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Research Article

Pioneering the Transdisciplinary Team Science Approach: Lessons Learned from National Cancer Institute Grantees

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Abstract

The National Cancer Institute has been a leader in supporting transdisciplinary (TD) team science. From 2005-2010, the NCI supported Transdisciplinary Research on Energetic and Cancer I (TREC I), a center initiative fostering the TD integration of social, behavioral, and biological sciences to examine the relationships among obesity, nutrition, physical activity and cancer. In the final year of TREC I, we conducted qualitative in-depth-interviews with 31 participating investigators and trainees to learn more about their experiences with TD team science, including challenges, facilitating factors, strategies for success, and impacts. Five main challenges emerged: (1) limited published guidance for how to engage in TD team science, when TREC I was implemented; (2) conceptual and scientific challenges inherent to efforts to achieve TD integration; (3) discipline-based differences in values, terminology, methods, and work styles; (4) project management challenges involved in TD team science; and (5) traditional incentive and reward systems that do not recognize or reward TD team science. Four main facilitating factors and strategies for success emerged: (1) beneficial attitudes and beliefs about TD research and team science; (2) effective team processes; (3) brokering and bridge-building activities by individuals holding particular roles in a research center; and (4) funding initiative characteristics that support TD team science. Broad impacts of participating in TD team science in the context of TREC I included: (1) new positive attitudes about TD research and team science; (2) new boundary-crossing collaborations; (3) scientific advances related to research approaches, findings, and dissemination; (4) institutional culture change and resource creation in support of TD team science; and (5) career advancement. Funding agencies, academic institutions, and scholarly journals can help to foster TD team science through funding opportunities, institutional policies on extra-departmental and cross-school collaboration, promotion and tenure policies, and publishing opportunities for TD research.

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ABBREVIATIONS

ISBNPA**:** International Society for Behavioral Nutrition and Physical Activity; NCI: National Cancer Institute; NIH: National Institutes of Health; PI: Principal Investigator; SciTS: Science of Team Science; TD: transdisciplinary; TREC I: Transdisciplinary Research on Energetics and Cancer I

INTRODUCTION

Over the past several decades, investigators, academic institutions, and funding agencies have been increasingly investing in cross-disciplinary team science initiatives with the aim of producing more comprehensive and innovative science that can effectively address important real-world problems [1,2]. Cross-disciplinary team science brings together investigators, community partners, and translational collaborators from multiple disciplines and fields to integrate concepts, theories, methods and approaches drawing from a breadth of expertise relevant to the scientific problem space [3]. This approach is a promising response to the increasing specialization and fragmentation of scholarship and the "data deluge" resulting from the rapid proliferation of scholarly knowledge across diverse fields [4].

The cross-disciplinary research approach can be conceptualized along a continuum of increasing disciplinary integration, with unidisciplinary research at one end of the continuum and transdisciplinary (TD) research at the other end [5,6]. Multidisciplinary and interdisciplinary research refer to increasing levels of disciplinary integration that fall between unidisciplinary and TD research. Elsewhere, we define TD research as "an integrative process whereby scholars and practitioners from both academic disciplines and non-academic fields work jointly to develop and use novel conceptual and methodological approaches that *synthesize and extend* discipline-specific perspectives, theories, methods, and translational strategies to yield innovative solutions to particular scientific and societal problems" [3]. This definition highlights the goals not only to synthesize approaches from the contributing disciplines, but also to extend beyond these origins to produce *new* approaches that yield scientific innovations and findings with practical relevance to solving real-world problems.

There is evidence that successful TD team science increases research productivity [7], yields more rapid and broader dissemination of research findings across the scholarly literature of multiple disciplines and fields [8], and produces highly significant scientific outcomes and practical applications [9]. Yet the approach also introduces unique challenges, including the added time and effort needed for communication with more diverse group of collaborators [2,10]; conflicts stemming from the varied goals, values, and implicit assumptions that collaborators from multiple disciplines and fields bring to the research endeavor [2,11]; competing obligations to one's home discipline/department [12]; and perhaps not unsurprisingly, a delay in productivity that likely results from the increased "start-up" time needed for TD teams to overcome these and other challenges [3,6,7,13,14].

Over the past 15 years, the National Cancer Institute (NCI) of the National Institutes of Health (NIH) has supported TD team science with the goals of catalyzing innovation and accelerating scientific progress. It has funded multiple large initiatives supporting TD research centers addressing major challenges relevant in fighting cancer, including tobacco use, cancer communication, health disparities, and the relationship between obesity and cancer [15- 19]. The NCI has simultaneously supported an internal Science of Team Science (SciTS) team that has conducted improvement-oriented evaluation of these TD center initiatives and generated new knowledge about the processes and impacts of TD team science, as compared to traditional research approaches [2,6,7,20-23].

In 2005, the NCI launched Transdisciplinary Research on Energetics and Cancer I (TREC I), a five-year, $54 million initiative focused on addressing the growing epidemic of overweight and obesity in the U.S., and its relationship to cancer. The goal of TREC Iwas to foster the TD integration of social, behavioral, and biological sciences to address obesity and overweight, physical inactivity, and poor diet within a cancer prevention and control context. From 2005-2010, TREC I funded four research centers (located at Case Western Reserve University, Fred Hutchinson Cancer Research Center, University of Minnesota and University of Southern California) to conduct research on cellular mechanisms, genetics, physiology, behavior, and socio-environmental influences using diverse approaches including animal models, human subjects, population data, and environmental data. It also funded an independent coordination center, located at the Fred Hutchinson Cancer Research Center. In 2011, the TREC initiative was renewed for another five years as "TREC II", with support for research centers at four different institutions, and continuing support for the original coordination center. The present study focuses on TREC I.

Examples of TREC I supported TD integration highlight the novelty of this approach. One TREC I supported study identified a statistically significant association of short duration and poor quality of sleep with colorectal polyps, which have the potential to become cancerous [24]. Another TREC I supported study found that participation in a 12-month exercise intervention led to increases in aerobic exercise and aerobic fitness that in turn decreased oxidative stress (which is closely linked to inflammation and cancer), even with minimal changes in body mass and composition [25]. Both of these studies integrated approaches from distinct fields in ways that had not been done before, producing innovative findings. The second study involved collaboration across two of the four TREC I supported research centers.

The TREC I initiative was designed to facilitate TD team science within and across the research centers, in order to assist in the maximal integration of expertise across research topics. Each research center was required to: (1) implement three or more primary research subprojects, each led by a senior scientist, similar in size and scope to a traditional NIH grant (R01), that together addressed multiple "levels" of science (e.g., mouse models, clinical trials, epidemiology); (2) establish shared administrative, statistical, and training infrastructure (referred to as "cores") to support science conducted at the center; (3) provide funds for "developmental pilot projects" consisting of small, short-term, yet highly innovative additional TD research

projects conducted by teams composed of collaborators within or across centers; (4) collaborate with other TREC I research centers, including but not limited to participation in cross-center working groups focused on shared areas of interest (e.g., nutrition assessment, biomarkers, and environmental influences); and (5) provide training and career development opportunities for new and established investigators.

TREC I provided additional support for cross-center collaboration via a number of structural elements, specifically: (1) the independently funded coordination center, that facilitated cross-center collaboration via communications, technological, and infrastructure support; (2) monthly teleconferences of the TREC I Steering Committee, consisting of the directors of the four research centers and coordination center, and the NCI TREC Scientific Program Director; (3) semi-annual grantee meetings; and (4) professional development and training opportunities including webinars, travel support for conferences, and travel support for short-term training with experts in other disciplines or fields to aid in efforts to pursue new TD research directions.

In the first year of TREC I, a comprehensive evaluation was launched in order to learn more about the processes and outcomes of the initiative, given its unique requirement for TD team science and structural elements supporting the approach (For examples of findings, see 22, 23 and 26). The final activity that fell under this evaluation was a set of in-depth one-on-one interviews with TREC I participants, the results of which are reported in this paper.

The NCI SciTS team, NCI program staff, and the TREC I Evaluation Working Group recognized that TREC I grantees were pioneers in using the TD team science approach in the obesity and cancer research fields, and in scientific research more broadly, whose lessons learned could benefit other investigators. They also wanted to learn more about TD team science processes and impacts in the context of a funding initiative such as TREC I that included structural elements expressly designed to facilitate TD team science. These interviews were conducted to document TREC I participants' perspectives on lessons learned about engaging in TD team science as well as the broad impacts of TD team science conducted in the context of TREC I.

METHODS

Sampling Strategy

Our aim was to capture a wide range of perspectives and knowledge about engaging in TD team science. To accomplish this, we purposefully recruited interview participants representing each of the formal roles in TREC I: research center directors, principal investigators (PIs) of primary scientific subprojects, PIs of developmental pilot projects conducted within and across centers, directors of the training cores, staff of the biostatistics cores, the director and other staff of the coordination center, and trainees. Due to the limited number of persons in each of these roles, we reached out to all TREC I center directors, PIs of primary scientific subprojects, and the directors of each training core. We consulted with the TREC Scientific Program Director at the NCI to identify interview participants in the other roles who would have perspectives to share related to our research questions, based on having participated in TREC I for two or more years, and having been successful in engaging in TD team science. When individuals who we approached declined to participate, we asked them to recommendation colleagues who represented the same roles within TREC I.

Data Collection

Semi-structured in-depth interview guides were developed for individuals in each of the roles identified above. Each guide included a core set of questions relevant to all interview participants (Appendix A) and additional questions tailored to the individual's particular role in TREC I (See for example, 27-29). Interviews solicited perspectives on the challenges of using the TD team science approach, facilitating factors and strategies for success in cross-disciplinary and TD team science, the broad impacts of participating in TD team science in the context of TREC I, and recommendations for future TD team science initiatives. Members of the TREC I Evaluation Working Group provided input on drafts of the interview guides.

In-person one-on-one interviews were conducted by two members of the NCI SciTS team at the International Society for Behavioral Nutrition and Physical Activity (ISBNPA) Conference and the final TREC I semi-annual grantee meeting, held sequentially in June 2010. For individuals who were not available for in-person interviews, telephone interviews were conducted over the next 6 weeks. All interviews lasted about an hour.

Interview participants received a written disclosure statement describing the study goals, methods, risks and benefits, protections, anticipated products, and the voluntary nature of participation. All of the participants agreed to have their interviews audio-recorded. To thank them for their time, each participant received a $10 gift card for a national coffee shop. The NIH Institutional Review Board approved this study.

Data Analysis

The two interviewers used thematic coding and memo-writing to analyze the interviews [30]. They read all of the transcripts and developed thematic codes using a combined inductive and deductive approach based on the goals of the study and themes that emerged from the data [31]. In addition, short memos were created to summarize themes and interpretations that emerged as transcripts were read. Codes were applied to the transcripts using QSR International's NVIVO9 qualitative data management software. The coded text was then read to identify additional themes and interpretations of the data. Finally, coded text was reviewed in its original context to ensure that it had been interpreted correctly.

To validate the preliminary results of the analysis, the NCI SciTS team engaged TREC leadership at NCI, the TREC I Evaluation Working Group, and other TD team science experts in a series of discussions about the findings [32]. Feedback from these groups led to additional exploration of the transcripts for particular themes, and enhanced the interpretation of the findings.

RESULTS AND DISCUSSION

Sample

Interviews were conducted with 31 TREC I participants (Table 1).They included the director of each of the four TREC I

research centers; the PIs of one or two of the primary research subprojects at each research center; and PIs of developmental pilot projects conducted at all four research centers and across centers, who also held roles as primary research subproject PIs, junior investigators, and postdoctoral trainees. Interview participants also included biostatistics core staff at all four research centers and training core directors at three of the research centers. Some training core directors also held roles as research center directors or primary subproject PIs. Finally, interview participants included two or more trainees from each center and three staff of the TREC I coordination center, including the director.

From this diversity of experiences and perspectives, a number of prevalent themes emerged related to challenges participants encountered in their TD team science projects; facilitating factors and strategies for success that contributed to effective TD team science; and a variety of impacts of participating in TD team science in the context of TREC I, including impacts for participating scientists, their research, and their academic institutions.

Table 1: Interview Participants.

Research Center Directors (n = 4)
Primary Research Project Principal Investigators (n = 7)
Developmental Pilot Project Principal Investigators (n = 8)
Biostatistics Core Staff (n = 4)
Training Core Directors (n=3)
Trainees (n = 9)
Coordination Center Staff (n = 3)*

*Sum is greater than 31 because some individuals held multiple roles in TREC I. For example, some individuals led a primary research project and a developmental pilot project.

Challenges

Interview participants reported a range of challenges related to embarking upon and implementing research that aimed for TD integration. As a group, they encountered five main types of challenges over the course of their TD team science projects: (1) limited published guidance for how to engage in TD team science, when TREC I was implemented; (2) conceptual and scientific challenges inherent to efforts to achieve TD integration; (3) discipline-based differences in collaborators' values, terminology, methods, and work styles; (4) project management challenges involved in TD team science; and (5) traditional incentive and reward systems that do not recognize or reward TD research and team science.

Limited published guidance for how to engage in TD team science: Many interview participants commented that when TREC I started, there was no universally agreed-upon definition of TD research that distinguished it from other forms of cross-disciplinary research, little in the way of published guidelines specifying how to engage in TD team science, and a paucity of published examples of prior TD team science projects. As a result, a major challenge to their TD team science projects was the lack of knowledge about "what TD research is", "how to get there", and why to do it. Interview participants said that the lack of prior exemplars of successful TD research, in particular, contributed to the extended time it took for some TREC I participants to realize the value of TD integration, particularly with disciplines that were outside of the scope of their work until interactions were created via TREC I grantee meetings. This environment made it challenging for TREC I participants to conceptualize, plan for, embark upon, and implement TD research.

Conceptual and scientific challenges inherent to efforts to achieve TD integration: Interview participants reported that TD research introduced unique conceptual and scientific challenges compared to approaches closer to the unidisciplinary end of the research continuum. They described how the work of TD integration "stretched" their intellectual capacity more than typical scientific endeavors, and also stated that the challenges increased with the number of disciplines represented in a TD research team.

If someone is coming in with a research question that might be valid in a different field, but looks really strange to you, I think it's quite difficult to change the way you think, to integrate research questions that you're not familiar with.

Interview participants called the effort to achieve TD integration "challenging," "head-scratching", and "somewhat painful", as it required them to move outside their comfort zones, both by exiting their discipline-specific approaches, and by working toward TD integration and extension of discipline-based approaches. They reported that TD research required them to invest extra time and effort to learn about other disciplines and to figure out how to integrate approaches from different disciplines. One participant used the metaphor of having to speak in a foreign language all day to describe the effort required to engage in TD research.

If you have some ability to function in another language, then you can see how fatiguing it is. You're tired by the end of the day.

Discipline-based differences in values, terminology, and work styles: Participants described how working with collaborators with roots in other disciplines or fields introduced challenges stemming from discipline-based differences in values, terminology, and work styles. These included strongly held, yet often implicit, beliefs around what constituted interesting and valuable research questions, variables, and methods. A number of interview participants said that these differences were reflected in an implicit devaluation of other disciplines.

There seems to be this attitude present in nearly every discipline that what they do is better than what the guys do across the hall. And they've been practicing for years and years how to criticize other people's work, without actually knowing what they do.

Disciplinary differences also produced challenges for communication. Collaborators from different disciplines might use the same terms when referring to different things, different terms when referring to similar concepts or methods, or terms that were entirely unfamiliar to others. A final challenge was that work styles varied by discipline, particularly as related to the statistical methods typically used, traditions around whether research is conducted and published individually or in teams, and the meaning attributed to the order of authorship.

These differences could lead to misunderstandings or conflicts. Participants described how these discipline-based differences often were not well understood before embarking on a TD research collaboration and that only through collaboration with colleagues from other disciplines– and experiencing the resulting challenges – did they come to recognize, understand, and address these differences.

Project management challenges: Interview participants said that the added scientific complexity of TD team science had greater potential to produce holistic findings with practical relevance to real-world problems, but created added project management challenges. TD science that incorporated data at multiple levels of analysis, from multiple sources, oftentimes required new data management systems. In addition, because TD team science often involved more collaborators, management and coordination of the research team required greater investments of time and effort, and a unique set of expertise. Composing the research team; developing a unified mission, vision and shared research questions; and managing the team's collaboration during the course of the research project all were more labor intensive than in more traditional research approaches. In addition, a unique skill set was required to deal with the multiple departments, colleges, universities or organizations that were involved in large TD teams. One participant used the analogy of "steering a large ship" to describe the skill and effort involved in successfully managing a large TD research center.

While the TREC I initiative included unique structural elements to facilitate collaboration among the funded centers, many interview participants nonetheless identified important project management challenges specific to cross-institutional collaboration. Institutional differences in routines and procedures, including the ways that samples and data are collected (e.g., measures), stored (e.g., electronic databases), and analyzed (e.g., assays), as well as related work processes (e.g., long-standing laboratory contracts), posed practical challenges to cross-institutional collaboration. In addition, communication via email and phone was generally less effective and efficient than in-person communication, producing miscommunication at times, and slowing the research process.

A number of interview participants stated that their experience in TREC I had taught them that for cross-institutional collaborations to be effective, the anticipated benefits needed to outweigh the considerable time and effort required to overcome these challenges. They suggested that very highly valued scientific goals that could never be met without cross-center collaboration would be required to motivate the efforts needed to overcome key barriers to cross-institutional collaboration.

Traditional incentive and reward systems: Many interview participants also stated that traditional incentive and reward systems that recognize and reward individual research and discipline-based contributions, to the exclusion of TD research and team collaboration, were important challenges to TD team science. Participants described a lack of systems for cross-departmental and cross-school collaboration at their institutions, as well as attitudes and incentives encouraging faculty to work within their own departments/disciplines. Interview participants at various career stages expressed particular concern that traditional promotion and tenure policies that emphasize individual research and discipline-based contributions, and offer little or no guidance related to recognition for team collaboration or TD research, could deter junior scientists from engaging in TD team science during the formative early years in their careers.

In terms of scientific reward and incentive systems more broadly, interview participants cited limited funding opportunities for TD team science despite the growing popularity of the approach. They also said there continued to be challenges in publishing TD work, as many journals are discipline-specific. Another challenge was their colleagues' general lack of familiarity with TD research, in the context of peer review. Colleagues held decision making roles as institutional review board members, grant application reviewers, manuscript reviewers, and promotion and tenure review board members. Interview participants stated that colleagues' lack of familiarity with the TD approach could negatively impact these critical review processes, potentially adversely affecting the progression of one's research and career.

Facilitating Factors and Strategies for Success

While interview participants encountered important challenges related to the TD team science approach, they also described how they were ultimately successful in using the approach. They identified four key facilitating factors and strategies for success at the levels of the individual team members, team, research center, and TREC I initiative. These were: (1) beneficial attitudes and beliefs about TD research and team science among participating investigators;(2) effective team processes; (3) brokering and bridge-building activities by individuals holding particular roles in a research center; and (4) funding initiative characteristics that supported TD research and team collaboration.

Beneficial attitudes and beliefs: Interview participants described how particular attitudes and beliefs helped them and their colleagues successfully engage in TD team science. In particular, they cited the importance of an attitude that each discipline, including one's own, has strengths and weaknesses, as well as a belief that the TD approach adds value by leveraging the strengths of multiple disciplines. Equally important was a belief in the added value that can be generated by team-based research, including an appreciation for the unique skills, knowledge and resources that team members can bring to a research project. One interview participant whose colleagues described her as particularly successful in TD team science described her attitude as follows:

Trying to be open-minded about the limitations and advantages of what I do. Being very cognizant that everything that a given person does, including myself, in terms of our methodologies, or our technologies, has these specific advantages and roles and limitations. And, when approaching another person, recognizing that you have to be open to the fact that you could help enhance other people's work, and they could help enhance yours. Just being open to the fact that no one person, including yourself, is going to bring in all the technology or methodology or scientific expertise. I think, being somewhat humble.

Participants also reported that scientific curiosity helped

them successfully engage in TD team science. They described how a drive to investigate scientific questions at the boundaries of our knowledge, a general "openness" toexploring areas of science that one knows little about, and a willingness to invest time and energy to learn about new research topics and approaches all helped to facilitate TD team science.

I definitely have been reading a lot, perhaps more than other junior investigators [not participating in TREC I], because I keep finding myself entering into a new area. And going back to transdisciplinary research, I think that's really key that you have to keep an open mind -- that you need to be willing to put the time in to really open yourself into new areas that you may find yourself in either by chance or by choice.

Effective team processes: Interview participants described a number of team processes that were essential to successfully developing and implementing TD team science projects. An important early step was the articulation of concrete shared goals, which often took the form of ideas for manuscripts and grant applications. Then, as new collaborations got underway, it was beneficial for members of a team to invest time and effort in developing mutual understanding.

Participants described the effectiveness of team members teaching one another about their respective disciplines, including the disciplines' implicit values, and what unique contributions each discipline could make to the team's research goals, in terms of concepts, theories, variables, and methods. This was done both formally and informally. One participant described how her research team had brown bag lunches in which each team member gave a talk about his or her discipline. Another described teaching and learning from colleagues over dinner at the TREC I semi-annual grantee meetings.

Having people listen to each other, what each other actually do, and trying to understand why they're doing it, makes a huge difference in accepting the legitimacy of all the different [research] questions.

Participants emphasized the importance of frequent communication among collaborators, both for small team projects and large cross-center collaborations to help develop shared goals and mutual understanding. They emphasized the value of face-to-face meetings.

I think that it was a series of different [events] -- it was the TREC meetings; it was [center level] meetings; it was some of the national meetings that TREC sponsored and participated in with NCI; it was personal conversations that we had. So it's hard to identify one particular event. But I think it was really a series of different events and conversations and discussions and arguments that transformed all of us so that we still recognize the differences but there's more respect and understanding and less intimidation. … I think we've gotten to the point where we understand enough that we … can pay attention and recognize, "oh, there's something important there. That is real science, after all."

These processes that helped build mutual understanding ultimately enabled collaborators to craft TD research projects that drew upon the strengths of each of the contributing disciplines.

Brokering and bridge-building activities: Many interview participants described how individuals holding particular roles in their TREC I research centers facilitated TD team science by brokering new TD collaborations or building bridges between research projects grounded in different disciplines, departments, or institutions. These individuals included center directors and primary subproject PIs, biostatisticians, and trainees.

Participants described how TREC I center directors created environments that helped to generate new TD collaborations, by creating networking opportunities and a culture of scientific dialogue across disciplines. One particularly effective approach was to host regularly scheduled symposia that brought together all of the members of the center to engage in cross-disciplinary networking and learning. Sometimes these events featured speakers from the center, and at other times they featured guest speakers whose expertise was relevant to ongoing research at the center, but introduced possibilities for novel TD integration.

[The center director] fosters [TD team science] every moment of the day. These [center-wide] meetings we have, there's all kinds of people in that room. And who knows what's going to be addressed at that meeting. There's always one out of town speaker, and he can be from almost any discipline. … After these meetings, I will often have somebody come up and say, "I need to talk with you about something," and make an appointment with me.

In addition, center directors and primary subproject PIs functioned as "matchmakers," facilitating meetings among two or three investigators to foster new collaborations in areas that they saw as ready for TD integration.

Interview participants also identified biostatistics core staff members as important to developing new TD collaborations at their centers. They described how biostatisticians had identified related themes or interests across projects they were involved in, that were run out of different departments, and had put PIs in contact. Biostatistics core members also played a unique leadership role in the TD integration of statistical methods. At one TREC I center, biostatistics core members conducted a series of projects in which they applied methods from one discipline to a data set generated in the context of another discipline. The results led to a novel and unexpected interpretation of the findings, with important implications.

We felt as methodologists, we were a little less pigeonholed into one method versus another. And we thought that, as a group, we could push some of the transdisciplinary thinking, because we could come at it kind of in a more objective way, because, you know, it's numbers.

Finally, interview participants in all roles in TREC I stated that trainees were important leaders in developing new TD projects both within and across TREC I research centers. As trainees worked to identify their professional niches, they provided innovative leadership to move into new TD areas of science. To do this, they bridged projects and investigators across various disciplines, fields, departments, schools, and TREC I research centers. They also brought more senior collaborators along with them, to engage in highly innovative TD research.

Funding initiative characteristics: Participants reported that particular requirements and structural elements of TREC I

were important facilitators of TD team science. Participants said they were motivated to persevere in their goal of TD integration despite challenges related to defining TD research, understanding how to engage in TD team science, and comprehending its potential value, in part because of NCI's explicit expectations for TD integration. This was reflected in the funding announcement and NCI leadership's sustained emphasis on TD integration in communications with grantees over the course of the initiative.

In addition, interview participants identified TREC I's cross-center working groups, developmental pilot projects, and semi-annual grantee meetings as particularly helpful in facilitating new TD research collaborations and sustaining existing collaborations. They described how monthly working group meetings generated new ideas for TD research that led to funded cross-center developmental pilot projects and other cross-center research, conference panel presentations, and publications. They credited the developmental pilot projects with enabling them to implement new TD research projects within and across their centers, as ideas emerged, without having to wait for new funding opportunities, and without having to worry about the "high-risk" nature of particularly innovative TD proposals. Meanwhile, they identified the semi-annual grantee meetings as important incubator spaces for new TD collaborations within and across TREC centers. Scientific sessions at these meetings kept them informed about research at other centers that was relevant to their own work. Opportunities to socialize with other TREC I participants in relaxed social situations at these meetings, such as group dinners, helped to support networking and brainstorming and led to new collaborations.

Finally, interview participants described how TREC I helped to advance TD research by allowing trainees to serve as co-PIs for developmental pilot projects, and by funding them to engage in cross-center training opportunities. They described how young investigators looking for ways to make novel scientific contributions and establish expertise unique from that of their mentors used the developmental pilot project funds to create new and highly innovative TD research projects. Trainees used the training funds to develop new knowledge and skills to design and implement new TD research. Senior investigators described how trainees brought them into these TD research projects, as co-PIs or mentors, effectively establishing TD collaborative links among senior investigators within and across centers (Table 2).

Impacts

Interview participants identified five major impacts of participating in TD team science in the context of TREC I, affecting participants, their science, and their institutions. These were: (1) new positive attitudes about TD research and team science; (2) new boundary-crossing collaborations; (3) scientific advances related to research approaches, findings, and dissemination; (4) institutional culture change and resource creation in support of TD team science; and (5) career advancement.

New positive attitudes about TD research and team science: Many interview participants emphasized that participating in TD team science in TREC I, although challenging, reinforced their preexisting beliefs that TD science and team collaboration can enhance scientific research. Other participants said that participating in TREC I caused them to develop a new sense of the value of TD research and team science. Many interview participants said they felt "enriched" by their TD team science experiences in TREC I. Others described a "transformation" in their attitudes.

I think that a number of the scientists at [my TREC center] were really transformed in our thinking by being part of this. And I'm one, but I know that there are others, as well, because we've had these conversations where we have a greater appreciation for other types of research approaches. We understand more than we did before that our approach isn't the end all and be all, and that we can potentially accomplish more by working with people from different disciplines right from the start, rather than bringing them in when we need them.

New boundary-crossing collaborations: Interview participants described how TREC I's requirements to collaborate across disciplines, levels of analysis, and TREC I research centers had led them to develop new collaborations that would not have formed organically. These new collaborations brought together colleagues from different disciplines, departments, schools, and institutions, as well as community-based organizations and translational partners (e.g., local health departments). Participants reported that these collaborations had generated new TD research directions and informed new thinking on the translational applications of their work. Both of these developments were new, as many TREC I investigators had not worked on translational studies before. Participants anticipated that these new collaborations would continue even after TREC I funding had ended.

Scientific advances related to research approaches, findings, and dissemination: Many interview participants described how, as a result of novel TD collaborations, their current research included new conceptual models and theories; innovative applications of methods from one discipline or field to another; development of new measures, instruments, and software; and novel and important research findings in previously unexplored areas of science. In addition, they said that their current research was more sophisticated, with more variables and assays, larger sample sizes, and more complex designs, including multiple endpoints and multi-level analyses. They explained that these enhancements had produced scientific findings that were more innovative, holistic, or relevant to solving real-world problems.

In addition, interview participants described how TD team science conducted in TREC I helped to spawn new TD areas of science. Examples are reflected in the book series, "Energy Balance and Cancer", edited by Dr. Nathan Berger, one of the four TREC I research center directors [33]. Titles of the nine books in the series include: "Impact of Sleep and Sleep Disturbances on Obesity and Cancer", "Obesity, Inflammation and Cancer", and "Insulin Resistance and Cancer". Other examples are in the extensive list of TREC I supported publications [34].

Interview participants also described how TD team science in TREC I led to cross-fertilization of concepts and findings across the fields involved in TREC -- including nutrition, physical activity, obesity, cancer, and sleep research, among other areas

Table 2: Challenges, Facilitating Factors, and Strategies for Success

Challenges	
(1) Limited published guidance for how to engage in TD team science	Lack of knowledge about "what TD research is", "how to get there," and why to do it
(2) Conceptual and scientific challenges inherent to TD integration	Requires added investments of time and effort
	Pushes investigators beyond their comfort zones
(3) Discipline-based differences	Communication challenges due to differences in terminology
	Misunderstandings or conflicts due to differences in discipline-based values, goals, methods, traditions, work styles
(4) Project management challenges	May necessitate new data management systems to store a complex mix of data at multiple levels of analysis, from multiple sources
	Leadership and coordination for a large TD team require unique set of expertise and additional time and effort
	Involves navigating varied department/organization/institution-level cultures, policies, routines, procedures, and work processes
(5) Traditional incentive and reward systems	Systems, attitudes, and policies at academic institutions that discourage TD research and/or team science
	Limited funding opportunities and publishing venues for TD team science
	Peer review (IRB, grant application review, manuscript review) by peers unfamiliar with TD team science
Facilitating Factors and Strategies for Success	
(1) Beneficial attitudes and beliefs	The attitude that every discipline has strengths and weaknesses
	Belief in the added value that can be generated by TD research and team science
	Scientific curiosity about questions at the boundaries of knowledge and areas of science outside of one's expertise
(2) Effective team processes	Articulation of shared goals
	Development of mutual understanding among team members (a) by teaching each other about their disciplines, including potential contributions to the shared research goals, and (b) through frequent communication
(3) Brokering and bridge-building activities	Networking opportunities at the center level, e.g., center-wide symposia
	"Matchmaking" and bridge-building among potential collaborators by individuals in unique roles, including senior investigators, biostatisticians, and trainees
(4) Funding initiative characteristics	Explicit expectations for TD integration in the funding announcement and funding agency communication with grantees
	Cross-center working groups around shared areas of shared interest, with regularly scheduled meetings
	Funding for additional small scale research projects addressing emerging TD research questions
	All-grantee meetings for information sharing and networking
	Funded TD investigator opportunities for trainees

via conference presentations and publications. Interview participants with expertise in one of these fields reported that they had found themselves presenting at conferences and publishing in journals specific to the other fields, disseminating their work to entirely new audiences.

Institutional culture change and resource creation in support of TD team science: The advances produced by the TREC I centers influenced the culture of their academic institutions more broadly. Interview participants reported that senior leaders and investigators at their institutions showed growing interest in TD team science as their TREC I centers produced exciting science, brought in additional funding related to TREC I activities, and communicated these achievements to their colleagues. This transformation in colleagues' receptivity toward TD team science was particularly evident at academic institutions that were homes to NCI-designated cancer centers, where there was a natural affinity for the research conducted at the TREC I centers.

Some interview participants reported that a result of TREC I, a number of senior leaders at their institutions, such as department chairs and deans, were now champions of the TD team science approach. Others reported thattheir institutions created additional resources to support TD science. This included hiring new faculty who specialized in TD areas of science developed in TREC I, who were now conducting research, mentoring junior investigators, and teaching new courses in their areas of expertise. Some interview participants also described how their institutions were investing in new infrastructure to answer emerging TD questions (e.g., laboratory equipment, electronic data management systems for the multi-level data typical of TD research).

Career advancement: Finally, interview participants at all career stages said that participating in TREC helped to advance their career development. Senior investigators reported that the TD research they conducted in TREC I led them to be invited keynote speakers and featured panelists at major conferences, and to publish in high profile journals. Multiple interview

participants credited their participation in TREC I with helping them to obtain grants for related research, including large center grants for senior investigators, and early-career grants for trainees and junior investigators.

A number of senior and junior investigators reported that important TD research they conducted in TREC I, and their ability to obtain additional grants for related research, helped them succeed when they came up for promotion review. In addition, a number of trainees reported that participation in TREC I had made them more competitive for faculty positions. They said that TREC I had given them a broader than usual range of scientific experiences, and that their TD team science skills and experiences were valued by hiring committees (Table 3).

DISCUSSION

Participants in these interviews were nationally known investigators and their mentees committed to pioneering TD team science at the intersection of two previously disconnected areas of science. As such, they represent a valuable source of experiential knowledge about challenges, facilitating factors, and strategies for success specific to the TD team science approach. They also provide important insights into the potential range of impacts of TD team science when conducted within the context of a funding initiative designed to facilitate this approach.

Some of the challenges that interview participants reported were due to their role as pioneers of the TD team science approach not only at the intersection of obesity research and cancer research, but also in scientific research more broadly. The challenges they identified related to the absence of a clear definition of TD research, lack of guidelines specifying how to engage in TD team science, and few published exemplars of prior TD team science reflect the novelty of the TD team science approach when TREC I was launched in 2005. Since then, a substantial and growing body of literature has been published that is building an evidence base for how to effectively conceptualize, develop, and implement TD team science initiatives [1-3,5-15,20- 23,26,35-46].

Other challenges identified by the interview participants reinforce findings in the published literature, and add new insights to our understanding. A number of prior publications have discussed the conceptual and methodological challenges involved in efforts to achieve TD integration [3,6], and others have focused, in particular, on the challenges created by discipline-based differences in values, terminology, methods, and work styles [2,6,10,11,13]. The qualitative nature of our findings provides first-person reports of these challenges that add nuance to the published findings, for example, emphasizing in particular the high levels of effort involved in the scientific work of TD integration and in bridging disciplinary differences.

The management challenges that interview participants described related to operating in TD teams and across academic institutions reflect prior findings that suggest that both large team size and cross-institutional collaboration may handicap team-based research [7,42,43]. However, the fact that interview participants identified certain structural elements of TREC I including cross-center working groups, developmental pilot projects, all-grantee meetings, and funded leadership opportunities for trainees – as effective facilitators of large-team and cross-institutional collaboration suggests that funding initiatives can attenuate these challenges when they incorporate particular structural features. These elements of TREC I can inform the design of future funding initiatives for TD team science. However, the remaining challenges to cross-center TD team science in TREC I described by interview participants suggest that additional targeted approaches are needed to facilitate cross-institutional TD team science. These might support the development of infrastructure for cross-institutional data sharing and data harmonization and address other institutional factors that pose challenges to cross-institutional TD team science.

Facilitating factors and strategies for success identified by interview participants also reflect themes in the published literature while offering a number of new perspectives. Interview participants highlighted the importance of positive attitudes and beliefs about TD research and team science, echoing the literature on the important influence of a "TD ethic" – comprised of related values, attitudes, beliefs, and behaviors – on successful TD collaborations [3,21,22,44]. Interview participants also

Table 3: Impacts of Participating in TD Team Science in TREC I

Impacts	
(1) New positive attitudes about TD research and team science	New positive attitudes about the potential added value of TD research and team science
	A feeling of being "enriched" by TD team science
(2) New boundary-crossing collaborations	Across disciplines, departments, schools, institutions
	With community-based organizations and translational partners
(3) Scientific advances related to research approaches, findings, and dissemination	New conceptual models, theories, measures, instruments, and software; innovative applications of methods; novel or important research findings
	More sophisticated, complex, innovative, and holistic research that is more relevant to solving real-world problems
	Development of new TD areas of science
	Dissemination of concepts and findings across previously disconnected fields
(4) Institutional culture change and resource creation in support of TD team science	Growing interest in TD team science among institutional leaders and senior investigators
	New faculty hires, courses, and infrastructure relevant to TD team science
(5) Career advancement	High profile speaking opportunities, high impact factor publications
	Grants for related research
	Related success in career progression, as appropriate to career stage

emphasized the importance of scientific curiosity to support success in efforts toward TD integration.

Interview participants' reflections on effective team processes for TD team science speak to the importance of team level factors in TD team science, as identified in the literature [6,21,45]. They described specific activities they engaged in to build mutual understanding, in particular, which can serve as helpful examples to other investigators embarking upon or engaged in TD team science. Their reports of the importance of brokering and bridge building activities by individuals in particular roles in a TD research center reinforce recent network analyses conducted by the NCI that also provide evidence for the importance of network brokers in facilitating TD collaborations within and across centers [46].

The qualitative nature of this study generates a holistic picture of the broad array of potential beneficial impacts of participation in TD team science in the context of an initiative designed to facilitate the approach. Interview participants reported that their participation in TREC I had far-reaching impacts ranging from changes in attitudes and beliefs to transformations in the ways they conducted their research, production of important and innovative research findings, development of new TD areas of science, cross-fertilization of ideas among participating disciplines, culture change and resource creation for TD team science at their academic institutions, and career advancement. These impacts can be interpreted as supporting future TD team science in multiple interacting ways among TREC I investigators and other investigators exposed to TREC I research. Overall, these reported impacts suggest the ability of TD team science center initiatives to influence research practices and accelerate progress and innovation in high priority research areas.

Nonetheless, interview participants identified important ongoing challenges to TD team science specifically related to incentive and reward systems related to promotion review, funding, publishing, and peer review. These challenges point to needed work by academic institutions, funding agencies, and journal editors to enhance support for TD approaches. Such support will include promotion and tenure policies that better recognize and reward TD research and team science; institutional policies that support cross-departmental and cross-school collaborations; funding opportunities designed to support collaborative and integrative science; guidelines for review of TD team science IRB applications, grant proposals, and publications for peer reviewers; and additional publishing venues for TD research. These changes are already beginning to occur, and more change in this direction is needed to maximally support effective TD team science.

Limitations

Like all qualitative research findings, those reported here may not be generalizable to other TD team science initiatives or investigators, because we did not attempt to recruit a representative sample of investigators across projects and initiatives. Rather, we focused on TREC I participants, recognizing them as pioneers in the TD team science approach who could share important experiential knowledge about using this approach, including challenges, facilitating factors, and strategies for success. We also purposefully sampled individuals who would be able to share perspectives based on successful experiences engaging in TD team science. However, to capture a diversity of perspectives and experiences with TD team science, we purposefully selected interview participants representing the full range of possible roles in the TREC I initiative, from trainees to biostatistics core staff members to center directors.

Future qualitative research into challenges, facilitating factors, and strategies for success in TD team science can benefit from cross-initiative perspectives. In addition, future research should explore examples of failures in TD team science. Such studies may produce valuable lessons learned that can complement findings from studies such as this one that focus on the perspectives of individuals who interpret their TD team science experiences as successful.

CONCLUSION

TREC I participants were among the first scientists nationally to apply the TD team science approach to address the intersection of obesity and cancer research. As leading investigators and trainees in these fields, their reflections on challenges, facilitating factors, and strategies for success can help to inform other investigators interested in applying the TD team science approach, as well as funding agencies that wish to develop initiatives with structural elements that facilitate TD team science within and across academic institutions. The challenges these interview participants experienced related to incentive and reward systems identify the need for changes in academia, publishing, and research funding to create a broader environment of support for the TD team science approach. The structural features of the TREC I initiative may serve as a model for future funding initiatives that wish to facilitate TD team science in scientific priority areas.

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Appendix A: Interview Questions

Below is the interview guide for TREC I investigators. Interview guides for TREC I center directors, training core directors, biostatistics core staff, and trainees included additional questions that addressed their unique perspectives, given their specific roles in TREC. Three of the TREC I interview guides are available for download on the Team Science Toolkit website: www.teamsciencetoolkit.cancer.gov.

[INSTRUCTIONS TO INTERVIEWERS – READ THE FOLLOWING SCRIPT]: Thanks, again, for agreeing to participate in this interview. Before we start, I want to tell you a little bit about our goals for these interviews. The NCI feels the TREC I initiative has made important contributions to our understanding of how to successfully implement cross-disciplinary research and training in energetic and cancer. This summer, the NCI Science of Team Science team is conducting interviews with TREC I center participants and program staff at the NCI, to record strategies for success and lessons learned from TREC. We'll be using the results of these interviews to showcase the TREC initiative, and produce a manuscript highlighting our findings. This interview should last about an hour. Do you have any questions before we begin? [ADDRESS QUESTIONS. THEN BEGIN RECORDING.]
1. To start out, could you tell me how you have been involved in the TREC center at [INSTITUTION NAME]?
2. As you know, one of the goals of the TREC initiative has been to foster *cross-disciplinary collaboration* in various stages across the research process, such as the formation of research questions, the methods that are used, and the ways that findings are analyzed and interpreted. We are interested in learning about the strategies TREC centers have used to achieve this goal. I'm going to start by asking you some questions about *cross-disciplinary collaboration.* Then I'm going to ask you some questions about *transdisciplinary* research, using a particular definition of that term. Based on your experiences with TREC, what factors have helped to facilitate or support productive *cross-disciplinary* collaborations? For example, things like interpersonal processes within teams, leadership, infrastructure, or institutional policies? a. What strategies have you and your collaborators used to facilitate productive *cross-disciplinary* collaboration? b. What factors at your TREC center, or at your institution, more broadly have helped to facilitate or support productive *cross-disciplinary* collaboration? For example: leadership, infrastructure, or institutional policies?
3. Could you give me an example of a collaboration that <u>came out of</u> one of these strategies, or that was <u>supported by</u> one of these strategies?
4. Based on your experiences with TREC, what challenges have emerged related to <u>engaging in</u> or <u>supporting</u> productive *cross-disciplinary collaborations?*
5. Were any of the challenges addressed? And if so, how?
6. Now I want to ask you specifically about what our team is calling "*transdisciplinary research*." Some researchers who study scientific collaboration differentiate between "*transdisciplinary research*" -- or "TD research" -- and *cross-disciplinary research*. They define TD research as a unique level of cross-disciplinary collaboration that involves [GIVE PARTICIPANTS THE FLASHCARD WITH THE WRITTEN DEFINITION, AS YOU READ IT ALOUD]: an "Integrative process whereby researchers from different disciplines work jointly to develop and use a shared conceptual framework that synthesizes and extends discipline-specific theories, concepts, methods, and approaches, to address a common problem." *C*an you reflect on the extent to which your research projects with the TREC center reflect this particular definition of *transdisciplinary* research, with its emphasis on the "integration" of disciplines? a. (IF RESPONSE IS GENERALLY POSITIVE:) Can you give me an example? b. (IF RESPONSE IS GENERALLY NEGATIVE:) Why do you think that your research has not been transdisciplinary, according to this definition?
7. Can you reflect on the extent to which your TREC center, as a whole, has engaged in research that reflects this particular definition of *transdisciplinary research?*
8. (ASK IF APPROPRIATE:) You mentioned a number of factors that helped to facilitate or support cross-disciplinary research at your TREC center. Were there any additional factors that helped to facilitate *transdisciplinary* research, as I just defined it? For example, things like interpersonal processes within teams, leadership, infrastructure, or institutional policies? a. Were there any additional strategies that you and your collaborators used to facilitate *transdisciplinary research*, in particular, as I just defined it? b. What factors at your TREC center, or at your institution, more broadly, have helped to facilitate or support transdisciplinary research, as I just defined it? For example: leadership, infrastructure, or institutional policies?

9. (ASK IF APPROPRIATE:) You mentioned a number of challenges that emerged related to engaging in or supporting cross-disciplinary collaboration. Were there any additional challenges that emerged related to engaging in or supporting *transdisciplinary research*, as I just defined it?
10. (ASK IF APPROPRIATE:) Were any of the challenges addressed? And if so, how?
11. Now I want to get your feedback about the TREC Initiative, as a whole. Based on your experiences, in what ways has the TREC Initiative, as a whole, helped to support *cross-disciplinary* collaboration, or even *transdisciplinary* research? a. Could you reflect, in particular, on the TREC Initiative's structure – such as the coordination center, working groups, scientific meetings and center retreats, and the requirement to have the TREC center cores? To what extent have these structures helped to support cross-disciplinary collaboration, or even transdisciplinary research?
12. Do you have any recommendations about how the TREC Initiative, or future center grant programs, can better support *cross-disciplinary* collaboration, or even *transdisciplinary* research?
13. Now I want to ask you about some of the impacts of TREC. Based on your experiences with TREC, were there any unique scientific outcomes –such as scientific innovations or advances -- that emerged due to *cross-disciplinary* collaboration, that would not have emerged otherwise?
14. In addition to scientific outcomes, have there been any other unique outcomes from the TREC initiative that you think would not have occurred otherwise? For example, translational outcomes, or outcomes for your academic institution, or participating scientists? [PROBE AS NEEDED:] a. Were there any unique translational outcomes, such as community programs or policy applications? b. Were there any other outcomes for your academic institution? Such as changes in institutional culture, administrative routines, or institutional policies? c. Were there any outcomes for you, academically or professionally, such as how you approach your research, or influences on your career trajectory? d. Were there any particular aspects of TREC that contributed to these outcomes? And if so, what were those?
15. That completes my questions for you. Is there any other feedback you'd like to share, before we end the interview?
Thank you very much for your time.

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