Stakeholder Engagement in a Long-Standing Community-Academic Research Partnership: A Social Network Analysis

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ABSTRACT

Background: The Rockefeller University Center for Clinical Translational Science (RU-CCTS) and Clinical Directors Network (CDN), a Practice-Based-Research-Network (PBRN), fostered a community-academic partnership involving clinicians from Community Health Centers (CHCs), Community Practices and Community Hospital Emergency Departments, laboratory scientists, clinical researchers and patient partners. The partnership conducted two projects: CAMP1, an observational study funded by the National Center for Advancing Science (NCATS), and CAMP2, a Comparative Effectiveness Research Study funded by the Patient-Centered Outcomes Research Institute (PCORI). We conducted a social network analysis (SNA) to characterize this community-academic research partnership.

Methods: Stakeholder attendance data, roles, and organizational affiliations formed the raw dataset. We used SNA software (GEPHI) to form networks for each of four project periods and characterize network attributes (size, density, degree, centrality, vulnerability). Polynomial regression models were used to study stakeholder participation and interactions. We visualized networks by density (GEPHI) and force-vector analysis (ForceAtlas2).

Results: The partnership held 47 progress meetings engaging 141 stakeholders (7 roles), affiliated with 28 organizations (6 types). Network size, density, and interactions across organizations increased over time. Interactions of stakeholders by role increased significantly, most notably between Community Members and each other role ($p<0.005$), and between Recruiters/Community Health Workers and almost all others ($p<0.005$).

Community members' centrality rose over time. Networks were most vulnerable during development periods.

Conclusions: SNA is a valuable tool to characterize a community-academic partnership and demonstrate engagement of community stakeholders throughout the life of the project. Lessons learned could be applied to other partnerships to gain valuable insights.

INTRODUCTION

The development of effective community-engaged translational science teams is a high priority for the National Center for Advancing Translational Science (NCATS) and its Clinical Translational Science Award (CTSA) program.[1] Successful community-academic partnerships can focus research priorities, improve study design, enhance study conduct, dissemination, and implementation, and ultimately improve population health.[2-5] Several collaboration models describe approaches to engaging community, clinical, and academic stakeholders to conduct community-engaged research (CEnR).[6-9] However, there are no consensus measures for successful collaboration and engagement,[10] and partnerships in early translational research are a challenge for CTSAs.[11, 12] There is an ongoing need for empiric evidence to support the effectiveness and impact of specific models for creating sustainable community-academic partnerships.

Social network analysis (SNA) is a mathematical approach for graphing interactions such as those between stakeholders in a partnership. Social network attributes are quantifiable, such as the size of the network (number of members), number and complexity of interactions among the members (density), connectedness of members to other members within network (degree), relative importance of a given member to the network (centrality) and the measures of how susceptible the network's connectedness is to the loss of one or some of its members (vulnerability). Analysis of network characteristics – e.g., by person, role, organization, or time -- can afford insight into network dynamics. Retrospective SNA can reveal what transpired within an existing network, and increasingly prospective SNA is used to identify opportunities to strengthen

a network as it evolves.[13, 14] Much of what has been written about Team Science networks has used co-authorship as the measure of collaboration among academic scientists, often without community partners among the stakeholders[15]. Similarly, network analyses of community partnerships rarely include scientists. New insights might be gained from applying social network analysis to a community-academic partnership engaging both basic scientists and community members in translational research.

The Rockefeller University Center for Clinical Translational Science (RU-CCTS) and Clinical Directors Network (CDN) previously reported a Community-Engaged Research Navigation (CEnR-Nav) model, a semi-structured, iterative, process to foster community-academic learning healthcare partnerships.[6] Through CEnR-Nav, expert intermediary navigators reach-in to scientists and reach-out to community clinicians, patients, and other stakeholders, to convene and cultivate interdisciplinary research teams whose research priorities span different phases of the translational spectrum to develop Full Spectrum Translational Research (FSTR). This inclusive collaborative approach engages stakeholders throughout the life of a research project including study design, conduct, problem solving, study analysis and dissemination. The interdisciplinary teams ultimately develop, secure funding for, and jointly conduct projects that integrate mechanistic research aims from basic scientists with the healthcare-related aims of clinicians, community representatives, patients, and other community stakeholders.

The Patient Centered Outcomes Research Institute (PCORI)[16], a major sponsor of community-engaged research, articulates an engagement rubric [17] of principles and activities to be incorporated into the design of PCORI-sponsored research: to foster equitable collaboration among researchers, patients, communities and other

stakeholders through shared decision-making, and by focusing on ongoing and multi-level communications and transparency at each step.[18]

The RU-CCTS/CDN collaborators developed and sustained an eight-year partnership with a large, diverse set of academic and community stakeholders. The partners designed, conducted, and completed two large, externally funded community-engaged research projects, CAMP1 and CAMP2. Completion of the projects required sustained collaboration, with highly interactive progress meetings to achieve partnered design, conduct, operational problem-solving, and other project activities. The nature of interactions fostered among stakeholders during the project have been described qualitatively ([6, 18, 19]. At the conclusion of CAMP1, we hypothesized that attendance data for these highly interactive progress meetings could serve as the basis for a social network analysis (SNA) of the engagement of stakeholders in the collaboration. Such an analysis could provide insights into partnership dynamics, vulnerability and sustainability. A project aim was developed (retrospective for CAMP1 and prospective aim for CAMP2) to: 1) conduct a social network analysis using attendance data, 2) visualize the network and characterize typical network attributes such as density and vulnerability, and 3) examine stakeholder engagement in the network in relation to study conduct metrics related to accrual and retention.

MATERIALS AND METHODS

CAMP projects: From 2010-2018, the RU-CCTS (an NCATS/CTSA grantee) and CDN (a Practice-Based Research Network (PBRN)), developed and fostered a collaborative multi-stakeholder partnership to study **c**ommunity-**a**cquired **m**ethicillin **r**esistant

staphylococcus **a**ureus (CA-MRSA) **p**rojects (CAMP). Two major research studies were developed, received extramural grant support, and were conducted and completed.

CAMP1 was developed initially with a CTSA-funded pilot award (2010-2011) and was conducted with support from a CTSA Administrative Supplement (NIH/NCATS 8 UL1 TR000043) from 2011-2015. CAMP1 built research infrastructure and capacity among the community /academic partners, RU-CCTS and CDN, and six NYC area CHCs serving predominantly minority and underserved populations. The partnership was fostered using the CEnR-Nav model.[6] CAMP1 aims were to engage the partners and enroll patients with skin/soft tissue infections (SSTIs) into an observational cohort study to characterize CA-MRSA in the patients attending those CHCs. The findings from CAMP1 included molecular characterization of the dominant clones among 129 individuals with CA-MRSA, and a high rate of recurrence of CA-MRSA among participants.[20-23] CAMP1 findings informed the preliminary data for a successful funding award from PCORI (PCORI/CER-1402-10800) supporting the CAMP2 study.

CAMP2 was a Comparative Effectiveness Research (CER) study to test whether a home-based decolonization and decontamination intervention, provided by community health workers/promotoras, could reduce the incidence of CA-MRSA recurrence in households receiving the intervention compared to usual care. Developed in 2014 and conducted from 2105-2018, the CAMP2 project engaged two of the original CAMP1 CHCs, one additional CHC, and three community hospital emergency departments (EDs) serving a similar population to that of CAMP1. Individuals presenting to participating CHCs and EDs with SSTIs suspicious for CA-MRSA were enrolled into CAMP2. Findings from CAMP2 demonstrated that home-based decolonization and decontamination did not alter

the CA-MRSA recurrence rate compared to usual practices among the 119 enrolled households.[19] The operational details of fostering sustained equitable engagement of stakeholders, and many qualitative themes of their interactions have been reported. [18] Together, the CAMP1/2 studies enrolled more than 270 participants, accomplished the stated aims, and produced a range of publications spanning the phases of translational research[24] that describe the basic biology and clinical aspects CA-MRSA in the study population[20-23, 25], the outcome of the CER intervention[18, 19], aspects of the community- engaged research team science model[6] [18], and resulted in dissemination of results to diverse audiences.

Ethical review

All research protocols related to CAMP1 (JTO-0749), CAMP2 (JTO-0889, NCT02566928) and related pilot studies were approved by the Rockefeller University Institutional Review Board (IRB) before any study-related procedures were initiated. Research activities at collaborating sites were approved by the IRBs of The Biomedical Research Alliance of New York (BRANY), Weill Cornell Medical Center, and Clinical Directors Network directly or under reliance agreements before research began at those sites.

Network Data

The CAMP1/2 projects entailed regularly scheduled team-wide progress meetings, held approximately monthly throughout both projects. Meetings entailed concept-generation, priority setting, protocol writing, study implementation, operational problem solving, analysis and dissemination.[6, 18]. Attendance data were collected at all meetings.

Stakeholders' roles in the project and institutional and site affiliations were captured in the protocol's delegation of authority and other protocol documents. Coding of roles and affiliations was performed independently by two of the authors (KV and RK); any rating differences were reconciled through discussion with additional team members.

Project stakeholders were characterized by their affiliated organization, and their role in the project. The affiliated organizations were characterized into six categories: Academic, Community Partner, Community Health Centers (including Federally Qualified Health Centers, Community Practices, and Community Hospitals) (CHC), Funder, Practice-Based-Research-Network (PBRN), and Private Partner. Stakeholders' roles were classified into 7 types: Clinician/Clinician-Researcher, Scientist, Community Engaged Research Core (RU-CCTS), Administrator, Recruiter/Community Health Worker (Rec/CHW), Community Member, or Research Team-other. Stakeholders were further characterized as fulfilling Leadership (e.g. medical/site director, principal investigator, etc.) or Non-leadership roles in the project.

Study milestones for CAMP1 and CAMP2 were routinely collected for each of the respective study sites and included the number of participants and signing informed consent, the number of participants ultimately enrolled or randomized into the study, completion of subsequent study visit or procedures, and the date of each timepoint. Informed consent was obtained at the time of initial clinical presentation with a skin/soft tissue lesion suspicious for CA-MRSA. In CAMP1, consented participants proceeded directly to study procedures. In CAMP2, randomization into the study depended on the microbial culture results available 48 hours after consenting; only patients whose culture grew *staphylococcus aureus* advanced to the interventional portion of the study.

The lifespan of the project was divided into 4 project periods covering the development and implementation of each of the two protocols: *CAMP 1-Development* – 3 meetings (December 2010- July 2011)*; CAMP 1-Implementation* - 13 meetings (October 2011-February 2013); *CAMP 2-Development* –12 meetings (May 2013- July 2015); and *CAMP 2-Implementation*- 19 meetings (July 2015 – May 2018).

Data Analysis Plan

Attendance data were used to represent stakeholder interactions in the social network analysis, supported by three rationales: 1) Monthly team meetings were highly interactive and participatory by design; 2) In defining interactions between stakeholders for the network analyses we chose the more rigorous the notion of a "weighted" network whereby two stakeholders could not merely be in the network together but must have attended the same meeting(s) to be considered to have interacted; 3) Collection of attendance data is ubiquitous in project operations, and incurs low overhead, whereas the collection of qualitative measures of collaboration in the course of project lifecycle can be burdensome to partners, challenging for teams, and lacks standardization.[10] If found to be valuable in SNA, attendance data could be a rich source of readily available information for performance improvement and research, particularly if enriched with other study and stakeholder characteristics, and more demanding qualitative assessments could be reserved for selective problem solving.

Descriptive statistics were used to analyze network size, number of meetings, interactions, and the diversity of stakeholder roles and affiliations.

Creation of the social networks: We examined interactions among stakeholders in the CAMP partnership by compiling the attendance records for each stakeholder meeting and creating a matrix where each row represents an individual stakeholder (present/absent) and each column represented an event (meeting date). Using social network analysis (SNA) software (Gephi) we conducted a social network analysis (SNA) by converting a two-mode (person→event) matrix to a one mode (person→person) matrix. [26-28] The matrix was further expanded to incorporate richer information to characterize the project stakeholders (e.g., role, affiliation, affiliation type) and formed the raw dataset for the network and interaction analyses.

When two individuals are present at the same meeting, this defines an interaction, expressed as an "edge" in the SNA; the number of interactions along that edge is its "weight". Similarly, when interactions are analyzed between groups (e.g., roles or affiliations as nodes) those interactions also form edges with weights.

There are two ways to compute the degree (measure of all interactions) of a given node in these networks. If one views the network as an *unweighted* network, where two nodes (stakeholders) are linked by an edge if they participated in at least one meeting, the degree of a stakeholder is the number of other stakeholders who co-attended *at least one meeting*. Alternatively, if one views the network as a *weighted* network, where the weight of an edge joining two nodes is the total number of meetings the two stakeholders co-attended, then the degree of a stakeholder is the *total number of interactions with other stakeholders*. We used the weighted notion of degree for assessing a stakeholder's interactions with others and to assess the distribution of degree in the network and over

time. We considered both weighted and unweighted notions of degree in the vulnerability analyses.

To study the participation of stakeholders over time, polynomial regression models were fitted to the number of affiliations and the number of roles involved in the project as a function of time. R software was used for all the computations. To compare the degree distribution of the stakeholders across different project phases, we used two-sample Wilcoxon tests to test whether the level of interactions changed significantly.

The social network analysis was visualized multiple ways to examine different characteristics of the network:

Visualization 1: Interaction (edge weight) among stakeholders across organization types, over time: Gephi software was used for network visualization of the social network longitudinally across the four project periods. A network was generated for each project period. Each stakeholder is represented as a node in the network, with attributes of organizational affiliation, affiliation type, and leadership. The edges between two nodes represent the interactions between those two individuals, and each edge has weight reflecting the number of interactions by line color and intensity. When an individual has affiliation to two organizations, their interactions are represented once in the creation of the network, to reflect their primary affiliation.

Interactions between role groups: To explore network interactions between groups of stakeholders fulfilling different roles in the project (role-role interactions), we aggregated the edge weights between stakeholders as classified by their roles, and compared the sum of all interactions (degree) between each possible role-role dyad of stakeholder

roles. We performed the Kolmogorov-Smirnov test[29] to compare interactions among different role-types.

Visualization 2: Force Vectors to reveal structural holes – To look for structure holes or weakness in the CAMP1/2 networks, we followed methods which leverage the concept of "force vectors" to reflect the interaction characteristics of the nodes (individuals) within the network. [30] We applied the ForceAtlas2 algorithm of the Gephi software [26, 31] using settings: Lin-log mode[32], Edge weight influence parameter=1, Gravity=0.2, Scaling=1, and Prevent Overlapping mode -enabled. ForceAtlas2 is a "force vector" algorithm employed to obtain an easily interpretable and aesthetic force-directed layout of complex networks.[31] To spatialize a given network, force-vector algorithms embed the network into a physical system, where nodes are viewed as "charged particles" and edges are viewed as "springs". The system simulates the effect of (i) repulsion forces between all pairs of nodes (charged particles) that drive the nodes apart, and (ii) attraction forces between nodes connected by edges (springs) that pull them to each other, converging to an equilibrium state. The form of the repulsion and attraction forces depend on the choice of the force-vector algorithm. The presence of Gravity improves the force-directed layouts by attracting all nodes toward the center of the spatialization area and preventing disconnected components (if any) from drifting too far away. Enabling the "Preventing Overlapping" mode modifies the repulsion based on the border-to-border distance between nodes so that the nodes do not overlap. This feature helps to illustrate if there is any structural hole (gap in the cluster structure) in the network and makes visible "bridging" interactions that may be critical to connecting otherwise unconnected clusters in the network.

Centrality: Measures of centrality are designed to quantify the 'importance' of a node in the network. There are several different centrality measures. The most common versions of the three classic types of vertex centrality measures are termed "degree", "closeness", and "eigenvector centrality". The degree-centrality score of a node x is the sum of all the weights of the edges shared by x. The closeness-centrality measure attempts to capture how many other vertices have a directed connection (edge) to a given vertex within a network graph by calculating how many steps are required to access every other node from node x, in the unweighted network. We chose a third class of centrality measures that are based on notions of 'status' or 'prestige' or 'rank.' They seek to capture the idea that the more central the neighbors of a vertex are, the more central that vertex itself is. There are many such measures, typically expressed in terms of eigenvector solutions of appropriately defined linear systems of equations..[33, 34] We used the "eigen_centrality" function of the R software, which is based on the method developed in [35] as the measure of most interest because it incorporates measures of the density of the network, and of the centrality of the other nodes that are connected in calculating a given node's centrality score.

Vulnerability: One of the important properties of any network involving several stakeholders is resilience of the network against "damage" to the network. How sustainable is the network in the face of loss of one or more stakeholders? Borrowing from the literature of digital networks, damage to the network can be random, such that all parts of the network are equally like to receive damage, or purposeful, where. the network structure is known, and the loss is targeted to the location in the network where

minimum effort gives maximum damage. For a given network, one can test how vulnerable it is to both random and purposeful damage.

We looked at different measures of network resilience against purposeful and random damage for the four networks corresponding to project periods of CAMP1 and 2. In all the measures we determined the fraction of nodes that must be removed to make the network damaged (one or more nodes disconnected). To study the effect of random damage, we start with a network and remove one randomly chosen node at a time until the remaining network becomes disconnected and count the number of nodes removed. We repeat the procedure 1000 times for each of the 4 networks and report the average number of nodes that need to be removed to disconnect each of the networks. We compared the averages as percentages of the nodes in each study phase. To study the effect of purposeful damage, we sort the nodes in descending order of degree, and determine how many high-degree nodes need to be removed (a) one at a time, and (b) all at once, to make the remaining network disconnected. There are two ways to compute the degree of a node in these networks. We used the notion of weighted degree for assessing purposeful damage. We also checked for “bottle-necks” in the networks. A network is said to have a “bottle-neck” if there is a small set of edges in the network such that the network without these edges, splits into two or more sizable disconnected components. We used the “min_cut” function of the “igraph” package of the R software to obtain the minimum number of edges for each of the 4 networks that need to be cut off to make the networks disconnected. [36]

RESULTS

Network size and diversity: In CAMP1/2, there were 47 meetings held across 89

months. In total, 141 unique individual stakeholders participated in the projects. Stakeholders were affiliated with 29 different organizations of 6 types; stakeholders held more than 50 different institutional roles sorted into 7 role types associated with the CAMP projects. Participation of stakeholders increased across all project periods, whereas the diversity of partnership participation by the affiliation and role of stakeholders increased across the first three project periods and decreased slightly in the last project period. (Figure 1 A-C). [37] A complete listing of organizations and stakeholder's organizational roles is provided in Supplemental Table S1.

Visualization of the Social Network, Degree, Density, and Interactions

A network diagram was generated for each project phase. The networks increased in size, and the density of interactions increased among stakeholders across the successive phases of the projects (Figure 2). The interactions among individuals across different organization types also increased in successive project phases, with the greatest interactions among the stakeholders from the PBRNs and the Academic institutions in the second and third phases, and among Community Partners and the PBRNs in the last project phase. The participation of Community Partner affiliates, who were predominantly patients, appeared in the third project phase and grew in prominence in the last project phase.

Figure 1

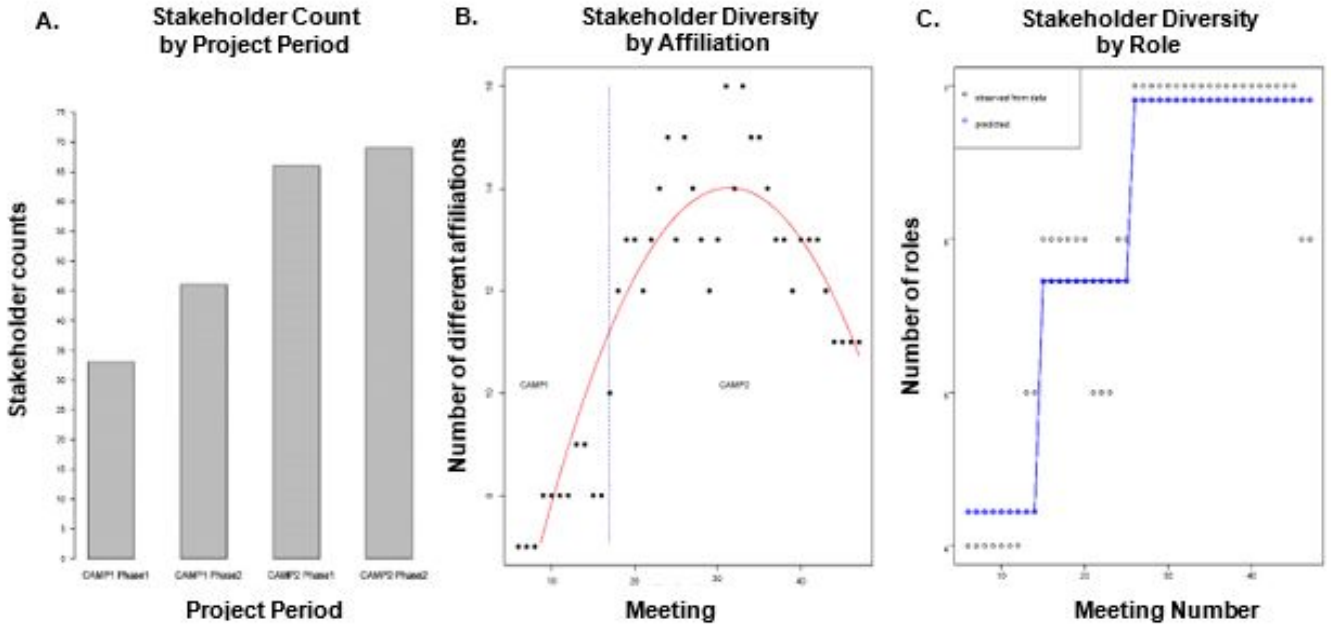
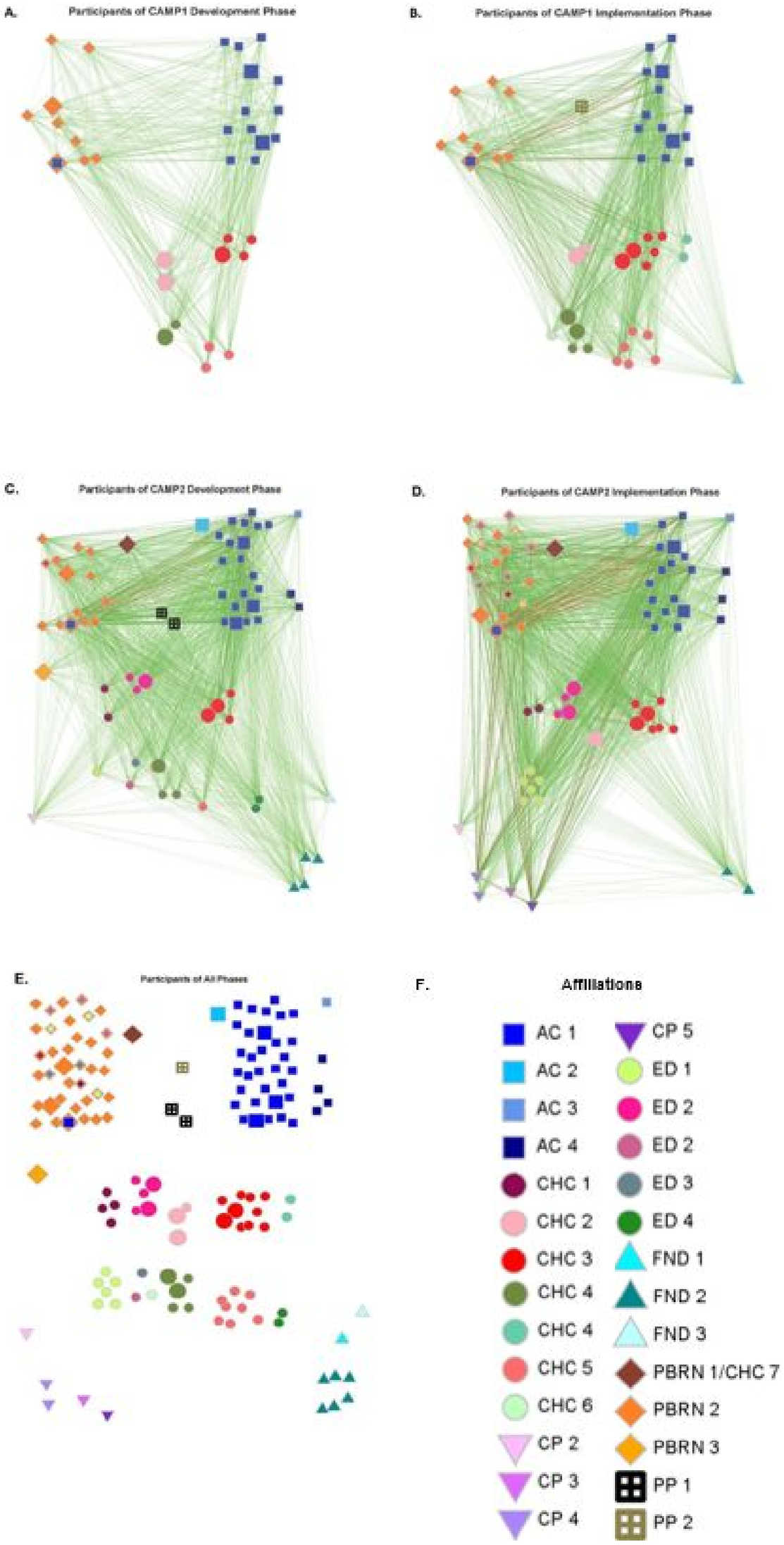


Figure 1 (A-C): Stakeholder counts and diversity. A. The number of stakeholders engaged in each phase of the project is shown for the four project periods. B. The number of different organizations (maximum 29) represented by the stakeholders who attended any one of the previous five project progress meetings is shown across the life of the project, shown by meeting number (1-47). C. The number of different major roles (7 types) fulfilled by stakeholders who attended any one of the previous five project progress meetings, across the life of the project. (Figure 1B and C). Min-cut (ref) was used to model the change in the diversity of affiliations using (Figure 1B) and tree regression[36] to model change in diversity of roles, based on the attendance at a given and the prior 5 meetings.

Figure 2


A.
Participants of CAMP1 Development Phase
B.
Participants of CAMP1 Implementation Phase
C.
Participants of CAMP2 Development Phase
D.
Participants of CAMP2 Implementation Phase
E.
Participants of All Phases
F.
Affiliations
AC 1
AC 2
AC 3
AC 4
CHC 1
CHC 2
CHC 3
CHC 4
CHC 4
CHC 5
CHC 6
CP 2
CP 3
CP 4
CP 5
ED 1
ED 2
ED 2
ED 3
ED 4
FND 1
FND 2
FND 3
PBRN 1/CHC 7
PBRN 2
PBRN 3
PP 1
PP 2

Legend: Figure 2 (A-F) Visualization 1: **Interactions among stakeholders according to their organizational affiliation type.** The social network analysis for each of four project phases is visualized using Gephi software. Panels represent the social network for stakeholder interactions during CAMP1-Development (A), CAMP1-Implementation (B), CAMP2–Development (C) and CAMP2-Implementation (D). Panel E shows all stakeholders in the network. Panel F is the key. Each shape (node) represents an individual stakeholder. The specific shape indicates the individual's affiliation to a type of organization (◆=Practice-Based-Research-Network(PBRN); ■=Academic Institution (AC); =Community Health Center (CHC); ▲=Funder (FND); ▼= Community Partner (CP; ☒ =Private Partner(PP)). The color of the node indicates the specific organization the individual is affiliated with (Key: Panel F). Larger size nodes indicate stakeholders fulfilling leadership roles. A second colored shape inserted within a given node indicates the individual's affiliation to a second organization. Lines (edges) between two given nodes indicate that the two stakeholders were in attendance for at least one meeting together. The number of meetings the two stakeholders attended together defines the "weight" of the edge shown on a green (least interaction) to red (most interaction) color scale. The arrangement of nodes on the network is intentional, with organizations of the same type placed together to make apparent the interactions among the stakeholders from different types of organizations.

Interactions at the stakeholder level:

To look more closely at how stakeholders' level of engagement changed across the project periods, we performed Two-sample Wilcoxon tests to compare degree distributions of the stakeholders across the four different project phases. In the network from the first project there

was a higher density of stakeholders with low degree representing little interaction with others in the network. As the project progressed, the number of stakeholders with very low degree declined, and level of stakeholder degree was more evenly distributed throughout the partnership. The change in distribution of degree was significant from CAMP 1 Development to CAMP 1 Implementation (p-value = 0.014), and from CAMP1 Implementation to CAMP2 Development (p-value = 0.009). Stakeholder interactions overall did not further increase significantly from CAMP2 Development to CAMP2 Implementation (p-value = 0.10). (Supplemental Figure S2)

Interactions among role groups

To identify patterns of increasing interactions among stakeholders, we analyzed the total interactions among stakeholders according to their role groups for each of the project periods and visualized the data using a heatmap (Figure 3). Interactions increased significantly among many role groups across the life of the project. The first project phase (CAMP1 Development, C1-D) had too few time points to test for significant change. In the transition from the second to the third project phase, CAMP1-Implementation to CAMP2-Development, the interactions between Scientists (Sci) and Research Team-Other (RTO), and those between the RU-CCTS Community Engagement core members and Research Team-Other stakeholders increased significantly, with p-values 0.04 and 0.003, respectively. From the third project period (CAMP2-Development) to the last period (CAMP2 Implementation), interactions increased significantly between Community Members (patients) and every other group (except administrators), and between the Recruiters/Community Health Workers and every other group (except administrators) (all p-values<0.005). An alternate visualization of the data is provided. (Supplemental Figure S2).

Figure 3: Interactions among different stakeholders by role group across the CAMP1/CAMP project periods

Interactions Among Partnership Stakeholders by Role Across Project Periods																												
	RU-CCTS				Admin				Scientist				Clinician				RTO				Rec/CHW				CoMember			
	C1-D	C1-I	C2-D	C2-I	C1-D	C1-I	C2-D	C2-I	C1-D	C1-I	C2-D	C2-I	C1-D	C1-I	C2-D	C2-I	C1-D	C1-I	C2-D	C2-I	C1-D	C1-I	C2-D	C2-I	C1-D	C1-I	C2-D	C2-I
RU-CCTS	28	76	180	159	0	5	49	45	23	134	250	186	85	255	263	270	65	171	**356**	**382**	0	0	17	**242**	0	4	8	**161**
Admin	0	5	49	45	0	0	6	11	0	3	22	18	0	5	49	37	0	5	51	48	0	0	2	32	0	0	0	7
Scientist	23	134	250	186	0	3	22	18	6	35	64	44	35	178	146	148	33	117	**203**	202	0	0	8	**112**	0	6	3	**82**
Clinician	85	255	263	270	0	5	49	37	35	178	146	148	48	157	90	87	88	209	251	292	0	0	13	**167**	0	6	2	**114**
RTO	65	171	**356**	**382**	0	5	51	48	33	117	**203**	202	88	209	251	292	31	61	152	171	0	0	22	**243**	0	8	5	**164**
Rec/CHW	0	0	17	**242**	0	0	2	32	0	0	8	**112**	0	0	13	**167**	0	0	22	**243**	0	0	1	58	0	0	0	**102**
CoMember	0	4	8	**161**	0	0	0	7	0	6	3	**82**	0	6	2	**114**	0	8	5	**164**	0	0	0	**102**	0	1	0	25

Figure 3: Inter-disciplinary interactions among CAMP1/CAMP2 stakeholders according to their project role over time. This figure illustrates for each project period, the number of interactions among stakeholders fulfilling different roles in the studies, regardless of their specific organizational affiliation. Project periods are indicated for each set of group-group interactions: C1-D = CAMP1 Development; C1-I = CAMP1 Implementation; C2-D = CAMP2 Development; C2-I = CAMP2 Implementation. The seven stakeholder roles are listed both as column and row headers to create a matrix of all possible interaction dyads. The roles are RU-CCTS = Rockefeller University Center for Clinical Translational Science, Community and Collaboration Core); Admin = Administrator); Scientist, Clinician = Clinician/Clinician Researcher, RTO = Research Team-Other; Rec/CHW = Recruiter/Community Health Worker); and CoMember = Community Member. The value in each cell is the number of meeting interactions in common (sum of edge weights) between stakeholders fulfilling the roles named in the intersecting column and row. Cells are conditionally formatted to shift from light yellow (lowest value in the table) to dark green (highest value in the table) for ease of visualization of trends. Values that represent a statistically significant change in level of interactions from the prior period are shown with **bold text and borders**. See text for specific p-values.

Centrality:

We conducted eigenvector centrality analyses to understand which stakeholders were most central to the network. We ranked stakeholders from highest to lowest eigenvector centrality. The 15 stakeholders with the highest eigenvector centrality are shown by affiliation type and leadership status for each project period (Table 1). The arbitrary cut-off was chosen to simplify presentation with the same number tracked across all phases. Individuals with leadership roles were prominent among the top 15 during the development phases of the two projects, CAMP1 (n=6) and CAMP2 (n=5), compared to the implementation phases (CAMP1 n=5, CAMP2 n=2). Seven of the 15 highest centrality stakeholders at the inception of the CAMP1/2 projects were from the CHCs, and 4 among them were CHC leadership. Over the life of the project, the number of stakeholders among the centrality Top 15 who were in non-leadership roles rose across the four project periods (n= 9, 10, 10, 13 respectively). In the last project phase, in

parallel with community members' statistically significant increase in interactions with all other role types (Table 1), the centrality of three community member/patients rose to be among the top 15. Three CHC-based stakeholders hired by the PBRN to support engagement at the CHC sites in the Recruiter/CHW role, also rose in centrality to rank among the top 15.

Table 1

Rank	CAMP 1 Development		CAMP 1 Implementation		CAMP 2 Development		CAMP 2 Implementation	
	Affiliation	Score	Affiliation	Score	Affiliation	Score	Affiliation	Score
1	PBRN/Academic -RU-CCTS-L	1.00	PBRN	1.00	PBRN	1.00	PBRN/Academic -RU-CCTS-L	1.00
2	Academic - RU-CCTS	1.00	PBRN/Academic -RU-CCTS-L	1.00	PBRN/Academic-RU-CCTS-L	0.98	PBRN	0.97
3	PBRN	1.00	PBRN-L	0.88	Academic - RU-CCTS-L	0.97	PBRN	0.90
4	CHC - L	1.00	Academic	0.88	Academic	0.95	Academic	0.88
5	CHC	1.00	Academic	0.82	PBRN	0.94	Academic - RU-CCTS	0.78
6	CHC - L	1.00	Academic - RU-CCTS-L	0.79	Academic	0.90	Academic - RU-CCTS	0.76
7	Academic	0.83	CHC	0.77	Academic - RU-CCTS	0.86	Community Partner	0.75
8	Academic - RU-CCTS-L	0.83	Academic - RU-CCTS	0.68	Academic	0.86	Community Partner	0.72
9	Academic - RU-CCTS-L	0.83	Academic - RU-CCTS	0.63	Academic - RU-CCTS	0.84	CHC/PBRN	0.67
10	CHC	0.64	CHC	0.59	CHC-L	0.78	Community Partner	0.67
11	PBRN	0.45	CHC	0.54	Academic	0.78	PBRN	0.66
12	PBRN	0.45	CHC-L	0.52	Academic - RU-CCTS-L	0.71	Academic - RU-CCTS-L	0.66
13	CHC	0.45	CHC-L	0.47	Academic	0.60	Academic	0.62
14	CHC	0.45	Academic	0.45	CHC	0.56	CHC/PBRN	0.56
15	CHC- L	0.45	Academic	0.44	CHC-L	0.53	CHC/PBRN	0.55

Table 1: Eigen Centrality scores in the CAMP1/CAMP2 Social Network. The stakeholders with the top 15 Eigen Centrality scores are shown for each of the CAMP1/CAMP2 project periods. Eigen centrality is scored between 0-1; values closer to 1 indicate higher centrality. Individual stakeholders are represented by their organization's affiliation type, **PBRN: Practice-Based-Research-Network; CHC: Community Health Center/Federally Qualified Health Center/Community Practice/Hospital; Academic; Community Partner.** When stakeholders have dual affiliations, both are listed. Stakeholders with leadership roles at their institutions and/or in the project are designated "L." Individuals affiliated with the Community and Collaboration Core of the Rockefeller University Center for Clinical Translational Science are designated "RU-CCTS".

Network resilience

The Force Vector analysis of the project period networks shows the level of interaction between any two stakeholders during that period as the relative closeness between those nodes (Figure 4A-D). In the two project development phases (Figure 4A and 4C), the center of the network appears looser compared to the two project implementation phases (Figure 4B and 4D), wherein the center of the network is denser. Across time, stakeholders move toward the center of the network (more interactions) and additional stakeholders are added at the periphery with newer, weaker interactions. No structural holes (isolated nodes or clusters) are apparent in the

social network at any of the project phases. There are no solitary edges that link sections of the network that would otherwise be disconnected. The networks are highly connected.

Figure 4

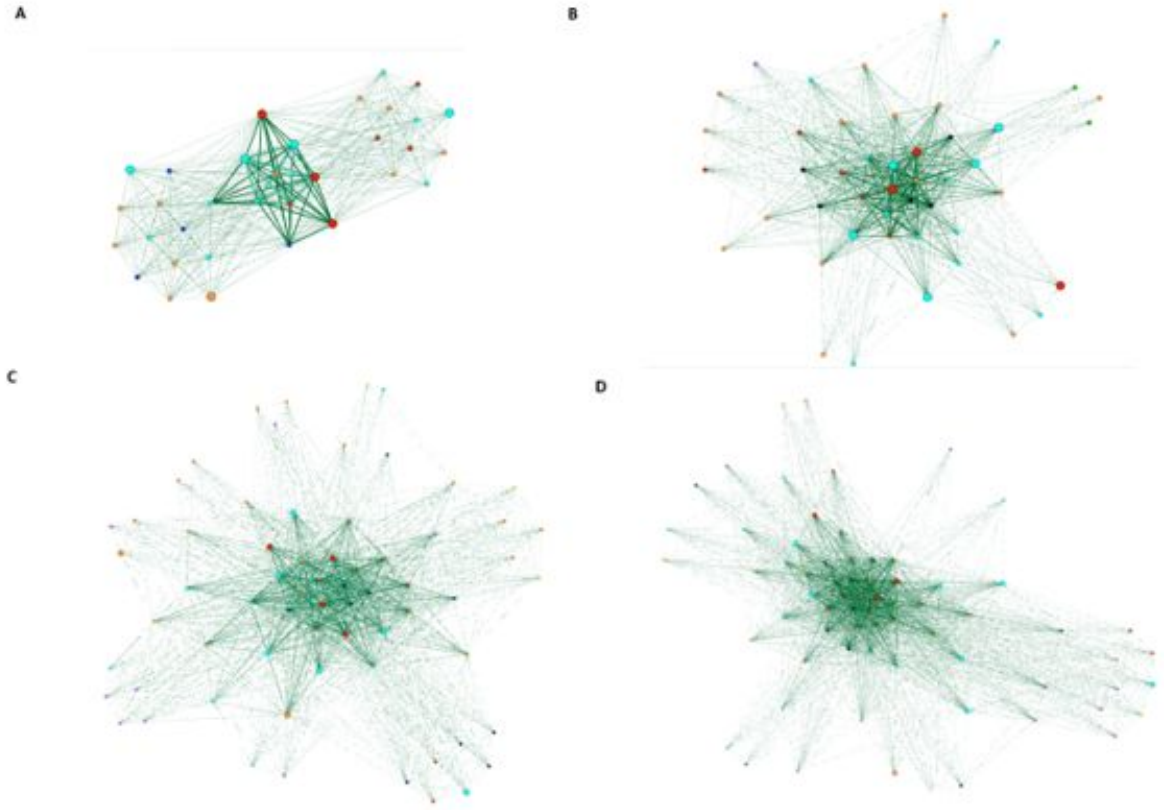
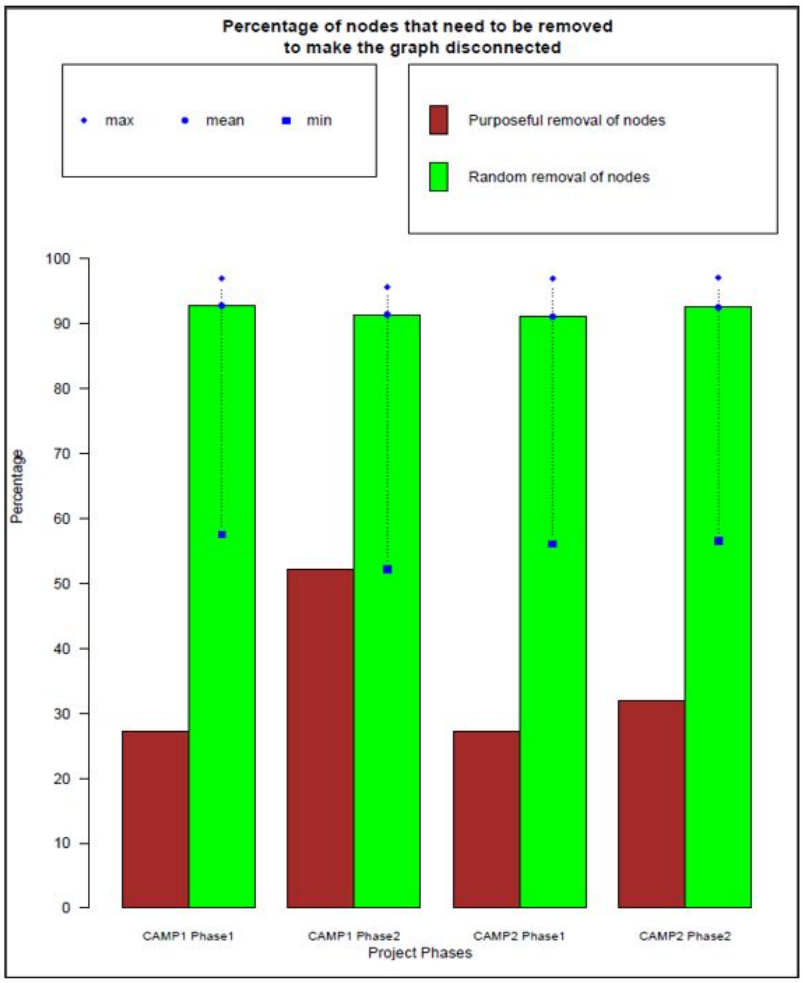


Figure 4 (A-D) Visualization 2, Force Vectors visualization. The force vector network for each project period was generated using the ForceAtlas2 algorithm of the Gephi software [2] with the following settings: Lin-log mode (see [3]), Edge weight influence parameter=1, Gravity=0.2, Scaling=1, and Prevent Overlapping mode -enabled. Projects phases are CAMP1 Development (A), CAMP1 Implementation (B), CAMP2 Development (C) and CAMP2 Implementation (D). Stakeholders are represented by nodes (shapes); the color of the shape reflects the role of the individual: ● Research Team-other (RTO); ● Clinician/Clinician researcher (Clin); ● The Rockefeller University Center for Clinical and Translational Science (RU-CCTS); ● Scientist (Sci); ● Administrator (Admin); ● Recruiter/Community Health Worker (Rec/CHW); ● Community Member (Comm). The network for each project period is independent of the other periods. Nodes are viewed as charged particles and edges are viewed as springs, and simulate the effect of (i) repulsion forces between all pairs of nodes (charged particles) that drive the nodes apart, and (ii) attraction forces between nodes connected by edges (springs) that pull them to each other.

Vulnerability

The network was relatively resilient against damage (loss of stakeholders) across each of the project phases (Figure 5). Each of the 4 networks was minimally vulnerable to the random removal of up to 90% of stakeholders. When subjected to purposeful one-at-a-time damage to the weighted networks, as targeted removal of stakeholders with a high degree, the implementation phase of CAMP1 was the least vulnerable – 50% of stakeholders could be removed before the network fragmented -- compared to the development phase of CAMP1 and both phases of CAMP2 (each vulnerable at 28-30% removal).

Figure 5



Legend: Figure 5. Vulnerability of the network to loss (removal) of stakeholders was modeled across the project phases using algorithms for random removal of stakeholders (green) or purposeful removal of highly interactive members of the network (red). Removal was conducted 1000 times to generate the average percentage (y axis) of stakeholders removed before the network fragmented. Variance across the 1000 replicates is shown.

Associations of social network measures with Study Milestones

Recruitment, enrollment, retention, and average degree in the network of each site's clinician stakeholders all varied widely across sites in both projects. The numbers of participants recruited, enrolled, and retained at each site were plotted against the average clinician degree for each study site (Figure 6). Overall, site recruitment and enrollment were positively associated with average clinician stakeholder degree in the network. The two sites that were outliers for recruitment and enrollment, ED1 and ED3, had extremely proficient recruiters. Retention was not associated with clinician degree in the partnership network.

Figure 6

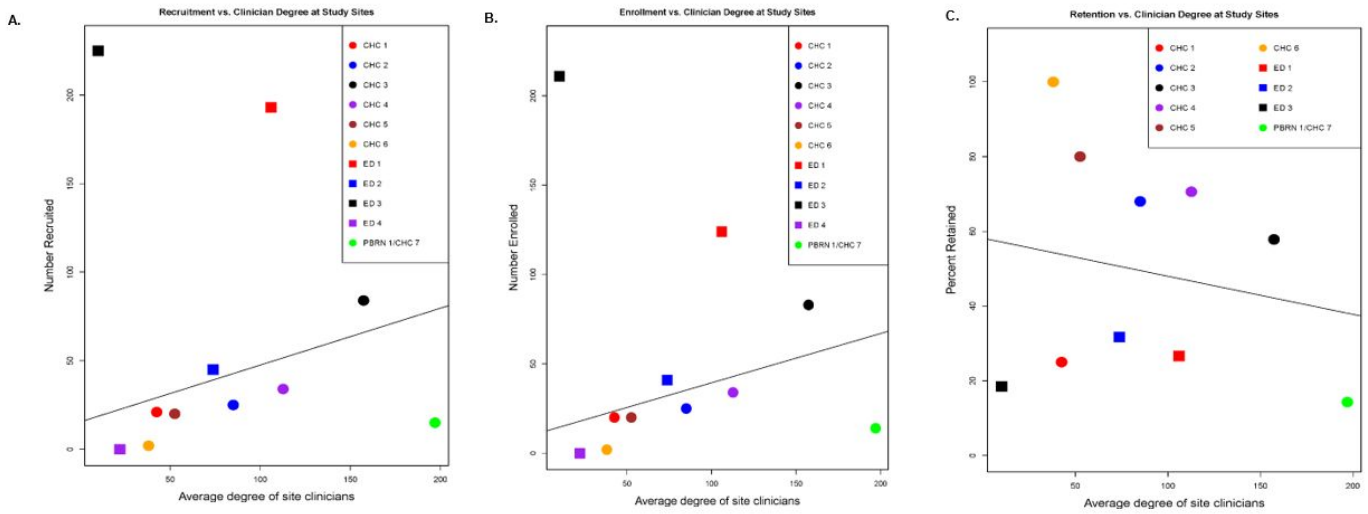


Figure 6 (A-C). This figure plots the achievement of CAMP1 and CAMP2 study milestones at each study site, versus the average degree in the network of the clinicians affiliated with the site. Panel A: Recruitment - Number of participants recruited at each site versus average site clinician degree; Panel B: Enrollment - Number of participants enrolled (signing informed consent) versus average clinician degree; Panel C: Retention - percentage of enrolled participants retained through defined study endpoints, versus the average clinician degree at the site. Sites are Community Health Centers, Federally Qualified Health Centers and Community Practices (CHC), a Practice-Based Research Network (PBRN) contributing two CHC sites (PBRN/CHC), and Emergency Departments (ED).

DISCUSSION

The CAMP1/CAMP2 collaborators formed a successful, sustainable community-academic research partnership that completed two large extramurally funded CEnR/CER research projects. The social networks formed by the CAMP1/CAMP2 partnership grew in size, degree

and complexity across over the life of the projects. Visualizations of the social network revealed increasing connectedness among organization types, partnership roles, and individuals over time, with no structural holes in the network. Specifically, the interactions of the Community Members with other role groups, and of the Recruiter/Community Health Workers with almost all other groups increased significantly during the fourth project period reflecting the engagement of communities, patients and diverse stakeholders together in research across the life of the project. The rise in centrality of Community Members through the CAMP2 project to be among the be among the top 15 for centrality, is another a tangible measure of participation in the project partnership.

The interactions among academic/scientists and community/clinicians were sustained from beginning to end of the CAMP1/CAMP2 projects. The success of this ongoing engagement is evident in publications across the translational spectrum illuminating molecular findings,[23, 38] clinical observations,[20, 22] and aspects of implementation[25, 39], and demonstrates the explicit intention of the RU-CCTS/CDN to foster engagement of community members and scientists together early in the design and execution of translational research to create Full Spectrum Translational Research Teams. In CAMP1, the Community Clinicians from CHCs were brought to the partnership through their relationship to the CDN PBRN and formed the initial critical bridge between the community and the scientists in this network. In CAMP2 the networks involved patients as the direct representatives of the community, as well as community health workers and non-academic partners, all strengthening the bridges between community and academic partners, and realizing RU-CCTS/CDN and PCORI principles of engagement. This SNA of the CAMP partnerships adds to the much-needed evidence base demonstrating the network characteristics resulting from an effective approach to building equitable community-academic partnerships. The SNA characterizes a successful partnership

network for research which simultaneously addresses basic science questions of T1/T2 early phase translational research[40] within the context of clinical effectiveness studies of later translational phases (T3/T4) while examining outcomes that matter to both clinicians and patients.

Vulnerability analysis revealed the partnership network to be resilient. The apparent resistance of the network to random stakeholder loss reflects a strength of centralized progress meetings that sustain connection to all stakeholders. Some level of redundancy within the partnership, such engagement of many CHC sites and overlapping expertise from multiple institutions may have added to resilience.

There are several limitations to the study. We inferred interactions from attendance at regularly scheduled progress meetings, relying on knowledge of the highly interactive CEnR-Nav engagement method and qualitative assessments reported elsewhere.[18] The network analysis did not account for interactions that occurred outside of progress meetings that may have contributed to network cohesion or to the creation of subnetworks we could not detect using this approach. It might have enriched the analysis to have collected qualitative data or validated assessments from the stakeholders specifically addressing their engagement experiences and perceived partnership strengths and weaknesses. During CAMP1 planning and conduct we discussed collaboration assessment tools with the stakeholders and distributed an assessment tool which stakeholders uniformly did not complete. In subsequent discussion, partners indicated they were eager to collaborate, but preferred not to be studied.

This SNA was conducted retrospectively. Lessons learned that might be applied prospectively to an evolving partnership include: 1) Data routinely collected in the course of project operations – such as attendance data, meeting notes, stakeholder characteristics and study milestones--

can provide a rich source of information about the partnership, to complement or guide selective use of more labor-intensive qualitative assessments. Prospective planning and the use of structured tools for routine data capture improve data quality. 2) Gaining stakeholder enthusiasm for the use of partnership assessment measures is important and could extend and validate network insights. 3) Different graphical visualization methods of the partnership network can be used to reveal different features of a network, such as patterns of interactions, structural gaps, or critical bridges among network components; 4) Centrality analyses can be helpful to identify stakeholders who may be facing barriers to full participation in the network; 5) Assessing and managing network vulnerability during an evolving partnership could improve network cohesion. Network relationships that form bridges across organizations types, such as the dual affiliations of PBRN/Academic partners, the role of PBRNs in facilitating research at CHCs, or the strategic embedding of PBRN/CHC stakeholders as recruiters, can help to keep the network connected.

The social network of the CAMP1/2 research partnership grew in size and complexity through the life of two major externally funded projects spanning eight years. SNA analysis afforded insights into the robustness of the network and revealed the course of specific group-group interactions over time. Scientists, RU-CCTS leadership, clinicians and CDN-PBRN members were engaged early in the study development and conduct of CAMP1. The interactions of community partners with most other stakeholder groups increased significantly during the implementation of CAMP2, and community partners rose to have high network centrality by study completion. SNA provided tangible evidence of realization of NCATS, RU-CCTS and PCORI principles of engagement. Lessons from this SNA could be applied to other partnerships mid-course to gain valuable insights.

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Supplemental Table S1-A

A. Institutional Roles of Stakeholders fulfilling specific roles in the Social Network Analysis

Administrator (Admin)
- Admin- Medical
- Admin- Research
- Program Officer

Scientist (Sci)
- Head of Laboratory (HOL)/Department Chair
- Research Assistant
- Scientist- Early Career
- Scientist- Clinical Scholar
- Scientist- Other

Clinician/ Clinician Researcher (Clin)
- Associate Medical Director*
- Chief Medical Officer*
- Chief of Clinical Strategy and Research*
- Clinician- Doctor of Medicine (MD)/Nurse Practitioner (NP)/Physician Assistant (PA)
- Clinician- Nurse
- Director of Research*
- Medical Director*Medical Site Director of Internal Medicine*
- Physician*
- Professor* (Infectious Diseases, Pharmacotherapy)
- Program Director- Translational Science Program*
- Scientist- Clinical Scholar
- Scientist- Early Career
- Scientist- Other
- Vice President- Quality Improvement and Population Health*

Community member (Comm)
- Grassroots community partner
- Grassroots– patient
- Volunteer

Recruiter/Community Health Worker (Rec/CHW)
- CHW- Trainer
- Community Health Worker (CHW)
- Research Assistant
- Recruiter

Research Team—Other (RTO)
- Commercial Partner- Collaborator
- Director of Research and Evaluation at Practice-Based Research Network (PBRN)*
- E-learning Staff
- Information Technology
- Intern
- Medical Assistant
- Medical Student
- Program Director*
- Research Assistant
- Project Manager
- Scientist- Social Network Analysis
- Scientist- Other
- Site Student
- Vice President for Clinical Affairs*

RU-CCTS (Rockefeller University Center for Clinical Translational Science)
- Administrative Director*
- Biostatistician
- Community Engagement Core Co-Director, Associate Professor*
- Community Engagement Core Co-Director, Professor *
- Community Engagement Specialist
- CTSA Principal Investigator (PI), Vice President, Professor, HOL, Scientist*
- Information Technology
- President/Chief Executive Officer - PBRN,
- Scientist- Clinical Scholar, Other

* Leadership

Supplemental Table S1-B

B. Organizations assigned to specific affiliation types in the Social Network Analysis*

Academic (AC)
- The Rockefeller University Center for Clinical Translational Science
- University of California, Irvine
- Washington State University
- Weill Cornell Medical Center

Practice Based Research Network (PBRN)
- ACCESS Community Health Network- Chicago
- Clinical Directors Network (CDN)
- South Texas Ambulatory Research Network (STARnet) & The University of Texas at San Antonio

Community Health Center/ Federally Qualified Health Center/Community Practice/Hospital (CHC)
- Brookdale Family Care Center
- Community Healthcare Network
- Coney Island Hospital
- Hudson River Healthcare
- Lincoln Hospital
- Lutheran Family Health Centers
- Lutheran Medical Center
- Manhattan Physician Group/AdvantageCare Physician
- Metropolitan Hospital Center
- Open Door Family Medical Centers
- Park Slope Family Health Center
- Urban Health Plan

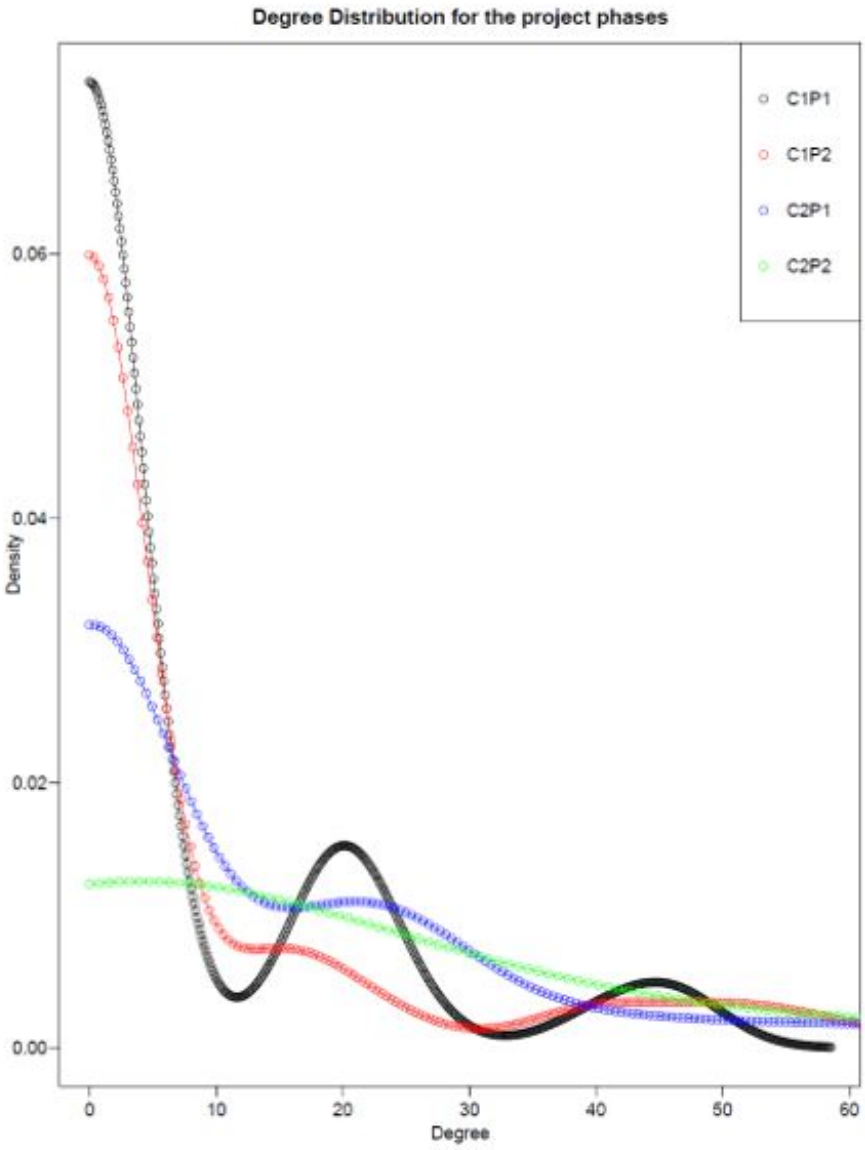
Community Partner (CP)
- Community Health Worker (CHW) Network of NYC
- Denny Moe's Superstar Barbershop
- Patient Stakeholder – Coney Island Hospital
- Patient Stakeholder -- Lutheran Family Health Center
- Patient Stakeholder – Metropolitan Hospital Center

Funder (FND)
- Agency for Healthcare Research and Quality (AHRQ)
- National Institutes of Health (NIH)
- Patient-Centered Outcomes Research Institute (PCORI)

Private Partners (PP)
- My Own Med (MOM)
- Visual Dx

*For some organizations, individual subsites are acknowledged here, whereas they are combined under one organization elsewhere in the manuscript. Thus, the total number of organizations may be slightly higher here.

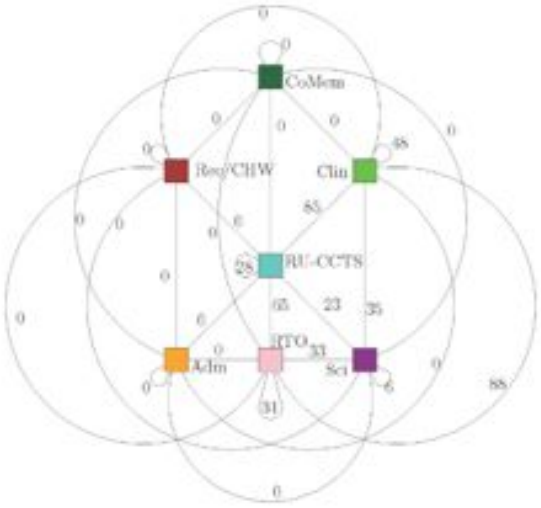
Supplemental Figure S1



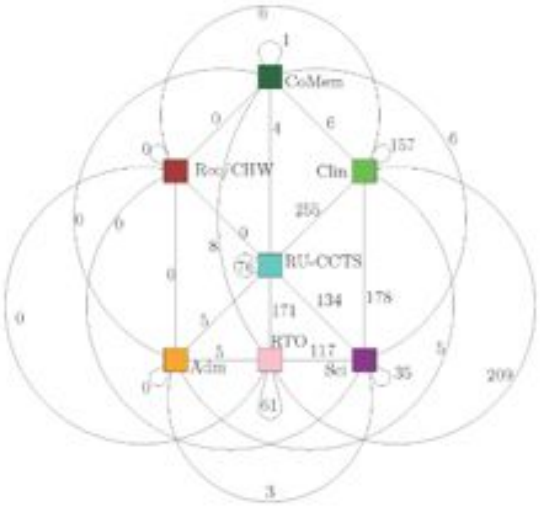
Supplemental Figure 1: Distribution of Degree. The stakeholders' degree in the network is shown for each of the project periods, CAMP1-Development (C1-D), CAMP1-Implementation (C1-I), CAMP2-Development (C2-D) and CAMP2-Implementation (C2-I). Density, on the vertical axis, reflects the proportion of all network members exhibiting the level of degree shown. Two-sample Wilcoxon test were performed; the distribution of degree changed significantly from C1-D to C1-I, (p=0.014) and from C1-I to C2-D (p-value =0.0009).

Supplemental Figure S2

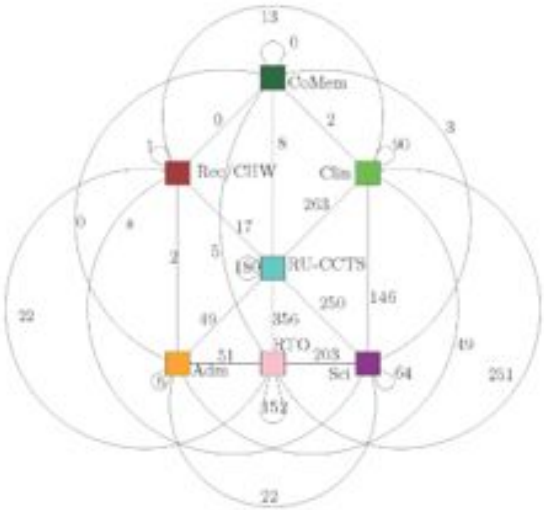
A. CAMP 1 Development



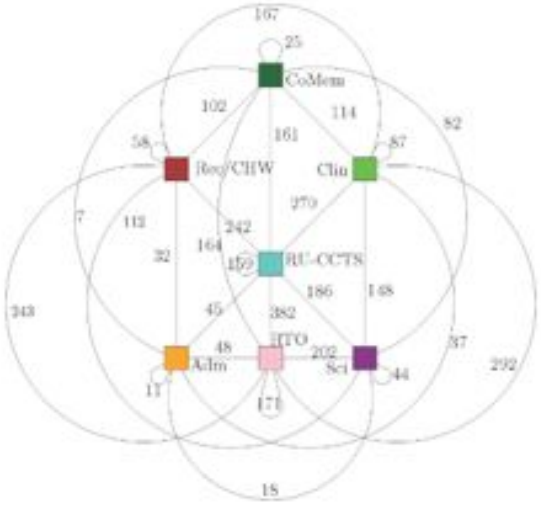
B. CAMP 1 Implementation



C. CAMP 2 Development



D. CAMP 2 Implementation



Supplemental Figure 2 – Interactions by Role. For each of the four project periods, diagrams show the edge number of interactions in the social networks formed by interactions between stakeholders fulfilling each Role type, in all possible combinations. Roles types are: Community Members (CoMem), Clinicians (Clin), Recruiter/Community Health Worker (Rec/CHW), Rockefeller University Center for Clinical Translational Science core members (RU-CCTS), Research Team Others (RTO); Scientists (Sci) and Administrators (Admin).