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On the Logic of Percutaneous Coronary Interventions

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Abstract

Performance of percutaneous coronary interventions (PCI) is largely based on empirical experience of individual operators. Due to the perceived mostly intuitive character to date little data concerning formal and reasoning structure of PCI is available. Non-axiomatic logic (NAL) provides consistent format allowing systematic analysis of reasoning applicable to PCI. In this report we introduce the basic principles of NAL and provide relevant introductory examples representing clinical reasoning in performing PCI.

Keywords

Percutaneous coronary interventions, Logical reasoning, Metrics, Professional competence

Abbreviations

AIKR: Assumption of Insufficient Knowledge and Resources, CTO: Chronic Total Occlusions, IC: Interventional Cycle, NAL: Non-axiomatic Logic, NARS: Non-axiomatic Reasoning System, PCI: Percutaneous Coronary Intervention, TIMI: Thrombolysis in Myocardial Infarction Coronary Flow Grades

Introduction

Due to the lack of proper metrics, judgments concerning the professional competence of operators performing PCI are difficult to make. Even the direct observation of the actions of the operator or careful evaluation of interventional angiograms may not be sufficiently telling. This lack of metrics is related to the widely held belief that PCI is a largely intuitive empiricism-based activity virtually inaccessible to detailed scrutiny.

Although initial attempts to formalize the PCI process and to analyze the cognitive skills needed to drive PCI have been reported [1], as far as we know, to date, no description of the reasoning process responsible for decision making applicable to PCI is available. Consequently, performance of PCI has remained to a large extent exclusively empirical.

Here we propose that the performance of PCI can be reproduced as reasoning process NAL and provide examples of PCI relevant applications.

Logic

Logic is an attempt to base human reasoning on rational principles rather than dogma, superstition, divination or other even more arcane systems. To date numerous logical systems have been designed to search and to establish patterns of valid inference [2]. The traditional logical systems employ *axioms* for truthful statements given as the starting point of all inference. Typically, axioms emerge in a four step process; first, propositions, i.e. symbols standing for objects, permissible relations, and operations, are defined; second, rules of logical reasoning (inferences) are defined and applied; third, truth values of the resulting propositions are assessed; fourth, axioms are selected to derive all relevant true propositions. In all subsequent logical operations, axioms are considered to represent confirmed and established knowledge no longer requiring further proofs. New propositions derived through chains of logical operations based on axioms are termed *theorems,* and they represent sound, consistent, and coherent statements.

Difficulty of applying the traditional logical systems to human reasoning comes not only from the rigor of grammar and inferential rules but also from the assumption of the sufficiency of axiomatic knowledge, as well as from the assumption of unlimited resources to carry out the required inference processes. In addition, the models dealing with uncertainties concerning the predictability of future events, such as Bayesian model of conditional probability [3] and game theory of von Neumann [4,5], appear rather cumbersome to reflect reasoning in real-life context.

To apply the principles of intelligent reasoning to PCI while avoiding some of the caveats associated with the traditional logical systems, we suggest the NAL providing the logical rigor and the required flexibility inherent to the PCI process.

Non-axiomatic Logic

Accounting for AIKR, NAL preserves the principles of rational reasoning and provides the right tool to portray the experience-grounded and evidence-based PCI process. In NAL the truth-value of statements, <f,c>, consists of a frequency (f) – degree of the belief, and a confidence (c) – strength of the belief. The frequency f is defined by the ratio w^+/w of the positive evidence (w^+) among available evidence (w); the confidence c is defined by the ratio $[w/(w+k)]$ of the current

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evidence (w) among the evidence at a near future (w+k). In contrast to binary (yes/no; 0/1) logic, in the multi-valued NAL logic the two factors in truth-value may assume any real number within the 0 to 1 interval (0, 1). While dropping the use of axioms, NAL applies inference rules consequently at all level of complexity of the ongoing rational reasoning process.

Conceptually, NAL is divided into 9 levels spanning the entire reasoning process.

NAL level 1

NAL level 1 defines atomic terms, inheritance statements (similar to propositions), and the local, ante grade and retrograde inference (reasoning) rules. A statement has the form of T1→T2 where T1 and T2 are terms, and the inheritance relation '→' indicates that subject term (T1) is a special case of predicate term (T2). While the consistency of propositions (evidence) is desired, in a real-life context it is rarely fully achieved. The adaptive NAL system resolves inconsistencies by introducing not only *positive* and *negative evidence* but also a *revision rule* determining the weighted averages of individual frequency values (f) considered, and the confidence value (c) of the conclusion is greater than the c-values of any premise. In determining the truth-value of the considered evidence the evidence-base is not allowed to overlap. In contrast, the *choice rule* deals with inconsistent evidence, and allows for overlapping evidential-bases to be compared. To account for the incomplete and inconsistent evidence, the reasoning process producing judgments normally selects the evidence with the higher confidence value (c) and delivers not the perfect but the "true as possible" answers.

NAL level 1 also defines the inference (syllogistic) rules carrying out *deduction, induction, abduction, conversion*, and *exemplification*. While the forward inference rules describe the reasoning process to arrive at the derived belief, backward reasoning rules generate sub-questions from given questions and beliefs. Furthermore, the basic mechanisms of *memory* and *control* are introduced at this level which organize the competition between rivaling concepts, structure the experience, and carry out the inference processes.

NAL level 2

NAL level 2 introduces the conceptual relation of *similarity* and the related inference rules for *comparison*, *analogy*, and *resemblance*. Other variants of inheritance like *instance* and *property* are also introduced. Furthermore, new types of terms are added to represent special concepts corresponding to proper names and adjectives.

NAL level 3

NAL level 3 introduces the notion of *compound terms*, and defines the syntactic complexity of those terms where the syntactic complexity of atomic terms equals 1 and that of compound terms being >1. *Intersections* and *differences* allow compound terms to be constructed by *extensionally* enumerating instances and *intentionally* enumerating properties of the multi-component compound. Inference rules are extended to account for the composition and decomposition of these compound terms.

NAL level 4

NAL level 4 introduces arbitrary conceptual relations between terms by converting them into the built-in conceptual relations (normally *inheritance* defined in NAL Level 1). This is possible because, intuitively speaking, "There is a relation *R* among arguments *a*, *b*, and *c*" is equivalent to "the tuple or ordered pair (a, b, c) is an instance of the relation *R*."

NAL level 5

NAL level 5 treats statements as terms to carry out higher-order inferences while the semantic principle of evaluating the evidence provided by the statements are retained. While statement terms are characterized by their truth-value and meaning, non-statement terms are defined by their meaning only. An inheritance statement T1 →T2 relating terms T1 and T2 in meaning; while in an implication statement S1⇒S2 relating two statements S1 and S2 in truth-value. In both cases the judgments are based on implicitly represented evidence and the premises provides evidence for the conclusions. Some higher-order inference rules are isomorphic to certain first-order inference rules (such as deduction, abduction, induction, revision, etc.) in the sense that they share truth-value functions.

NAL level 6

NAL level 6 introduces variable terms that represent other terms, which can change their meaning by referring to different terms in different situations. Based on them, symbolic reasoning is introduced and NAL can be used to process an arbitrary language, as well as to emulate an arbitrary reasoning system.

NAL level 7

NAL level 7 introduces "events" as statements with time-dependent truth-value. At this level the reasoning process takes place in real-time and acknowledges the changes occurring in the environment over time, so as to represent and process time-dependent phenomenon. It does not attempt to describe the world as it is, but as perceived and rationalized at a given time by the system.

NAL level 8

NAL level 8 introduces new forms of interactions with the environment to achieve goals through operations; operations being events actualized by the system itself. As opposed to declarative statements, operations express procedural knowledge. Procedural knowledge associates baseline conditions outcomes and feed-back responses to executable operations. Using compound operations more complex structures (programs) can be expressed and learned gradually and incrementally. Procedural knowledge provides ways to achieve specific goals; goals are sentences containing events that the rational system wants to achieve. Competing goals are differentiated by numerical desirability, which is a variant of the truth-value explained previously. Thus, operations represent the realizable events and goals represent the desired and plausible events. Practical reasoning is based on (procedural) actions (what is to do) while theoretical reasoning is based on beliefs (what is to believe). Procedural knowledge is acquired by conditioning trough repetitions, as well as via various types of inference, like declarative knowledge. Combinations of useful operations become skills; skills eventually turn routines through practice. NAL level 8 also introduces the concept of NARS+ that is a non -axiomatic reasoning system implemented in a specific host. Brain represents a reasoning system that employs syllogistic and other forms of inferences, and selects goals by marking candidate goals with certain desire-values. Procedural decision making turns in the final stage a binary process; the action is taken or it is not. The feedback on outcomes that is critical to formation of procedural knowledge can be immediate or delayed.

NAL level 9

NAL level 9 finally is about self-monitoring and self-control employing internal and external sensors and actuators associated with the automatic and voluntary reasoning processes. These processes represent mental operations such as *observe, expect, know*, etc. These mental operations allow the system to think about its own thinking process (self-awareness), to appraise the overall status of the system ("satisfaction", somatic feelings, emotions) while considering consciousness as a thinking process derived from a train of thought.

In summary, NAL is a multi-valued logical system generating knowledge through consistent and systematic application of inferences at all levels of the reasoning process. The evidential support defines the soundness of judgments (not all conclusions are true); evidence captured by the inferential (reasoning) process defines the completeness of judgments (not all truth can be derived as conclusions). Memory is subject of self-organization of knowledge; rather than sifting through all accumulated knowledge it looks for the most promising part of it, similar to the process termed as heuristics.

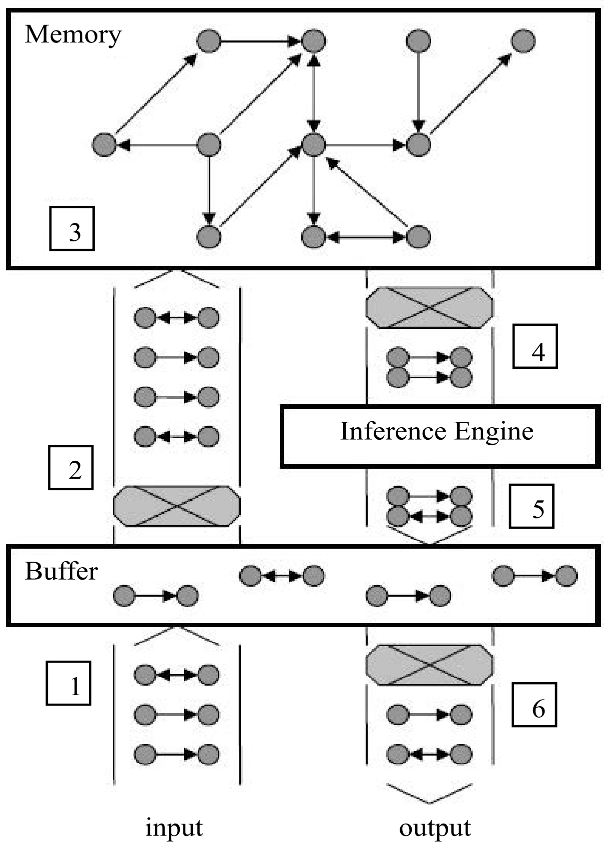

Figure 1: NARS architecture

To explore NAL in a greater detail the standard textbook should be consulted [6].

Non-axiomatic Reasoning System

NARS is the implementation of NAL in a computer system. The overall architecture and working flow is given in the following figure 1.

Briefly speaking, the system runs by repeating the following working cycle:

1. The input inference tasks (new knowledge and questions) can be added into the task buffer at any moment, and each task can have different time requirements attached.

2. Selected tasks are inserted into the memory, and when the system is busy with many tasks, only tasks with high priority values are selected to be processed.

3. The system's memory consists of interrelated concepts. Inserted tasks may produce new beliefs and concepts, as well as revise the existing ones.

4. In each inference step, a task and a belief are selected from a concept, and feed to the inference engine as premises. The inference engine implemented the rules of NAL, and different premises will trigger different rules.

5. The conclusions derived from the premises by applicable rules are added into the buffer as derived tasks.

6. If a derived task provides the best-so-far answer to a question, it is reported to the user, while the system may continue to look for better answers for the question.

While to explain the working process in detail is beyond the scope of this paper, and such a description can be found in [6], here it is enough to say that all the inference rules mentioned in the previous section can be carried out accurately in a computer system.

PCI and NAL

Performance of PCI requires a number of operators' skills. At the basic level the PCI operator generates and interprets images of coronary arteries, designs strategies and executes interventional actions. Each action (interventional or diagnostic) produces an immediate outcome (feed-back) and triggers the subsequent action; a recursive process that is described in a greater detail elsewhere [7]. Due to the high cognitive complexity associated with translating images into strategies and strategies into actions the entire PCI process has been considered largely intuitive, arty and individual; common threads and logical traits have remained to a large extent hidden. Although, as far as we know no written technical notes from the pioneer of PCI Andreas Grüntzig are available, clearly to resume teaching of PCI courses held in Zürich between 1978 and 1980 he has had to be the first to explicate some of the patterns of the tacit procedural knowledge and logic. (Appendix).

Although the need for special knowledge and skills to conduct PCI consistently and safely has been acknowledged in the following years, the underlined logic of the PCI process has remained for the most part uncharted. Perhaps the largest obstacle to logical structuring of PCI has been the difficulty to decide upon the validity (truth-value) of individual interventional actions because in the end different actions and different strategies may result in similar or even identical outcomes. However, according to NAL outcome is not the ultimate arbiter of the validity of actions and strategies; it is rather the intention to treat based on consistency and logic of reasoning and decision making. Although it is not to be expected that definite verdicts will be always possible it is suggested that NAL shall provide an appropriate tool to mirror PCI logic. While foregoing axioms NAL retains the rigor and consistency of the inferential process prescribed to any logical system. Yet, in contrast to other logical systems it retains the flexibility to account for imperfections of the rationale as applied by the real-life reasoning systems, including the humans.

Getting Started

Because PCI is primarily guided by visual data based on coronary arteriograms, vast majority of logical propositions appears to be image-based. To define complete sets of visual propositions high quality cine-images of the target sites and target lesions are needed. Thus, visual propositions should define, classify and name "all" target site specific procedure relevant findings including proximal accessibility, presence of side-branches and dependent collaterals, lesion's geometry, severity, length, surface morphology, expected plaque burden, degree of calcification, presence of thrombi, presence of collateral vessels, state of the antegrade coronary flow and myocardial perfusion etc. Systematic cataloguing of visual findings defined in NAL's atomic terms allows individual case-specific categorization of sites/lesions. Examples of established terminology corresponding to atomic terms in NAL level 1 include definitions of TIMI flow grades [8], TIMI frame counts [9], thrombus burden [10], coronary artery bifurcations [10], coronary collateral circulation [12], stent fractures [13], chronic total occlusions (CTO) [14],dissections [15] etc. An excellent example of compound NAL terms represents the SYNTAX score [16].

To begin the reasoning process, in addition to visual terms systematic definition of technical performance characteristics of PCI-instrumentation including the sheath, guiding catheters, guide-wires, dilatation balloon- catheters, stent- delivery systems and stents is required. However, lacking quantitative measurements of the mechanical properties of individual components of the working chain [17] recourse to surrogate terms such as deliverability, trackability, crossability, pushability [18] is required at present.

The actual reasoning process consists of integrating and subsequently matching the visual data with the mechanical properties of the instrumentation aiming to achieve optimum PCI-results. In the course of this matching process PCI domain-specific statements are developed. For example, given pairs of NAL's atomic and compound

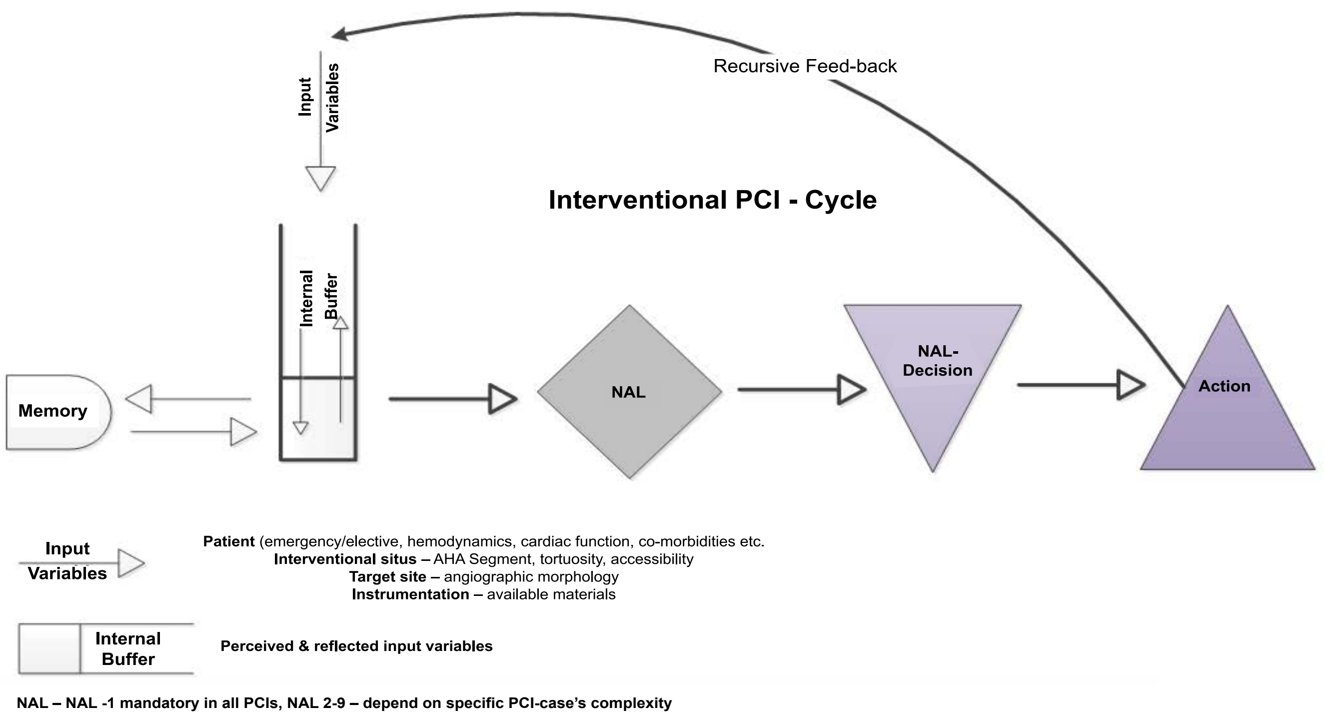

Figure 2: Flow- chart of an interventional PCI cycle based on NAL

terms (NAL level 2) characteristic of a specific target site, target lesion and selected instrumentation the operator may assign confidence value of 70% to successful crossing and dilatation. The truth value of operator's prediction becomes evident following the execution and angiographic documentation of the interventional action. Each outcome then enters into each subsequent prediction. According to the dynamics of individual interventions the compound terms turn NAL level 7 events increasing the complexity of each subsequent judgments and decision making. It is important to realize that besides positive and negative evidence (pros and cons) concerning the feasibility of the aim and the resulting predicted truth-value of statements such as overall 70% expected success risk accounting is always critical to all decision making. While NAL level 1 is mandatory in all PCIs, NAL level 2-9 while also present may interact differently largely depending on the complexity of cases. Each interventional cycle (IC), consisting of the input variables, their sensory perception, NAL- based interpretation and decision making and interventional (or diagnostic) action triggers the next IC (Figure 2).

Weighing benefits, feasibility and risk (not everything what can be possibly technically done should be done) however, does not start with the performance of the PCI, it begins with the decision upon the optimum treatment abiding to the heart team in elective cases [19].

PCI is unique process in the sense that it provides angiographic documentation of outcomes virtually of all interventional actions, thus providing immediate visual and tactile feed-back allowing instant adjustments of both frequency (degree of the belief) and confidence (strength of the belief) levels for all steps of given PCI. Naturally, given the important limitations concerning the capability of coronary angiograms to visualize coronary sites and lesions in the course of interventions deployment of adjunct technology such as pressure- wire measurements or intravascular coronary ultrasound (IVUS) and optical coherence tomography (OCT) imaging may be required.

It is important to understand that the accumulating new evidence becomes a part of the continuously updated case-base; with each new entry, the frequency and confidence values of the matching process can be confirmed, enhanced or reduced. Given the multitude of lesions and available instrumentation, and given the number of interventional cycles employed in complex PCI (up to about n=50) the scope and the dynamics of the judgment and decision making process corresponding to the NAL level 8 can be appreciated. Constant self-monitoring and self-control represented by NAL level 9 provides an indispensable element required to develop PCI expertise.

Summary

PCI represents a highly structured judgment- and decision-based process requiring an extensive theoretical and procedural PCI knowledge that can be described, studied and evaluated in term of NAL. Although substantial effort shall be required to explicate the key principles of the PCI process, this effort should be rewarded by developing rational approach to PCI and by establishing representative metrics to study and enhance professional PCI competence.

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Appendix

After completing some 25 clinical PCI cases (Ms. M. Schlumpf, personal communication) Andreas has compiled sufficient procedural knowledge-base for him to organize the first course in percutaneous coronary transluminal angioplasty (PTCA)/ percutaneous transluminal angioplasty (PTA) in 1978 in Zürich.

In order to teach the techniques Andreas has needed to explicate at least some of his newly acquired procedural knowledge and skills to communicate those principles to the summoned colleagues. However, as far as we know, no written notes concerning either the descriptive or the procedural knowledge are extant. Table reviews the dates and attendance of Dr. Grüntzig's Zürich courses.

It is important to recognize that Andreas has not only pioneered the technique of PTCA but also introduced a new teaching tool: life-case demonstration. Performing interventions live that is without the "safe net" of post hoc analysis, has allowed the audience for the first time to witness the unfiltered dynamics of the recursive decision making process applicable to catheter-based cardiovascular interventions. Direct and unfiltered access to interventional therapies in life-case demonstrations has soon become an important and indispensable teaching tool worldwide allowing free and open transfer of procedural interventional knowledge.

Table: Andreas Grüntzig teaching courses in Zürich during 1978-1980.

Course number	Number participants	Dates	Number of life- cases and involved vascular territory
1	28*	August 7-10,1978	PTCA (coronary) 7 PTA (femoral) 2 PTA (renal) 1
2	97	April 9-12,1979	PTCA (coronary) 5 PTA (renal) 1
3	171	January 2-5,1980	PTCA (coronary) 5
4	221	August 3-7,1980	PTCA (coronary) 7

*The final number of attendees was actually higher (n=35) (personal communication Ms. M. Schlumpf).