outpatients had markedly elevated blood pressure, of whom many had multiple consecutive elevations despite coming in contact with the health system.
- Less than a third of these patients had a follow-up visit within the time window recommended by guidelines and <20% subsequently achieved control targets within 6 months, highlighting an immense opportunity to improve care and outcomes in this high-risk group.

What Are the Clinical Implications?

- This study shows the power of leveraging electronic health record data to identify patients who have a gap in care and signal the need for more attention.
- There is an urgent need for identifying effective implementation strategies to ensure that patients with markedly elevated blood pressure have opportunities to follow up with healthcare providers and receive adequate supports to achieve blood pressure control.

Nonstandard Abbreviations and Acronyms

EHR	electronic health records
BP	blood pressure
SBP	systolic blood pressure
DBP	diastolic blood pressure
BMI	body mass index
YNHHS	Yale-New Haven Health System
PCORnet	The National Patient-Centered Clinical Research Network
KP	Kaiser Permanente

especially those with markedly elevated blood pressure (eg, systolic blood pressure [SBP] ≥ 160 mm Hg or diastolic blood pressure [DBP] ≥ 100 mm Hg), despite coming in contact with the health system. Even fewer studies have assessed patients' follow-up care pattern.

To identify opportunities to improve care for patients, we used EHR data from the Yale–New Haven Health System (YNHHS) to describe the prevalence and follow-up care patterns of patients with markedly elevated blood pressure. Specifically, we sought to

determine the prevalence of markedly elevated blood pressure in outpatient settings, describe how often these patients have timely subsequent visits, and how commonly they ultimately achieve guideline-based blood pressure control targets. The goal is to determine the extent of opportunity to improve care by focusing on patients in the health system whose hypertension is inadequately managed.

METHODS

Because the EHR data contain confidential information of patients, such data will not be made available to other researchers for purposes of reproducing the results. However, the source codes will be available from the corresponding author upon reasonable request. We performed a retrospective analysis of data on adult patients in the YNHHS, Connecticut's largest healthcare system, consisting of 5 hospitals and 1 outpatient provider network. These hospitals and practices provide care for >3 million residents in the states of Connecticut, New York, and Rhode Island. All YNHHS hospitals used a secure, centralized EHR system designed by the Epic Corporation to collect and store clinical and administrative claims data. The EHR data are maintained in a data repository at the YNHHS server and integrated into the National Patient-Centered Clinical Research Network common data model. This study was approved by the institutional review board at Yale University, and informed consent was waived.

Cohort Development

We included adults aged 18 to 85 years old with at least 1 outpatient encounter from January 1, 2013 (the go-live date for Epic EHR system at YNHHS) through December 31, 2017. We excluded adults who were pregnant or on dialysis. We also excluded inpatient, emergency department, or ambulatory surgery center blood pressure values to reduce the risk of transiently elevated blood pressure from acute medical conditions.^{5,10} We extracted the following data from the EHR of all outpatient visits in which a patient met our criteria: demographic characteristics (age, race, ethnicity, sex), recorded systolic and diastolic blood pressure, height, weight, and smoking status. Race was determined on the basis of what was recorded in the chart. Body mass index (BMI) was calculated as weight in kilograms divided by the square of height in meters. The following measurements were considered errors and recoded as missing: SBP of <70 mm Hg or >250 mm Hg, DBP of <50 mm Hg or >150 mm Hg, BMI of <5 or ≥ 90 , a height of <3 or ≥ 8 feet, and a weight of ≤ 40 pounds or ≥ 500 pounds at any encounters during the study period. If a patient had >2 blood pressure measurements from a single encounter, we dropped the first measurement

and used the mean of the rest of the measurements as the blood pressure for that particular encounter.

Definition of Markedly Elevated Blood Pressure

In this study, we focused on 2 groups of patients with markedly elevated blood pressure, regardless of diagnosis and treatment of hypertension. Group 1 included patients who had at least 1 encounter with an SBP ≥ 160 mm Hg or DBP ≥ 100 mm Hg during the study period. Group 2 included patients who had at least 1 encounter with an SBP ≥ 180 mm Hg or DBP ≥ 120 mm Hg during the study period, which corresponded to hypertension crisis in accordance with the 2017 American College of Cardiology/American Heart Association Guideline for High Blood Pressure in Adults.¹¹ Patients in Group 2 represented a more extreme phenotype and was a subset of patients in Group 1.

Statistical Analysis

We used descriptive statistics to characterize the study population overall and by patients' blood pressure levels. We evaluated the number and percentage of the 2 groups of patients with markedly elevated blood pressure as defined above. For patients in each of these 2 groups, we first examined how often these patients had follow-up visits with a blood

pressure assessed after a markedly elevated blood pressure. Current clinical guidelines recommend repeating blood pressure evaluation in 1 month for SBP ≥ 160 mm Hg or DBP ≥ 100 mm Hg.¹¹ We calculated the number and percentage of patients who had at least 1 SBP or DBP elevation with a subsequent visit within 1, 3, or 6 months overall and in subgroups of age, sex, and race. Second, we examined whether blood pressure control targets were achieved within 3 or 6 months. We calculated the number and percentage of patients who had at least 1 SBP or DBP elevation with a subsequent SBP < 130 mm Hg and DBP < 80 mm Hg within 3 or 6 months¹¹ overall and in subgroups of age, sex, and race. We also calculated the median durations between the first measurement of elevated blood pressure and follow-up visit and between the first measurement of elevated blood pressure and control target achievement. Third, we evaluated the percentage of patients with > 2 , 3, 4, or 5 markedly elevated SBP or DBP measurements during the study period. To test the robustness of our results, we conducted a sensitivity analysis among patients with at least 5 visits during the study period (ie, on average at least 1 visit per year) and assessed how follow-up pattern and control target achievement change. We conducted another sensitivity analysis in which we defined markedly elevated blood pressure based on 2 consecutive blood pressure elevations.

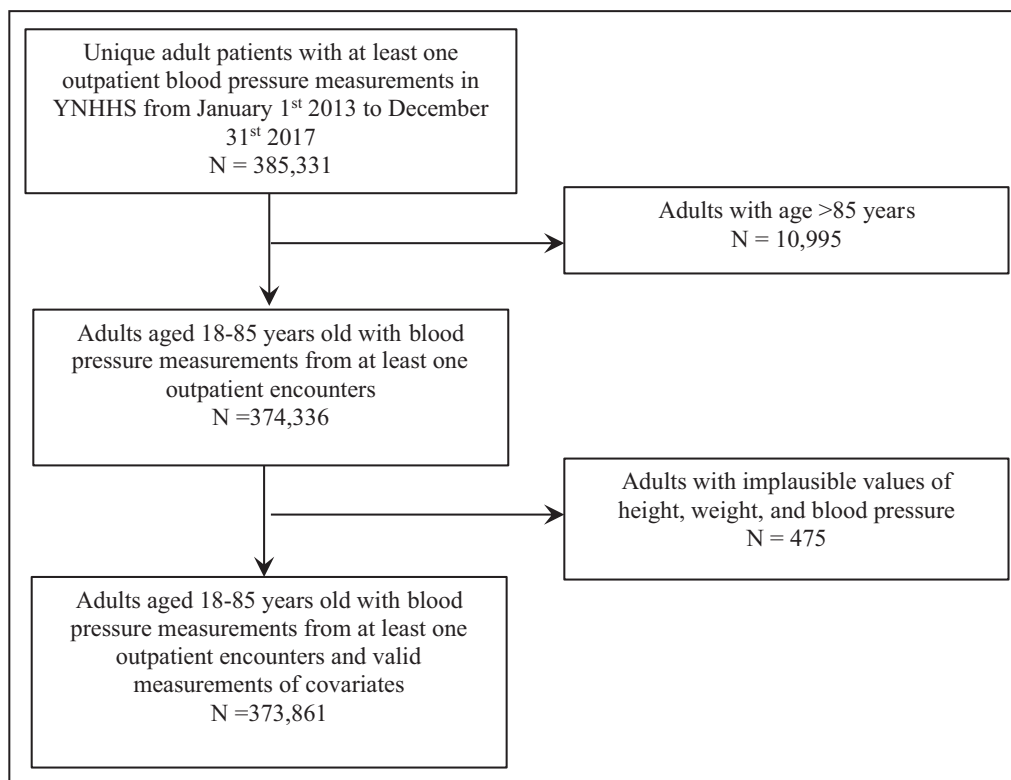


Figure 1. Flow diagram for study cohort identification. YNHHS indicates Yale–New Haven Health System.

Table 1. Characteristics of Patients Included in the Analysis

	All Patients With at Least 1 Blood Pressure Measurement (N=373 861)	Patients With SBP \geq 160 mm Hg or DBP \geq 100 mm Hg (N=56 909)	Patients With SBP \geq 180 mm Hg or DBP \geq 120 mm Hg (N=10 476)
Age at first visit, y, mean (SD)	51.2 (16.9)	61.0 (14.2)	64.5 (13.2)
Sex, N (%)			
Female	236 590 (63.3)	30 119 (52.9)	5778 (55.2)
Male	137 270 (36.7)	26 790 (47.1)	4698 (44.8)
Race, N (%)			
Black or African American	43 807 (11.7)	9754 (17.1)	2244 (21.4)
White or Caucasian	269 616 (72.1)	40 344 (70.9)	6972 (66.6)
Asian	8162 (2.2)	732 (1.3)	145 (1.4)
Other/not listed	31 322 (8.4)	3601 (6.3)	685 (6.5)
Patient refused	8342 (2.2)	1093 (1.9)	176 (1.7)
Ethnicity, N (%)			
Hispanic or Latino	38 059 (10.2)	4681 (8.2)	941 (9.0)
Non-Hispanic	319 091 (85.4)	50 573 (88.9)	9283 (88.6)
SBP at first visit, mm Hg, mean (SD)	126.9 (17.5)	163.8 (13.1)	186.3 (10.8)
DBP at first visit, mm Hg, mean (SD)	76.6 (10.6)	91.3 (12.9)	94.5 (16.8)
BMI, kg/m ² , mean (SD)	28.8 (6.9)	30.4 (7.3)	30.3 (7.5)
BMI category, N (%)			
\geq 30 kg/m ²	129 670 (35.3)	25 330 (44.9)	4549 (43.8)
25 to <30 kg/m ²	119 911 (32.6)	18 744 (33.2)	3419 (32.9)
<25 kg/m ²	117 984 (32.1)	12 327 (21.9)	2423 (23.3)
Smoking status, N (%)			
Current smoker	45 942 (12.3)	7746 (13.6)	1420 (13.6)
Former smoker	100 741 (26.9)	21 055 (37.0)	4069 (38.8)
Never smoker	201 184 (53.8)	25 989 (45.7)	4637 (44.3)

BMI indicates body mass index; DBP, diastolic blood pressure; and SBP, systolic blood pressure.

Finally, we assessed how percentage of patients and time to achieve control target changed if we defined control target as SBP <140 mm Hg and DBP <90 mm Hg.

RESULTS

A total of 373 861 patients with blood pressure measurement from at least 1 outpatient encounter were included in the study cohort (Figure 1). The mean age at the first encounter was 51.2 (SD, 16.9) years; the majority were women (63.3%), white (72.1%), and non-Hispanic (85.4%). A total of 35.3% had a BMI of 30.0 kg/m² or more, and 32.6% had a BMI of 25.0 to <30.0 kg/m²; 12.3% of patients were current smokers, and 26.9% were former smokers (Table 1). Mean (SD) blood pressure of the population at the first encounter was 126.9 (17.5) mm Hg systolic and 76.6 (10.6) mm Hg diastolic. The missing rate of covariates at the first encounter among all included patients was 0.1% for ethnicity; 1.7% for BMI; 2.9% for smoking status; and 0% for age, sex, and race.

Prevalence of Markedly Elevated Blood Pressure

Among the study cohort, we identified 56 909 (15.2%) patients who had at least 1 encounter with an SBP \geq 160 mm Hg or DBP \geq 100 mm Hg. Of these people, 83.3% of patients with SBP \geq 160 mm Hg, 40.6% of patients with DBP \geq 100 mm Hg, and 20.1% of patients with SBP \geq 160 mm Hg and DBP \geq 100 mm Hg. Compared with the overall study cohort, patients with SBP \geq 160 mm Hg or DBP \geq 100 mm Hg were older and more likely to be male, black, obese, and current smokers (Table 1). A total of 22 875, 12 283, 7460, and 4848 patients (40.2%, 21.6%, 13.1%, and 8.5% of patients) had at least 2, 3, 4, and 5 measurements of SBP \geq 160 mm Hg or DBP \geq 100 mm Hg respectively, during the study period (Table 2). Consecutively high blood pressures were also common. A total of 14 572, 5129, 2143, and 1023 patients (25.6%, 9.0%, 3.8% and 1.8% of patients in this group) had at least 2, 3, 4, and 5 *consecutive* measurements of SBP \geq 160 mm Hg or DBP \geq 100 mm Hg, respectively (Table 3).

Table 2. Number and Percentage of Patients With at Least 1 Measurement of SBP ≥ 160 mm Hg or DBP ≥ 100 mm Hg, SBP ≥ 180 mm Hg or DBP ≥ 120 mm Hg, Respectively

Number of Blood Pressure Elevations	Patients With SBP ≥ 160 mm Hg or DBP ≥ 100 mm Hg (N=56 909)	Patients With SBP ≥ 180 mm Hg or DBP ≥ 120 mm Hg (N=10 476)
1	34 034 (59.8)	7718 (73.7)
2	10 592 (18.6)	1681 (16.0)
3	4823 (8.5)	496 (4.7)
4	2612 (4.6)	252 (2.4)
≥ 5	4848 (8.5)	329 (3.1)

DBP indicates diastolic blood pressure; and SBP, systolic blood pressure.

We identified 10 476 (2.8%) patients who had at least 1 encounter with an SBP ≥ 180 mm Hg or DBP ≥ 120 mm Hg. Similar to patients with SBP ≥ 160 mm Hg or DBP ≥ 100 mm Hg, patients with SBP ≥ 180 mm Hg or DBP ≥ 120 mm Hg were older and more likely to be male, black, obese, and current smokers compared with the overall study population. A total of 2758, 1077, 581, and 329 patients (26.3%, 10.3%, 5.5%, and 3.1% of patients in this group) had at least 2, 3, 4, and 5 measurements with SBP ≥ 180 mm Hg or DBP ≥ 120 mm Hg, respectively, during the study period (Table 2). Consecutively high blood pressures were also common. A total of 1488, 373, 125, and 37 patients (14.2%, 3.6%, 1.2%, and 0.4% of patients) had at least 2, 3, 4, and 5 *consecutive* measurements with SBP ≥ 180 mm Hg or DBP ≥ 120 mm Hg, respectively (Table 3). The results in the sensitivity analysis among those with at least 5 visits over 5 years were consistent with the main analysis (Table S1).

Follow-Up Care Patterns of Patients With Markedly Elevated Blood Pressure

About 22.0% of patients with SBP ≥ 160 mm Hg or DBP ≥ 100 mm Hg and 20.3% of patients with SBP ≥ 180 mm Hg or DBP ≥ 120 mm Hg did not have any follow-up visit after the blood pressure elevation. Among those with follow-up visits, 36.2%, 52.8%,

Table 3. Number and Percentage of Patients With at Least 2 Consecutive Measurements of SBP ≥ 160 mm Hg or DBP ≥ 100 mm Hg, SBP ≥ 180 mm Hg or DBP ≥ 120 mm Hg, Respectively

Number of Consecutive Blood Pressure Elevations*	Patients With SBP ≥ 160 mm Hg or DBP ≥ 100 mm Hg (N=56 909)	Patients With SBP ≥ 180 mm Hg or DBP ≥ 120 mm Hg (N=10 476)
2	9443 (16.6)	1115 (10.6)
3	2986 (5.2)	248 (2.4)
4	1120 (2.0)	88 (0.8)
≥ 5	1023 (1.8)	37 (0.4)

DBP indicates diastolic blood pressure; and SBP, systolic blood pressure.

*These patient groups overlapped with each other. For example, patients with 3 consecutive blood pressure elevations was a subset of patients with 2 consecutive blood pressure elevations.

and 62.0% of patients with SBP ≥ 160 mm Hg or DBP ≥ 100 mm Hg had a subsequent visit within 1, 2, and 3 months (Table 4). The corresponding percentages among patients with SBP ≥ 180 mm Hg or DBP ≥ 120 mm Hg were 40.0%, 56.8%, and 65.7%, respectively. The median durations between the first blood pressure elevation and follow-up visit were 54 days for patients with SBP ≥ 160 mm Hg or DBP ≥ 100 mm Hg, and 45 days for patients with SBP ≥ 180 mm Hg or DBP ≥ 120 mm Hg (Figure 2). Compared with patients who were younger, male, or black, those who were older, female, or white were less likely to have a follow-up visit after a blood pressure elevation or needed a longer time to get a follow-up visit (Tables 5 and 6).

About 60.1% of patients with SBP ≥ 160 mm Hg or DBP ≥ 100 mm Hg and 63.9% of patients with SBP ≥ 180 mm Hg or DBP ≥ 120 mm Hg did not subsequently achieve blood pressure control targets (SBP < 130 mm Hg and DBP < 80 mm Hg; Table 7). Among those who had achieved control targets, 32.8% and 50.0% of patients with SBP ≥ 160 mm Hg or DBP ≥ 100 mm Hg had achieved the control targets within 3 and 6 months. The corresponding percentages among patients with SBP ≥ 180 mm Hg or DBP ≥ 120 mm Hg

Table 4. Follow-Up Patterns for Patients With First SBP ≥ 160 mm Hg or DBP ≥ 100 mm Hg, SBP ≥ 180 mm Hg or DBP ≥ 120 mm Hg, Respectively

N (%)	Patients With SBP ≥ 160 mm Hg or DBP ≥ 100 mm Hg (N=56 909)	Patients With SBP ≥ 180 mm Hg or DBP ≥ 120 mm Hg (N=10 476)
No follow-up visits after blood pressure elevation	12 492 (22.0)	2128 (20.3)
Had follow-up visits after blood pressure elevation	44 417 (78.0)	8348 (80.0)
Among those with follow-up visits		
Median days between the first blood pressure elevation and follow-up visit	54	45
Had follow-up visit within 1 mo	16 077 (36.2)	3338 (40.0)
Had follow-up visit within 2 mo	23 465 (52.8)	4744 (56.8)
Had follow-up visit within 3 mo	27 529 (62.0)	5487 (65.7)

DBP indicates diastolic blood pressure; and SBP, systolic blood pressure.

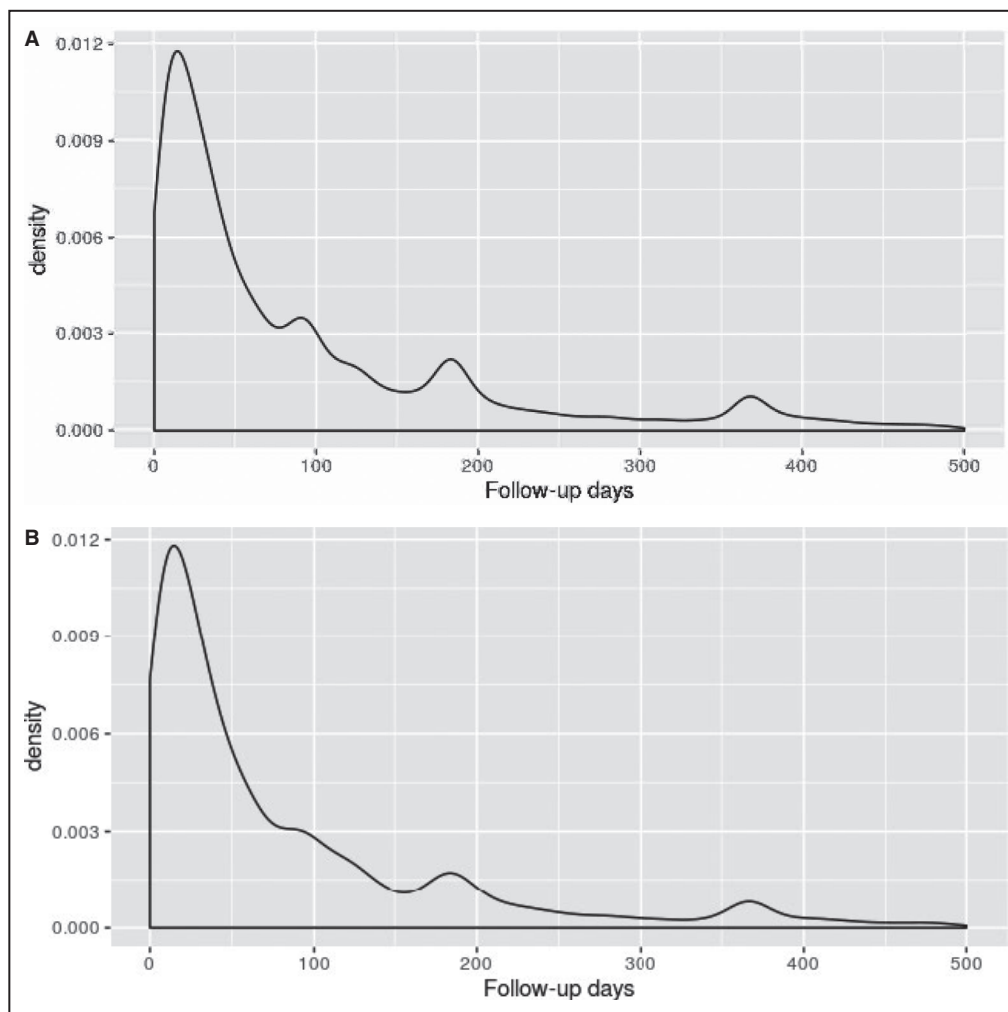


Figure 2. Duration between blood pressure elevated measurement and follow-up visit among patients with (A) SBP ≥ 160 mm Hg or DBP ≥ 100 mm Hg, and (B) SBP ≥ 180 mm Hg or DBP ≥ 120 mm Hg who had follow-up visits.

DBP indicates diastolic blood pressure; and SBP, systolic blood pressure.

were 30.2% and 47.7%, respectively. The median durations between the first blood pressure elevation and control target achievement were 181 days for patients with SBP ≥ 160 mm Hg or DBP ≥ 100 mm Hg, and 192 days for patients with SBP ≥ 180 mm Hg or DBP ≥ 120 mm Hg (Figure 3). Compared with younger patients, older patients were less likely to achieve blood pressure control targets or needed a longer time to achieve the control targets. Compared with patients who were black, patients who were white were much older (mean [SD] age of 63.0 [13.6] in whites versus 55.4 [14.1] in blacks) and thus were less likely achieve blood pressure control targets (Tables 8 and 9). The pattern of control target achievement was similar between men and women. The sensitivity analysis showed results consistent with the main analysis (Tables S2 through S5). If we used SBP < 140 mm Hg and DBP < 90 mm Hg as the control target, 39.4% of patients with SBP ≥ 160 mm Hg or DBP ≥ 100 mm Hg and 46.0%

of patients with SBP ≥ 180 mm Hg or DBP ≥ 120 mm Hg did not subsequently achieve these targets. The median durations between the first blood pressure elevation and control target achievement were shorter and the percentages of patients who achieved the targets within 3 and 6 months were higher compared with using SBP < 130 mm Hg and DBP < 80 mm Hg as the control target (Tables S6 through S8).

DISCUSSION

Using clinical data from real-world usual care in a large health system, we found that 15.2% of patients attending ambulatory visits in a large healthcare system had at least 1 encounter with an SBP ≥ 160 mm Hg or DBP ≥ 100 mm Hg, and 2.8% had at least 1 encounter with an SBP ≥ 180 mm Hg or DBP ≥ 120 mm Hg. These markedly elevated blood pressure levels were

Table 5. Follow-Up Patterns for Patients With SBP ≥160 mm Hg or DBP ≥100 mm Hg, by Age, Sex, and Race

N (%)	Age*		Sex		Race	
	<55 years (N=17 345)	≥55 years (N=39 564)	Men (N=26 790)	Women (N=30 119)	White (N=40 344)	Black (N=9754)
No follow-up visits after blood pressure elevation	4077 (23.5)	8415 (21.3)	6081 (22.7)	6411 (21.3)	8960 (22.2)	1840 (18.9)
Had follow-up visits after blood pressure elevation	13 268 (76.5)	31 149 (78.7)	20 709 (77.3)	23 708 (78.7)	31 384 (77.8)	7914 (81.1)
Among those with follow-up visits						
Median days between the first blood pressure elevation and follow-up visit	50	56	50	56	56	47
Had follow-up visit within 1 mo	4976 (37.5)	11 101 (35.6)	7713 (37.2)	8364 (35.3)	10 927 (34.8)	3127 (39.5)
Had follow-up visit within 2 mo	7220 (54.4)	16 245 (52.2)	11 188 (54.0)	12 277 (51.8)	16 138 (51.4)	4444 (56.2)
Had follow-up visit within 3 mo	8425 (63.5)	19 104 (51.3)	13 035 (62.9)	14 494 (61.1)	19 028 (60.6)	5143 (65.0)

DBP indicates diastolic blood pressure; and SBP, systolic blood pressure.
*Age at first elevation.

associated with exceptionally high risk of morbidity and mortality. However, among patients with markedly elevated blood pressure, less than a third had a follow-up visit within 1 month (time window of follow-up recommended by the guideline) and <60% subsequently achieved blood pressure control targets within 6 months. These findings suggest that there are immense opportunities to improve care by prioritizing patients with markedly elevated blood pressure in the health system and partnering with them to efficiently and effectively control their blood pressure.

We extend the prior literature in 2 important ways. First, we used real-world clinical data to better determine the prevalence of patients with markedly elevated blood pressure in the health system. Previous studies using EHR have focused on overall hypertension or resistant hypertension,^{3-6,12} and data on those with markedly elevated blood pressure are limited. A better identification of people with markedly elevated blood pressure, who are at particularly high risk of

cardiovascular outcomes and renal failure, may allow for more focused interventions in the healthcare system to prevent the adverse sequelae of hypertension. We showed that a significant proportion of outpatients had markedly elevated blood pressure, of whom many had multiple consecutive elevations despite coming in contact with the health system. This finding highlights an immense opportunity to improve care and outcomes in this high-risk group.

Second, the analysis of follow-up care patterns of patients with markedly elevated blood pressure helps to better identify targets for intervention. Successful control of blood pressure, particularly for those at markedly elevated levels, requires frequent follow-up appointments with healthcare providers to monitor blood pressure and adjust medications. However, to our knowledge, previous studies did not systematically assess follow-up care patterns among patients with markedly elevated blood pressure in the health system.^{3-6,12} We showed that less than a third of these

Table 6. Follow-Up Patterns for Patients With SBP ≥180 mm Hg or DBP ≥120 mm Hg, by Age, Sex, and Race

N (%)	Age*		Sex		Race	
	<55 years (N=2301)	≥55 years (N=8175)	Men (N=4698)	Women (N=5778)	White (N=6972)	Black (N=2244)
No follow-up visits after blood pressure elevation	467 (20.3)	1661 (20.3)	982 (20.9)	1146 (19.8)	1510 (21.7)	349 (15.6)
Had follow-up visits after blood pressure elevation	1834 (79.7)	6514 (79.7)	3716 (79.1)	4632 (80.2)	5462 (78.3)	1895 (84.4)
Among those with follow-up visits						
Median days between the first blood pressure elevation and follow-up visit	35	49	43	48	49	37
Had follow-up visit within 1 mo	833 (45.4)	2505 (38.5)	1510 (40.6)	1828 (39.5)	2089 (38.2)	841 (44.4)
Had follow-up visit within 2 mo	1128 (61.5)	3616 (55.5)	2136 (57.5)	2608 (56.3)	2989 (54.7)	1179 (62.2)
Had follow-up visit within 3 mo	1278 (69.7)	4209 (64.6)	2460 (66.2)	3027 (65.3)	3484 (63.8)	1343 (70.9)

DBP indicates diastolic blood pressure; and SBP, systolic blood pressure.
*Age at first elevation.

Table 7. Number and Percentage of Patients With SBP ≥ 160 mm Hg or DBP ≥ 100 mm Hg, and SBP ≥ 180 mm Hg or DBP ≥ 120 mm Hg Who Subsequently Achieved Control Targets (SBP < 130 mm Hg and DBP < 80 mm Hg), Respectively

N (%)	Patients With SBP ≥ 160 mm Hg or DBP ≥ 100 mm Hg (N=56 909)	Patients With SBP ≥ 180 mm Hg or DBP ≥ 120 mm Hg (N=10 476)
Did not achieve control targets or never came to a visit after blood pressure elevation	34 213 (60.1)	6689 (63.9)
Achieved control targets	22 696 (39.9)	3787 (36.1)
Among those who achieved control targets		
Median days between the first blood pressure elevation and control target achievement	181	192
Achieved control targets within 3 mo	7442 (32.8)	1143 (30.2)
Achieved control targets within 6 mo	11 342 (50.0)	1808 (47.7)

DBP indicates diastolic blood pressure; and SBP, systolic blood pressure.

patients had a follow-up visit within the time window recommended by guidelines, suggesting that patients being unable to get or keep follow-up appointments is an important barrier to effectively control blood

pressure. There may be multiple reasons why these patients might not have had timely follow-up or subsequent control. For example, the clinicians may have thought the hypertension was measurement error

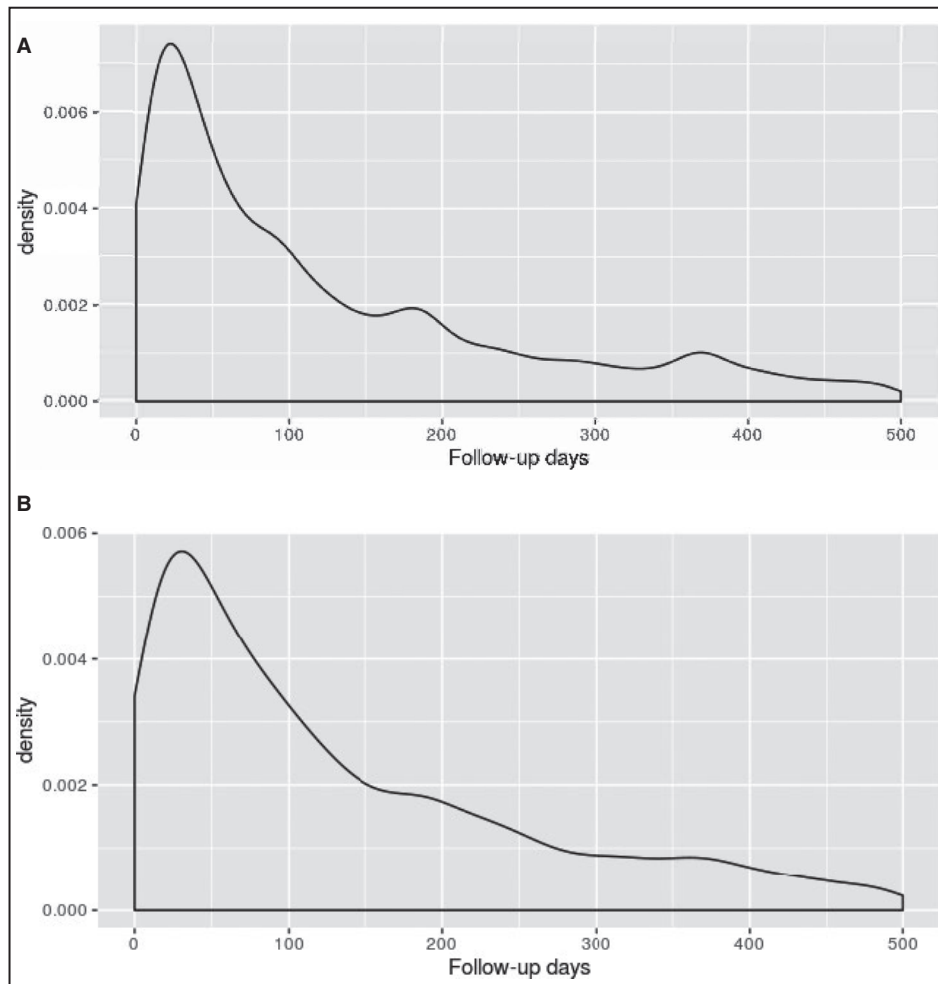


Figure 3. Duration between blood pressure elevated measurement and control target achievement among patients with (A) SBP ≥ 160 mm Hg or DBP ≥ 100 mm Hg, and (B) SBP ≥ 180 mm Hg or DBP ≥ 120 mm Hg who achieved control targets.

DBP indicates diastolic blood pressure; and SBP, systolic blood pressure.

Table 8. Number and Percentage of Patients With SBP \geq 160 mm Hg or DBP \geq 100 mm Hg Who Subsequently Achieved Control Targets, by Age, Sex, and Race

N (%)	Age*		Sex		Race	
	<55 years (N=17 345)	\geq 55 years (N=39 564)	Men (N=26 790)	Women (N=30 119)	White (N=40 344)	Black (N=9754)
Did not achieve control targets or never came to a visit after blood pressure elevation	10 873 (62.7)	23 340 (59.0)	16 708 (62.4)	17 505 (58.1)	24 484 (60.7)	5468 (56.1)
Achieved control targets	6472 (37.3)	16 224 (41.0)	10 082 (37.6)	12 614 (41.9)	15 860 (39.3)	4286 (43.9)
Among those who achieved control targets						
Median days between the first blood pressure elevation and control target achievement	182	178	180	182	179	194
Achieved control targets within 3 mo	2123 (32.8)	5319 (32.8)	3285 (32.6)	4157 (33.0)	5234 (33.0)	1313 (30.6)
Achieved control targets within 6 mo	3184 (49.2)	8158 (50.3)	5057 (50.2)	6285 (49.8)	7960 (50.2)	2037 (47.5)

DBP indicates diastolic blood pressure; SBP, systolic blood pressure.

*Age at first elevation.

attributable to white coat hypertension, or the patient may have expressed a personal preference not to be treated by medications.^{13–15} The point is that we found the rates of failure to have timely follow-up or subsequent control to be quite high, indicating an opportunity to improve care. It also highlights the need for future research to uncover other barriers to poor blood pressure control, including adherence to medication and clinical inertia for the overall population and subgroups.

This study has important clinical and public health implications. We provide proof of concept for the use of a large, integrated, clinical data repository in performing digital population health surveillance. It shows the power of leveraging EHR data to identify patients who have a gap in care and signal the need for more attention. With the goal of creating health systems in which patient care and evidence inform each other, EHR data from large health systems may be increasingly used to improve quality of care, support the design and conduct of intervention, and enhance public health efforts.

This study also identifies the need for effective implementation strategies to ensure that patients with markedly elevated blood pressure have opportunities to follow up with healthcare providers. Many strategies may be considered to address this need, including clinical reminders for appointments,^{16,17} inclusion of patient navigators,¹⁸ telemedicine, and pharmacist comanagement.^{19–22} For example, combined intervention of telemedicine with pharmacist-led care and pharmacist-physician collaborative management of hypertension have been shown to be effective for reducing blood pressure levels and improving blood pressure control rate.^{19–21,23,24} Pharmacists could play an important role in teaching patients general knowledge about hypertension management, instructing patients on medication use, prescribing and changing antihypertensive therapy within specified parameters, and following up with patients until blood pressure control is achieved. Another example is from the Kaiser Permanente Group, who has undertaken systematic implementation strategies to improve blood pressure control rate to 90%.^{25–27} Of particular relevance are their strategies to inreach

Table 9. Number and Percentage of Patients With SBP \geq 180 mm Hg or DBP \geq 120 mm Hg Who Subsequently Achieved Control Targets, by Age, Sex, and Race

N (%)	Age*		Sex		Race	
	<55 years (N=2301)	\geq 55 years (N=8175)	Men (N=4698)	Women (N=5778)	White (N=6972)	Black (N=2244)
Did not achieve control targets or never came to a visit after blood pressure elevation	1472 (64.0)	5217 (63.8)	3070 (65.3)	3619 (62.6)	4539 (65.1)	1307 (58.2)
Achieved control targets	829 (36.0)	2958 (36.2)	1628 (34.7)	2159 (37.4)	2433 (34.9)	937 (41.8)
Among those who achieved control targets						
Median days between the first blood pressure elevation and control target achievement	203	189	184	197	184	215
Achieved control targets within 3 mo	268 (32.8)	875 (29.6)	482 (29.6)	661 (30.6)	762 (31.3)	253 (27.0)
Achieved control targets within 6 mo	392 (47.3)	1416 (47.9)	796 (48.9)	1012 (46.9)	1192 (49.0)	417 (44.5)

DBP indicates diastolic blood pressure; and SBP, systolic blood pressure.

*Age at first elevation.

and outreach patients. When a patient is at a Kaiser Permanente medical facility, the healthcare team (consisting of medical assistants, licensed practical nurses, and pharmacists) is trained and encouraged to close care gaps through inreach. Kaiser Permanente also uses visit-independent regional and local coordination of outreach by using mass outreach calls, letters, and emails to advise patients to take action as well as providing an EHR for healthcare providers of all outreach attempts to reinforce the message. These strategies could be potentially adapted and implemented in other health systems to improve blood pressure control.

This study has several potential limitations. First, these data are not necessarily generalizable to the adult population of Connecticut or adult populations in other states. Systematic differences exist between people who engage the healthcare system and those who do not. For example, patients in the healthcare system are sicker than the general population, which could result in overestimation of the prevalence of markedly elevated blood pressure in the general population. Conversely, some people with low socioeconomic status and no medical insurance may forgo routine outpatient visits. To date, only 1 federally qualified health center uses the YNHH EHR; thus, we are likely missing patients with markedly elevated blood pressure, who are commonly being treated in the community. Second, we used data from only outpatient settings and excluded potential patients with markedly elevated blood pressure in which care was received only in an inpatient or emergency department setting; however, blood pressure elevations in these acute settings are less likely to be indicative of the true blood pressure. Third, the assessment of follow-up visits is based on review of a single EHR. If patients had their follow-up visits with primary care providers who are not part of YNHH, their data would not be captured, which may lead to underestimation of the number of patients with follow-up visit after blood pressure elevation. However, the blood pressure readings used to define this cohort were derived from Evaluation and Management codes of outpatient visits; thus, our assumption is that these patients were receiving at least some of their ongoing care with providers in our EHR. Fourth, the EHR data do not capture the exact device or technique used for blood pressure measurement in each encounter. However, our study focused on information that was available to the clinicians. Finally, we were not able to evaluate access to care, provider inertia about initiating treatment or escalating medication, and patient adherence to medication in this study. All of these are important factors that may contribute to poor blood pressure control.²⁸ A comprehensive evaluation of multifaceted factors at the provider, patient, and system level is warranted to assess barriers to poor blood

pressure control, but this is outside of the scope of this paper.

In conclusion, digital population health surveillance with an EHR identified within a health system a large number of patients with markedly elevated blood pressure and inadequate follow-up visits. Many of these patients subsequently failed to achieve blood pressure control targets. There are opportunities to improve care by prioritizing patients in the health system whose markedly elevated blood pressure has been inadequately managed.

ARTICLE INFORMATION

Received November 12, 2019; accepted February 6, 2020.

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Disclosures

Dr Lu is supported by the National Heart, Lung, and Blood Institute (K12HL138037) and the Yale Center for Implementation Science. Dr Krumholz is a recipient of a research grant, through Yale, from Medtronic and the US Food and Drug Administration to develop methods for postmarket surveillance of medical devices; is a recipient of research agreements with Medtronic and Johnson & Johnson (Janssen), through Yale, to develop methods of clinical trial data sharing; works under contract with the Centers for Medicare & Medicaid Services, through Yale, to develop and maintain performance measures that are publicly reported; was a recipient of a research agreement, through Yale, from the Shenzhen Center for Health Information for work to advance intelligent disease prevention and health promotion, and collaborates with the National Center for Cardiovascular Diseases in Beijing; received payment from the Arnold & Porter Law Firm for work related to the Sanofi clopidogrel litigation and from the Ben C. Martin Law Firm for work related to the Cook inferior vena cava filter litigation; chairs a Cardiac Scientific Advisory Board for UnitedHealth; is a participant/participant representative of the IBM Watson Health Life Sciences Board; is a member of the Advisory Boards for Element Science and for Facebook, and the Physician Advisory Board for Aetna; and is the founder of Hugo, a personal health information platform. Dr Schulz is a consultant for Hugo, a personal health information platform. Dr Spatz receives support from the Centers for Medicare & Medicaid Services to develop and maintain performance measures used in public reporting programs and from the Food and Drug Administration to support projects within the Yale-Mayo Clinic Center of Excellence in Regulatory Science and Innovation. She also receives support from the National Institute on Minority Health and Health Disparities (U54MD010711-01) to study precision-based approaches to diagnosing and preventing hypertension and the National Institute of Biomedical Imaging and Bioengineering (R01EB028106-01) to study a cuffless blood pressure device. The remaining authors have no disclosures to report.

Supplementary Material

Tables S1 to S8

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SUPPLEMENTAL MATERIAL

Table S1. Number and percent of patients with at least 2 consecutive measurements of SBP \geq 160 mmHg or DBP \geq 100 mmHg, SBP \geq 180 mmHg or DBP \geq 120 mmHg, among those with at least 5 visits over 5 years.

Number of consecutive blood pressure elevation*	Patients with SBP \geq 160 mmHg or DBP \geq 100 mmHg, N=36,106	Patients with SBP \geq 180 mmHg or DBP \geq 120 mmHg, N=7,180
2	6,021 (16.7)	760 (10.6)
3	1,897 (5.3)	184 (2.6)
4	700 (1.9)	64 (0.9)
\geq 5	676 (1.9)	23 (0.3)

*These patient groups overlapped with each other. For example, patients with 3 consecutive blood pressure elevations was a subset of patients with 2 consecutive blood pressure elevations.

SBP= systolic blood pressure; DBP = diastolic blood pressure.

Table S2. Follow-up patterns for patients with first SBP ≥ 160 mmHg or DBP ≥ 100 mmHg, SBP ≥ 180 mmHg or DBP ≥ 120 mmHg, among those with at least 5 visits over 5 years.

N (%)	Patients with SBP ≥ 160 mmHg or DBP ≥ 100 mmHg, N=36,106	Patients with SBP ≥ 180 mmHg or DBP ≥ 120 mmHg, N=7,180
No follow-up visits after BP elevation	2,053 (5.7)	471 (6.6)
Had follow-up visits after BP elevation	34,053 (94.3)	6,709 (93.4)
Among those with follow-up visits		
Median days between the first BP elevation and follow-up visit	46	42
Had follow-up visit within 1 month	13,376 (39.3)	2,853 (42.5)
Had follow-up visit within 2 months	19,155 (56.3)	4,022 (59.9)
Had follow-up visit within 3 months	22,374 (65.7)	4,624 (68.9)

BP= blood pressure; SBP= systolic blood pressure; DBP = diastolic blood pressure.

Table S3. Number and percent of patients with SBP \geq 160 mmHg or DBP \geq 100 mmHg, and SBP \geq 180 mmHg or DBP \geq 120 mmHg who subsequently achieved control targets (SBP $<$ 130 mmHg and DBP $<$ 80 mmHg), among those with at least 5 visits over 5 years.

N (%)	Patients with SBP \geq 160 mmHg or DBP \geq 100 mmHg, N=36,106	Patients with SBP \geq 180 mmHg or DBP \geq 120 mmHg, N=7,180
Did not achieve control targets or never came to a visit after BP elevation	15,163 (42.0)	3,596 (50.1)
Achieved control targets	20,943 (58.0)	3,584 (49.9)
Among those who achieved control targets		
Median days between the first BP elevation and control target achievement	180	190
Achieved control targets within 3 months	6,862 (32.8)	1,074 (30.0)
Achieved control targets within 6 months	10,496 (50.1)	1,716 (47.9)

BP= blood pressure; SBP= systolic blood pressure; DBP = diastolic blood pressure.

Table S4. Follow-up patterns for patients with first 2 consecutive SBP ≥ 160 mmHg or DBP ≥ 100 mmHg, SBP ≥ 180 mmHg or DBP ≥ 120 mmHg, respectively.

N (%)	Patients with SBP ≥ 160 mmHg or DBP ≥ 100 mmHg, N=14,572	Patients with SBP ≥ 180 mmHg or DBP ≥ 120 mmHg, N=1,488
No follow-up visits after BP elevation	2,551 (17.5)	289 (19.4)
Had follow-up visits after BP elevation	12,021 (82.5)	1,199 (80.6)
Among those with follow-up visits		
Median days between the first BP elevation and follow-up visit	49	44
Had follow-up visit within 1 month	4,583 (38.1)	497 (41.5)
Had follow-up visit within 2 months	6,680 (55.6)	663 (55.3)
Had follow-up visit within 3 months	7,868 (65.5)	775 (64.5)

BP= blood pressure; SBP= systolic blood pressure; DBP = diastolic blood pressure.

Table S5. Number and percent of patients with first 2 consecutive SBP \geq 160 mmHg or DBP \geq 100 mmHg, and SBP \geq 180 mmHg or DBP \geq 120 mmHg who subsequently achieved control targets (SBP $<$ 130 mmHg and DBP $<$ 80 mmHg), respectively.

N (%)	Patients with SBP \geq 160 mmHg or DBP \geq 100 mmHg, N=14,572	Patients with SBP \geq 180 mmHg or DBP \geq 120 mmHg, N=1,488
Did not achieve control targets or never came to a visit after BP elevation	9,009 (61.8)	1,029 (69.2)
Achieved control targets	5,563 (38.2)	459 (30.8)
Among those who achieved control targets		
Median days between the first BP elevation and control target achievement	197	231
Achieved control targets within 3 months	1,662 (29.9)	118 (25.7)
Achieved control targets within 6 months	2,627 (47.2)	199 (43.3)

BP= blood pressure; SBP= systolic blood pressure; DBP = diastolic blood pressure.

Table S6. Number and percent of patients with SBP \geq 160 mmHg or DBP \geq 100 mmHg, and SBP \geq 180 mmHg or DBP \geq 120 mmHg who subsequently achieved SBP $<$ 140 mmHg and DBP $<$ 90 mmHg, respectively.

N (%)	Patients with SBP \geq 160 mmHg or DBP \geq 100 mmHg, N=56,909	Patients with SBP \geq 180 mmHg or DBP \geq 120 mmHg, N=10,476
Did not achieve SBP/DBP $<$ 140/90 mmHg or never came to a visit after BP elevation	22,430 (39.4)	4,823 (46.0)
Achieved SBP/DBP $<$ 140/90 mmHg	34,479 (60.6)	5,653 (54.0)
Among those who achieved SBP/DBP $<$ 140/90 mmHg		
Median days between the first BP elevation and achievement of SBP/DBP $<$ 140/90 mmHg	100	119
Achieved SBP/DBP $<$ 140/90 mmHg within 3 months	15,906 (46.1)	2,395 (42.4)
Achieved SBP/DBP $<$ 140/90 mmHg within 6 months	22,063 (64.0)	3,416 (60.4)

BP= blood pressure; SBP= systolic blood pressure; DBP = diastolic blood pressure.

Table S7. Number and percent of patients with SBP \geq 160 mmHg or DBP \geq 100 mmHg who subsequently achieved SBP<140 mmHg and DBP<90 mmHg, by age, sex, and race.

N (%)	Age*		Sex		Race	
	< 55 yr N=17,345	\geq 55 yr N=39,564	Men N=26,790	Women N=30,119	White N=40,344	Black N=9,754
Did not achieve SBP/DBP<140/90 mmHg or never came to a visit after BP elevation	6,633 (38.2)	15,797 (39.9)	10,947 (40.9)	11,483 (38.1)	16,123 (40.0)	3,397 (34.8)
Achieved SBP/DBP<140/90 mmHg	10,712 (61.8)	23,767 (60.1)	15,843 (59.1)	18,636 (61.9)	24,221 (60.0)	6,357 (65.2)
Among those who achieved SBP/DBP<140/90 mmHg						
Median days between the first BP elevation and achievement of SBP/DBP<140/90 mmHg	91	106	100	100	105	98
Achieved SBP/DBP<140/90 mmHg within 3 months	5,280 (49.3)	10,626 (44.7)	7,308 (46.1)	8,598 (46.1)	10,946 (45.2)	2,974 (46.8)
Achieved SBP/DBP<140/90 mmHg within 6 months	7,067 (66.0)	14,996 (63.1)	10,172 (64.2)	11,891 (63.8)	15,338 (63.3)	4,080 (64.2)

* Age at first elevation.

BP= blood pressure; SBP= systolic blood pressure; DBP = diastolic blood pressure.

Table S8. Number and percent of patients with SBP \geq 180 mmHg or DBP \geq 120 mmHg who subsequently achieved SBP<140 mmHg and DBP<90 mmHg, by age, sex, and race.

N (%)	Age*		Sex		Race	
	< 55 yr N=2,301	\geq 55 yr N=8,175	Men N=4,698	Women N=5,778	White N=6,972	Black N=2,244
Did not achieve SBP/DBP<140/90 mmHg or never came to a visit after BP elevation	1,009 (43.9)	3,814 (46.7)	2,195 (46.7)	2,628 (45.5)	3,340 (47.9)	861 (38.4)
Achieved SBP/DBP<140/90 mmHg	1,292 (56.1)	4,361 (53.3)	2,503 (53.3)	3,150 (54.5)	3,632 (52.1)	1,383 (61.6)
Among those who achieved SBP/DBP<140/90 mmHg						
Median days between the first BP elevation and achievement of SBP/DBP<140/90 mmHg	103	124	119	119	121	114
Achieved SBP/DBP<140/90 mmHg within 3 months	593 (45.9)	1,802 (41.3)	1,043 (41.7)	1,352 (42.9)	1,532 (42.2)	586 (42.4)
Achieved SBP/DBP<140/90 mmHg within 6 months	832 (64.4)	2,584 (59.3)	1,511 (60.4)	1,905 (60.5)	2,175 (59.9)	849 (61.4)

* Age at first elevation.

BP= blood pressure; SBP= systolic blood pressure; DBP = diastolic blood pressure.