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Networks and temporality in the development of a radical medical treatment

Discovered around 1979, coronary angioplasty has emerged to be one of the principal treatments for advanced coronary artery disease. This paper uses methods from social network analysis to understand how this mode of treatment developed. By using a bibiliographic database of over 11,000 medical journal articles related to coronary angioplasty spanning the 25 years of its history, a large citation network was constructed. The powerful but relatively unknown main path algorithm was then used to capture the underlying change in structure of this network and identify the major streams of events that define this specialised field of coronary medicine. This method was first used in the study of historiography of DNA theory (Hummon and Doreian, 1989) and later by Carley et al. (1993) to explore the social and intellectual factors in the then emerging field of conflict resolution. We believe that main path analysis enabled us to identify the problem sequence that is characteristic medical innovation. We have also identified from the network, periods of exploration by the medical community and periods of consolidation as the emerging field of coronary angioplasty took shape. In leading to this comparison we identify the issue of complementarity among methods and reflect upon the theorizing of knowledge in social science.

1. Introduction

Cardiovascular disease is a major health problem for Western economies (American Heart Association, 2000; British Heart Foundation, 2004). Perhaps this is why this area of medicine has been the focus of enormous innovative effort (Steinwachs et al., 2000) and one of the most important innovations to emerge over the past three decades has been a revolutionary new approach for the treatment of coronary artery disease called coronary angioplasty. It was first introduced into clinical practice in the late 1970s and has become a highly regarded

innovation within the profession, being ranked third behind MRI and CT scanning in a recent survey of internists (Fuchs and Sox, 2001).

The task of this paper is to understand how coronary angioplasty developed using methods from social network analysis. By any account the development of this technology is not a solitary event. Although the breakthrough was made and championed in the early days (around the late 1970s) by Andreas Gruentzig, a German clinician working in Zurich, its prominent status today reflects the work of thousands of medical scientists, practitioners, firms and patients who have been involved in the course of its development, use, improvement and diffusion over the last two and a half decades. It is would not be unrealistic to suggest that coronary angioplasty is the outcome of an innovation network and one of the key issues that innovation scholars have begun to become interested in is how such networks develop and how they evolve over time. To this end, the literature suggests various approaches that could be used for analysing network evolution. For example some authors favour agent based modelling- in-silico laboratories where rule based agents are used to replicate stylized facts observed in reality.[1] In these models the concern is with the macro-structure that emerges as time unfolds. They are about how simple but predictable local interactions among many individuals can generate familiar but perplexing aggregate patterns, such as stock market crashes, revolutions or fads. Other approaches focus instead on the relative movements and importance of agents within the network as it evolves. Stark and Vedres (2006) for example use a novel combination of social network analysis and sequence analysis to study inter-enterprise network formation of Hungarian firms and their relationship with foreign investment from 1987 to 2001. They followed the trails made by enterprises as they make, break, and reshape ties to other firms to identify distinctive pathways where firms make use of network resources to buffer uncertainty, hide or restructure assets, or gain knowledge and legitimacy.

In this paper we also employ methods of social network analysis but in a different way to Stark and Vedres (2006). Using a bibiliographic database of 11,240 medical journal articles related to coronary angioplasty spanning 25 years of its history, we construct a large citation network as the start point of our analysis. We then use the powerful but relatively

[1] Although quite clearly associated with the work of the much celebrated Santa Fe Institute, one of the forerunners to this genre is the model devised by game theorist Thomas Schelling (1971) to demonstrate how extreme segregation tends can emerge even in populations that prefer ethnic diversity, and in the absence of any institutional pressures.

unknown main path algorithm to capture the underlying change in structure of this network and identify the major streams of events that define the field. This was first used in the study of historiography of DNA theory (Hummon and Doreian, 1989) and later by Carley et al. (1993) to explore the social and intellectual factors in the then emerging field of conflict resolution. We believe that main path analysis enables us to identify the *problem sequence* that is characteristic medical innovation (Tampubolon and Ramlogan, 2004; Metcalfe et al., 2005; Mina et al., 2004). Moreover our analysis also leads us to conclude that the coronary angioplasty community can be characterised by the features of exploration and exploitation characteristic of organisational learning (March 1994). We have identified from the network periods of exploration by the medical communities and periods of consolidation as the emerging field of coronary angioplasty took shape. We see below that Gruentzig's innovation of PTCA was pivotal in that, to a large extent, it influenced subsequent history of how to deal with the clinical condition. In other words, this created path-dependency in the history of PTCA. As suggested by March and others (see e.g. March 1994; Senge 1990; Argyris and Schön 1978) exploration and exploitation are essential for the successful accumulation of knowledge or learning. Exploration is understood in terms of search, variation, risk taking, experimentation, flexibility, discovery and innovation whereas exploitation involves refinement, choice, production, efficiency, selection, implementation and execution. We can succinctly delineate/depict these periods of exploration and exploitation by following paths or sequences of important papers as these serve as a proxy for accumulation of knowledge within the scientific community working on PTCA. We can understand the history of PTCA over the last 25 years in these terms as we observe paths or sequences of citations that together suggest variation or experimentation or *breadth* which expresses exploration; we also see paths or sequences of citations that resemble further refinement or implementation or *depth* which expresses exploitation.

We turn now to providing a brief historical overview of the developments surrounding coronary angioplasty and later on we present data and methods that independently capture these ideas and present them visually.

2. A brief overview of the development of coronary angioplasty

In this section we propose to give only a flavour of the historical development of coronary angioplasty and the context in which it emerged. Coronary artery disease (CAD) is the most common cause of death in developed countries. It is the end result of a process called atherosclerosis that occurs when atheroma or plaque forms on the inner layer of the coronary artery and impedes the flow of blood to the heart. In the early stages, the build up of these deposits is silent (symptom-less) but as the disease progresses chest pains of varying degree (angina) as well as shortness of breath occur; the eventual outcome could be a heart attack.[2]

As recently as the decade of the 1960s treatment options for angina (chest pain) or acute myocardial infarction (heart attack) consisted of few medications (mainly nitroglycerin in use from the mid to late 1800s to provide transient relief from angina by dilating vessels and enabling more blood to get to the heart), rest and hope. In the 1960s and 1970s respectively, two new classes of drugs (beta-blockers and calcium channel blockers) were added to the cardiologist's arsenal for dealing with angina. But the 1960s heralded a new surgical treatment modality - coronary artery bypass surgery, which at the time was regarded as being truly revolutionary. This was based on the idea of stopping a heart, using a vessel harvested from another part of the body (upper leg) to restore the blood flow between those areas of the heart that were separated by the occlusion, and then restarting cardiac activity.

The technique spread rapidly[3] although the diffusion of this procedure was not without controversy and this was primarily related to the evidence base on which bypass surgery was being promoted. A debate raged throughout the 1970s about the quality of evidence that was being assembled about the efficacy of bypass surgery relative to medical therapy. In a review of the medical literature at the time Mullins and Lipscomb (1977) noted that analyses were based on incomplete studies or that some studies were less that ideally designed. Given the weight of evidence available they were hesitant to unambiguously recommend surgery other than in special cases.

2.1. The development of a new treatment modality

[2] It only becomes painfully evident when the vessel is approximately 70% occluded (blocked). At this level of closure, the oxygen-enriched blood that the heart receives is only adequate when the body is at rest.

[3] Figures about the volume of procedures undertaken in the early period are patchy. In 1973 around 25,000 operations were performed in the US and this increased to 70,000 by 1977 (OTA, 1978). Elsewhere, the absolute numbers of procedures was small in comparison. In the UK for example 2,297 operations were carried out in 1977 and this increased to 4,057 by 1980 (British Heart Foundation, 2004)

It is against this background of uncertainty about the efficacy of coronary bypass surgery that coronary angioplasty (formally, percutaneous transluminal coronary angioplasty or PTCA) was developed. While this achievement secured Gruentzig's name in the annals of medical history, his key insight of using a balloon tipped catheter to dilate the diseased coronary artery was built around cardiac catherisation and transluminal angioplasty, already established medical techniques. The former is a diagnostic procedure in which a catheter (a thin flexible tube) is inserted into the right or left side of the heart. This could be then used to produce angiograms (x-ray images) of the coronary arteries and the left ventricle, the heart's main pumping chamber, and/or used to measure pressures in the pulmonary artery and to monitor heart function. But by the 1950s, following the work of Cournand, Seldinger and others, diagnostic catherization had become established as the main technique for investigating cardiac function.

The second technique, transluminal angioplasty also known as 'dottering' after its developed Charles Dotter, consisted in the dilatation of occluded peripheral arteries by means of a catheter that inserted into the vessel to break the plaque. Gruentzig learned of the Dotter method during a seminar given by Zeitler, one of the European followers of Dotter, at the Ratchow Clinic in Darnstadt, Germany in the mid 1960s. He later moved to the University of Zurich and there, collected and evaluated a small series of 'dotter' cases. By the 1970s he was actively considering how this technique could be applied to the heart recognising that 'any application of the dilatation procedure to other areas of the body would require technical changes' (King 1996: 1624). Encouraged by his colleague and Joint Head of Cardiology, Wilhelm Ruttishauser, Gruentzig went on to develop a prototype balloon catheter, the foundation for PTCA. One of the challenges he had to overcome was to find the right material for the balloon. He experimented with several and by 1972 settled on a PVC balloon as he found this to be a tough, less compliant material than latex which he also considered. In 1975, he developed a single and then more importantly a double lumen catheter – one for inflating the balloon and the other for injecting contrast media and monitoring intravascular pressure. The following year (1976) he presented results based on animal experimentation to a less than enthusiastic audience at the American Heart Association meeting. Undaunted he succeeded in performing first PTCA on a human patient in Zurich in 1977. The technique gained credence and spread quickly thereafter particularly in the US.

The growth of practice was naturally associated with several improvements in devices and in practice including the invention of the steerable balloon catheter by Simpson in the early 1980s (Simpson, et al. 1982).[4] However, the structure of these many contributions to the innovation sequence also reflects the shift in the nature of the dominant problem. The solution to the catheter problem and Greuntzig's balloon device to compress the plaque opened up new territory but it was soon found that restenosis - the re-narrowing of the artery after it has been treated - occurred in a significant number of patients drastically reducing the efficacy of the treatment and raising its real cost. The solution to this problem was the invention and innovation of the stent, an expandable metal device to give support to the blood vessel wall (Eeckhurst, Kappenbergen and Goy, 1996). Stenting cuts residual restenosis by over 50% and is a major complementary development in PTCA technology. However even this solution is not complete as restenosis can occur on the inside of the stent and subsequent attention shifted to the design of drugs to coat the stent that will prevent this occluding process (Serruys, et al, 1991; Lincoff, 2000; Suwaidi, et al, 2000).

3. Data, Methodology and the idea of the Main Path

Clinicians regularly publish papers that report on more localised trials and this information base is of crucial significance in understanding the growth of understanding in the community of PTCA practitioners. This literature provides for us an effective and innovative way to trace the emergent problem sequence. The data we used were retrieved by searching the Institute for Scientific Information (ISI) database using a number of search words determined after extensive discussions about the key developments in the field with medical practitioners and scholars at the University of Manchester. This search procedure yielded a database of 11,240 articles titles between 1979 and 2003 and these contained over 300,000 references.

A number of scripts written in Perl were used to extract information to help us understand the dimensions of the data. Profiles are given in Figure 1. The data is also used to create of a citation network; this is further discussed below. Starting with two articles

[4] We explore these developments in other papers (Mina et al. 2004, Ramlogan et al. 2006)

published in 1979, the number of articles that delineate the field increased annually reaching a peak in 1996 and declined slightly thereafter.

Table 1.

Year	Publications	Cumulative Authors	Institution	Of which Firms	Countries/US states
1979	2	4	2	0	2
1980	9	28	15	0	8
1981	19	130	30	0	15
1982	29	209	54	0	20
1983	40	252	74	1	26
1984	80	501	120	1	34
1985	125	862	191	1	41
1986	111	1140	232	1	45
1987	143	1493	291	3	49
1988	154	1866	355	5	53
1989	175	2320	422	7	58
1990	222	2831	513	12	66
1991	460	4131	716	27	70
1992	504	5690	942	39	76
1993	584	7195	1174	60	83
1994	608	9071	1473	82	92
1995	669	10790	1754	101	95
1996	845	12786	2021	131	98
1997	937	15772	2445	159	102
1998	934	18008	2953	195	105
1999	987	20445	3484	229	108
2000	996	23295	4035	277	110
2001	892	25633	4531	336	113
2002	901	27849	5006	389	116
2003	814	29883	5469	416	118

Source: Calculated

Some 29,883 authors contributed to this body of scholarship over the period and as the table shows the cumulative author count increased from 4 in 1979 to 29,883 by 2003. It is also

interesting to note that single authors accounted for only 6 percent of publication and in fact 46 percent of all publications involved teams of more than 5 co-authors. In coronary angioplasty, like in other areas reporting medical research there is clearly a lot of teamwork as these are essentially communities of practice in the Brown and Duguid (1991) mould, where formal and informal institutional bases become important loci for the development of new knowledge.

Further analysis of the data enabled us to uncover other attributes. For example, one might assume a priori that publications in this area would be dominated by public institutional authors from universities, hospitals and research organisations. While this is the case we however find that co-authorships from firm affiliations show up in the database from 1983 and by 2003 account they account for 7.6 percent of all institutional authors. We explored the dimensions of these firm related collaborations using patents in a related paper (Mina et al, 2004). Further insights relate to geographical distribution of the research activities. The ISI data does not easily facilitate a one to one mapping of author and address as these are listed in separate or unconnected fields. However from the address field we can identify and extract those papers that were collaboratively written across institutions or geographical domains. Annual publications are shown in the top left panel and map a sigmoid curve indicative of a near complete life cycle of knowledge growth in the field (Figure 1). Note also that the top right panel shows the cumulative number of authors contributing to field increasing exponentially. This is indicative of the growing pool of codified ideas and clinical study as researchers formulate and test hypotheses and record and share the evidence within their community.

Figure 1

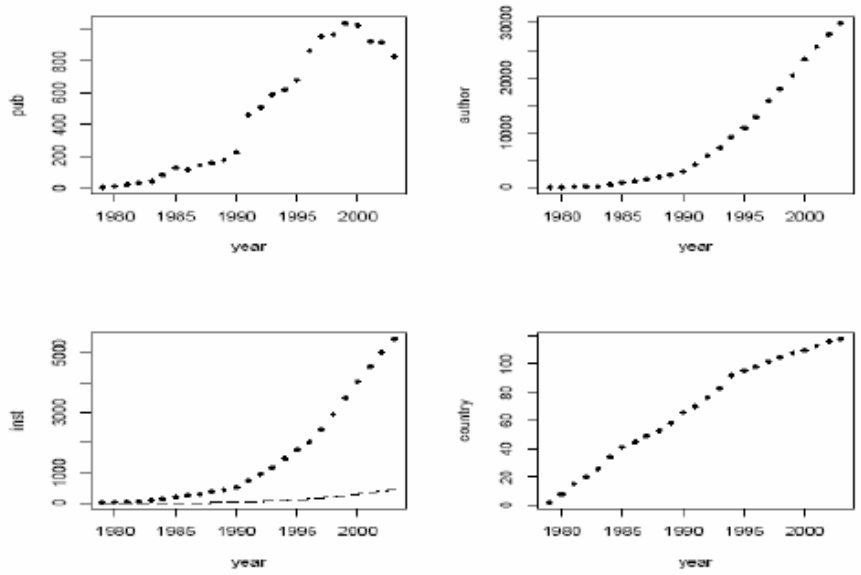

Figure1. Various aspects of growth during the 1970 – 2003, clockwise from top-left panel (1a) Growth of publications (1b) Growth of authors (1c) Growth of institutions (public institutions in thick dots, firms in dashes) and (1d) Growth of contributing countries.

As mentioned above, our principal use of the data was for the construction of a large citation network where papers are used as nodes and are linked through their citations. Network analysts have long suggested that such networks are a fruitful avenue for exploring ideas related to the sociology of science. Indeed citations have been acknowledged as explicit linkages between papers that have some important content in common since Garfield's pathbreaking analysis in the 1950s and 1960s (Garfield, 1955: Garfield et al., 1964). De Solla Price (1965) proposed a network of scientific papers model by which scientific advances could be traced by analysing citation patterns in published journal articles.

The greater the number of citations to an earlier work, the greater the likelihood that this paper may be a milestone or key event in that subject field (Garfield, 1970). Studying citation patterns between articles, journals and other publications can therefore help in

providing new insights about the interaction between disciplines and individuals in relation to the growth of understanding. There are of course obvious limitation in taking bibliographic citations at face value. Differences exist in propensity to cite across countries, cultures and disciplines (MacRoberts and MacRoberts, 1989) as well as authors' use of self-citation. Inappropriate, indirect and negative citation, window dressing and politically motivated flattery can, if widely practiced, severely undermine such modes of analysis (Hummon and Doreian, 1989). Other problems recognised by users of bibliometric data include typographical errors, incorrect spelling of authors' names or unsystematic citation for example citing Smith, T. W. as Smith T. in some instances or Smith T.W.[5] Moreover, the citation provided by the ISI credits only the first named author for any multi-authored paper and this could biases the allocation of credit in any analysis.

With the above caveats in mind we make the assumption that if a publication is taken as an event of the reporting of (new) knowledge then its citation by subsequent scientific publications can be taken as a follow-up event which in some way has been affected by the original publication. In pursuing this line of approach we conceived the corpus of codified knowledge, i.e. scientific publication, on coronary angioplasty as a large directed acyclic graph (DAG). By keeping this duality of event-publication and effect-citation in mind we can think of the traditional citation network made up of publications linked by their citations as a ***directed acyclic graph***. It is directed because any publication can only be cited by a subsequent publication, in other words the graph is *weakly ordered* in time or it has a direction parallel with time. In certain cases a publication can be cited contemporaneously but this does not change the properties of *weak* ordering. Moreover the graph is also *acyclic* in that an earlier publication cannot cite a later publication to form a cycle. In our case the network we are analysing comprises around 94,400 nodes including the lead authors of the 12, 400 primary references plus each unique cited article connected by 300,000 arcs.

[5] It might have been assumed that journal, year and page would together uniquely identify a paper. However, we found out in this reasonably large corpus that this is not the case. We then resorted to make use of author names as part of the identification scheme. This decision in particular imposes a considerable time burden on the researcher in data cleaning to ensure some reasonable level of consistency. In our case, we identified the top two hundred authors and systematically checked data entries.

3.1 Main Path

In the area of social network analysis, the idea of the main path was first proposed by Hummon and Doreian (1989) in their analysis of the development of DNA theory. In this research and in a subsequent study of the literature on measures of centrality in social networks research (Hummon and Carley, 1993) distinctive pathways through the respective citation networks were found to be related to the key intellectual developments that defined the respective fields (see also Carley et al., 1993).

The main path captures a structural feature of a network that contrasts with the orthodox approaches such as bibliometric coupling or co-citation, used for studying structure, in that these latter approaches focus on the clustering of nodes. The novelty Hummon and Doreian's proposed is to make use of the links of the network rather than the nodes, that is, on the network's connectivity. Recall from above that our citation network is a DAG and even though there is a temporal ordering we are not yet in a position to say too much about its structure. For all intents and purposes it is still very much a set of nodes connected by links of equivalent value. However with this in mind it is relatively easy to visualise that it is possible for one to start at any early located article (position) in this network and attempt to find a route (or routes) that will link this node (article) to another published later in time. Hummon and Doreian used this basic idea which is called a *traversal path* to propose a solution to valuing the network so that the most important parts of it and especially its main path can be extracted for further analysis.

The main path of the network refers to the 'structurally determined most-used path' in a network; it is the path with the *highest traversal counts* (Batagelj and Mrvar, 1998). This measures the number of times that a tie or link between articles is involved in connecting other articles in a citation network (Hummon and Doreian, 1989). The main path analysis then determines all possible search paths through the network starting with an origin article through to endpoint articles, and calculates the traversal counts of each link in the network. Main path analysis thus provides for a longitudinal examination of how a citation network or research field has evolved through their citation patterns.[6]

[6] For more technical explanations of the main path see also de Nooy et al, 2005 and Verspagen , 2005.

The algorithm for extracting a main path is embedded in the software Pajek, a tool for visualising and analysing large network (Batagelj and Mrvar, 1998).[7] Batagelj (2002) implemented algorithms to efficiently compute a number of indices suggested by Hummon and Doreian (1989) in Pajek so that they can be used with networks of very large dimensions – up to several thousands of nodes or vertices. These three indices (NPPC, SPLC, SPNP)[8] or weights of edges provide us a way to computationally identify the (most) important part of the citation network – the main path.

It is rather unfortunate that the algorithm is called the *main*-path algorithm. This label unnecessarily prejudices our expectations about understanding the dynamics of the network of knowledge accumulation as captured by citations. The main-path algorithm, in fact, not only presents *the* main-path but also other paths which are explored and compares those paths. In this sense, the main-path algorithm indeed clearly presents paths of *exploration* and paths of *exploitation* evident in any knowledge accumulation or learning process (March 1994). However we stick to the label due to its well-known designation.[9]

4. Coronary Angioplasty Research: The results

The results of the main path exercise are presented in Figures 2a and 2b. Figure 2a shows the connectivity between documents among the most important pathways through the network as determined by the Hummon and Doreian procedure. This sub-network represents a highly synthetic quantitative summary of development in the angioplasty community over the thirty years covered by the study. It is made up of 758 papers, arguably the most important pieces of research.[10] In some respects we can perceive of this diagram as representing part of the angioplasty search space in which we locate and link the research activities as they evolved

[7] Pajek is available from http://vlado.fmf.uni-lj.si/pub/networks/pajek/.
[8] We use the *search path link count* (SPLC) method, which is a simple count of the number of times a link between articles is found along all possible search paths through the citation network
[9] While it is also possible to do blockmodelling to identify bifurcations in the network, we deem it superfluous because both processes of exploration and exploitation (March 1994) are necessary and ever present at any moment in time in any accumulation of knowledge or learning process. The emphasis may be different at different times.
[10] We used an arc cut of 0.0011 to partition the network. We tried different cut-off points without significantly altering the results. In cases where there were reciprocal citations for example papers citing each other in the same year we removed them from the network by combining them into a single node with combined citations. We chose also not to label the nodes as this would make the diagram incomprehensible.

over time. Notice that overall there seems to be a pattern consistent with what might be considered to be a phase of exploration in the bottom part of the diagram, a phase of convergence towards the middle and finally a second period of exploration. The significance of this will be discussed further on.

Figure 2a

The Coronary Angioplasty Network 1979- 2003

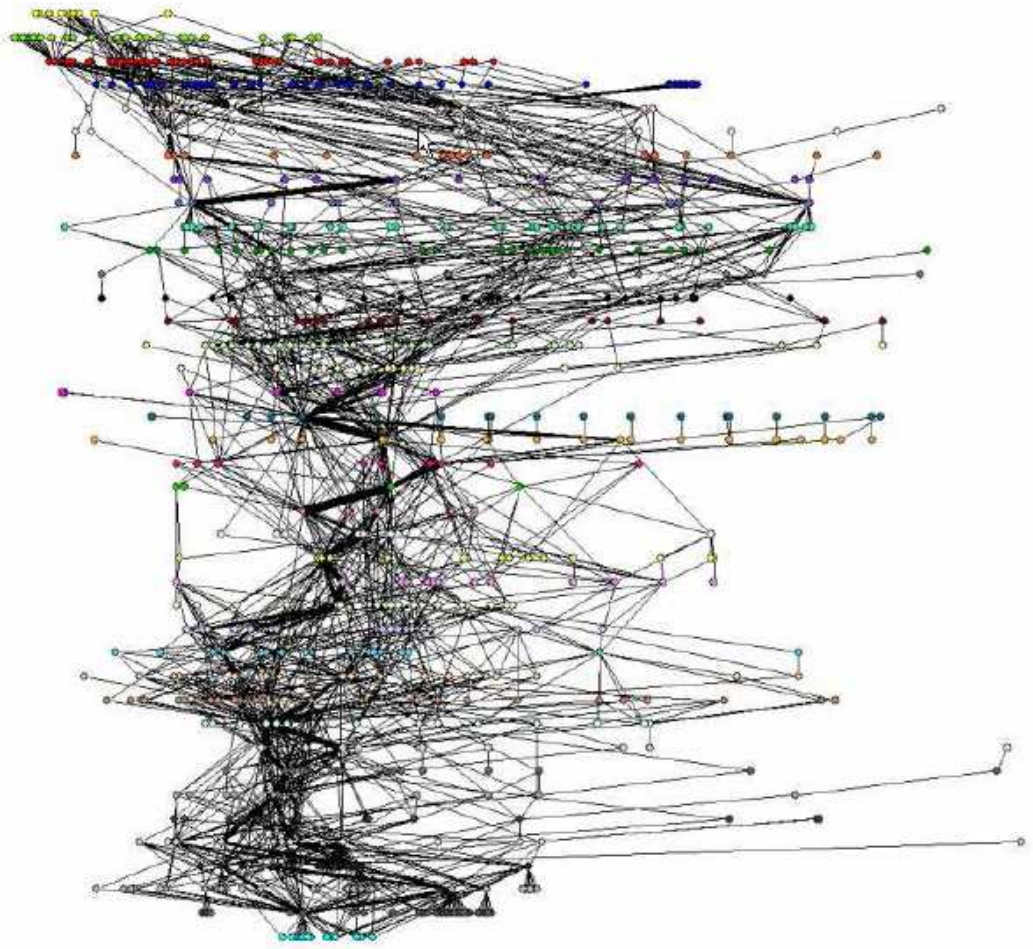

Figure 2b

The Main Path through the Coronary Angioplasty Literature

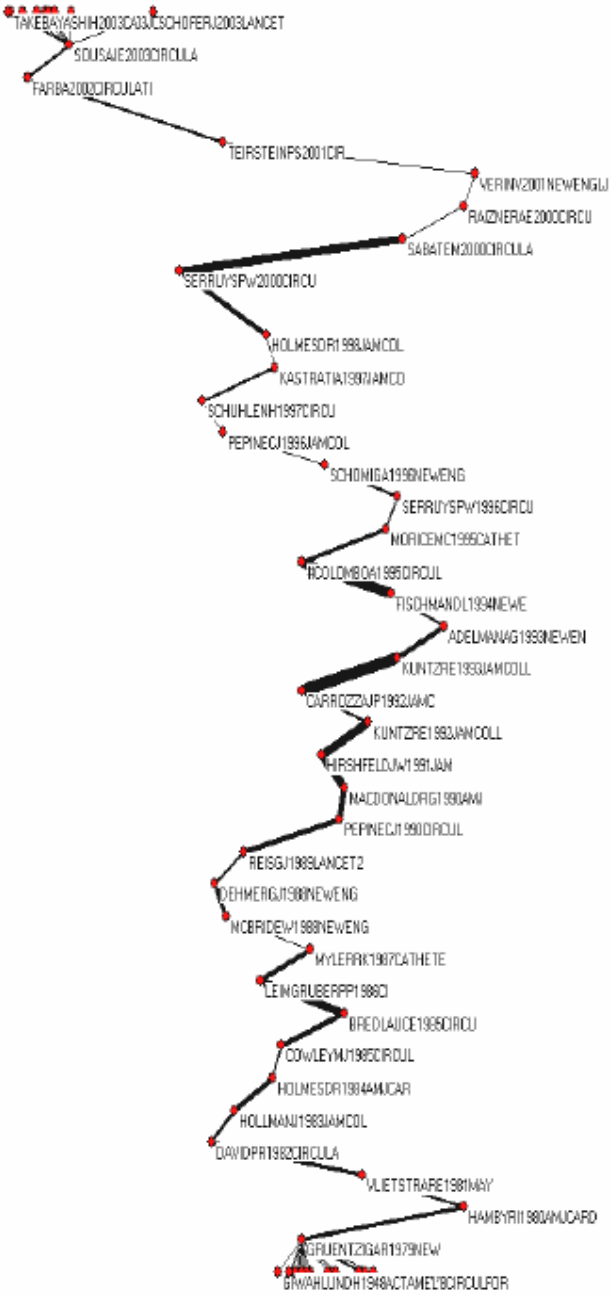

Figure 2b shows the main path that we have extracted from sub-network. This path connects 61 nodes.[11] We studied the paper abstracts associated with each node and have concluded that in general they confirm interview and other qualitative accounts of the key developments in angioplasty that have been reported in several review studies (Mueller and Sanborn, 1995, Myler, 2002, King, 1996, 1998).[12] The story of course largely begins with Gruentzig's 1979 paper which he co-authored with Ake Senning and Walter Siegenthaler, colleagues from Zurich. This lies to the lower end of the main path diagram. Some of the nodes below Gruentzig represent the foundation from which the angioplasty community emerged. Nodes to the top of the diagram on the other hand are a sample of the state of the art by 2003.

Following Gruentzig's breakthrough, the concerns of practitioners were with identifying the medical conditions under which this new technique would provide benefits to patients under tolerable margins of risk. The study by Cowley et al., 1985 is one of a number of foundation papers that was produced under the sponsorship of the National Heart Lung and Blood Institute in the US in this early period. These provided early evidence from a Registry set up in 1979 to collect, analyse and disseminate the results from using the balloon angioplasty procedure in medical centres across the US and in other countries (Mullin et al., 1984).

As operational experience was gained, the medical community began to recognise a number of problems. First, in a small but significant number of cases, the procedure resulted in weakening and collapse of the internal structure of the artery which would subsequently require emergency bypass surgery. Thus in the early days, the practise of coronary angioplasty was contingent on having emergency coronary artery by-pass operating facilities available. Second, tissue trauma at the site of the procedure sometimes triggered blood clotting which, depending on severity, would require major invasive treatment. Over time however the occurrence of this would be addressed with anti-thrombolytic drugs. The third problem was restenosis – the appearance of a new constriction in the artery. This tended to occur during the first 3 to 6 months after the procedure. It is not atherosclerotic in nature but results from the outgrowth of "endothelial" cells that normally line blood vessels. It has been

[11] In the discussion that follows we limit the discussion to just a small number of the 61 publications that characterise the main path. The respective bibliographies are available from the authors upon request.
[12] Abstracts were obtained from the Medline database and for those that were not electronically available, we studied the hard copy.

likened to “over exuberant” tissue healing and regeneration similar to scar formation after the trauma of angioplasty.

Between 1986 and 1995 (marked on the main path with papers by Leimgrubber et al, 1986 and Colombo et al, 1995) together with developments in equipment (Mina et al. 2005) and with accumulated practical experience of the procedure dealing with the problem of restenosis became increasingly important issue that would determine successful adoption of angioplasty. This technique had the potential to be a serious competitor to bypass surgery. Certainly in these early days it was proving to be so in some specific medical circumstances. However restenosis would undermine any perceived (economic) advantage simply because its occurrence would necessitate repeated procedures. This prompted the exploration of a number of possible complementary treatments to be implemented pre and post procedure in the hope of ameliorating restenosis. For example, Dehmer et al. (1988) investigated whether there were any benefits taking n-3 fatty acids prior to or subsequent to the angioplasty procedure. This was found to be of ‘limited success’ for a small population segment. Reis et al. (1989) investigated fish oil supplementation and concluded that did not influence post angioplasty restenosis. Pepine et al. (1990) in another study found corticosteroids to be ineffective on the development of restenosis after angioplasty.

During the latter part of the 1980s, one solution gathered momentum. This was the application of a stent – a scaffolding structure, applied either with balloon angioplasty or on its own (self expanding stent). The stent was a solution to two problems. First, it would act as a support structure to prevent the collapse of the inner vessel which sometimes occurred. This would ultimately limit the requirement for the procedure to be conducted in an area co-located with emergency surgical facilities. And second, it would reduce the impact of restenosis by mechanically maintaining the artery patency and thus the need for multiple angioplasty procedures. By the mid 1990s studies were being published that confirmed the beneficial deployment of stents: The study by Fischman et al. (1994) and Colombo et al. (1995) were pivotal in this respect. The former compared the effects of stent placement and standard balloon angioplasty on restenosis and found that the placement of an intra-coronary stent outperformed ‘simple’ balloon angioplasty resulting in an improved rate of procedural success and a lower rate of angiographically detected restenosis. The latter study showed that better stent placement with the use of high-pressure final balloon dilatations would reduce problems with anticoagulation that had periodically been occurring. This technique

contributed to significantly reducing hospital time and vascular complications. Subsequent studies along the main path followed another problem the emerged, one that was quite unexpected. While the use of stents greatly improved the outcome of angioplasty it was soon found that scarring occurred within stents (in-stent restenosis), restricting blood flow. Among the various solutions that have been explored are drug eluting stents (Serruys et al., 1996), medical therapies before and after stenting (Schomig et al., 1996) and radiation (Sabate et al, 2000 and Verin et al, 2001). Of these treatments and based on current evidence it appears that drug eluting stents offer the most promising new treatment for coronary artery disease. This involves coating the outer surfaces of the standard coronary stent with a thin polymer containing medication that inhibits formation of scar tissue intervention site. Accumulating medical evidence shows this to dramatically decrease the chance of restenosis

5. Summary and Conclusions

In this paper we used the idea of the main path analysis to test our understanding of the development of a novel treatment for coronary artery disease. This technique has previously been proven to be useful in understanding the development of DNA theory conflict resolution research and the growth of the social network literature. Carley et al. (1993: 444) observed that the main path mapped the intellectual influences and cross fertilisations that are important to cumulative scientific process. They further noted that technique the main path when combined with historical analysis provides a rich and detailed understanding of a historical period because while historical analysis has the advantage of locating and describing institutional context, tools of structural analysis such as the main path has the advantage of controlling for the powerful influence of institutional contexts.

We believe that the application of main path analysis to the area of innovation research allows us to discover an interesting dynamic. While out main path map represents a highly synthetic quantitative summary of the evolution of this medical community, it is also provides firm evidence of the flux within the community as the new method for combating the debilitating effects of severe coronary artery disease was introduced. Our results lend credence to the notion that medical innovation is driven by the idea of a problem sequence and that this is the central concept around which we can build an understanding of how

innovation processes are instituted. Innovations as we have expressed previously are rarely if ever uniquely circumscribed events and outcomes. From the analysis above we clearly observe that as problems were solved, extending the range of application and improving practice, new problems would be defined requiring further exploration of the broad cardiology search space in the search for new solutions. Thus we can account for what we described earlier as phases of exploration and consolidation and show the development overtime of the network of relevant scientific contributions.

The findings here also speak to the literature on learning in general (March 1994). The method applied here clearly captures both exploration and exploitation observed over the last 25 years in the development of PTCA. This particular case study also extends the literature in its treatment of the scope of where learning is observed. Previously, learning is to be understood as an individual and, more recently, organisational phenomenon (Argyris, C. & Schön, D. 1978, March & Olsen 1975). One important feature of these subjects (individual or organisations) is the presence or availability of an overarching cognitive guide or director. Here we see that among independent groups of scientific researchers, the phenomenon of learning is also observed. In a sense there is a self-organising mechanism that is taking place at the community level without the presence of a cognitive guide/director.

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