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Review

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The potential use of game theory in decision-making in CHD

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Abstract

Background: Congenital cardiac care involves multiple stakeholders including patients and their families, surgeons, cardiologists, anaesthetists, the wider multidisciplinary team, healthcare providers, and manufacturers, all of whom are involved in the decision-making process to some degree. Game theory utilises human behaviour to address the dynamics involved in a decision and what the best payoff is depending on the decision of other players. *Aim*: By presenting these interactions as a strategic game, this paper aims to provide a descriptive analysis on the utility and effectiveness of game theory in optimising decision-making in congenital cardiac care. *Methodology*: The comprehensive literature was searched to identify papers on game theory, and its application within surgery. *Results*: The analysis demonstrated that by utilising game theories, decision-making can be more aligned with patient-centric approaches, potentially improving clinical outcomes. *Conclusion*: Game theory is a useful tool for improving decision-making and may pave the way for more efficient and improved patient-centric approaches.

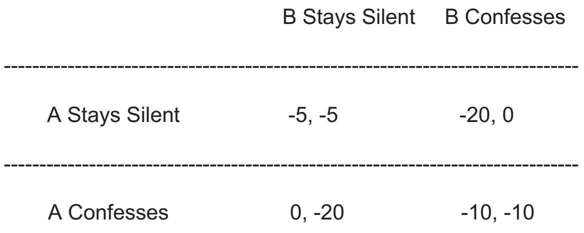
Introduction

Congenital cardiac care deals with large areas of complexity and uncertainty.[1] In clinical terms, this stems from a wide spectrum of morphology, severity, and comorbidities. At the same time, iterative progress in treating these rare conditions has made it difficult to conceptualise and generate robust clinical studies. Despite these uncertainties, significant advances have been made leading to improved hospital survival and a changed focus on the best decisions for better quantity and quality of life. Clinicians working in the field have eloquently made the point that good outcomes cannot be achieved without good decisions at various nodes in patient journeys that can be very complex.[2] A good example is the joint cardiac conference, but similar scenarios can be envisaged for the catheterisation or operating suites.[3] Decision theory is based on utilitarian philosophy where decision-makers aim to maximise benefit[4] (expected utility). If this is seen as a "game," the other player is "nature" with all its inherent complexity and uncertainty. Game theory is a related mathematical framework whereby the outcome of one player's decisions and payoffs is related to the decisions of the other players; at the same time, they are mathematically "independent," therefore adding a strategic dimension to complex interactions.

Game theory seeks to understand and predict the strategic interaction amongst individuals and is commonly used in economics, politics, and science as a decision-making model. Each player creates a strategy based on the preferences and beliefs of the other players in the game. This dynamic strategy allows for a multitude of payoffs depending on the combination of strategies used. The most famous example of the use of game theory is known as the '"Prisoner's Dilemma." In this game, two players are arrested for a crime, player A and player B. Both players are questioned separately in a room and the following rule is read out: (1) If both players stay silent, each player will serve 5 years; (2) if one player implicates the other, then the accuser is immediately released, and the other player serves 20 years; and (3) if both players confess, then they both serve 10 years. In this game, the potential payoffs are to serve no time, 5 years, 10 years, or 20 years as highlighted in Figure 1.

This dilemma highlights that the decision-making process requires an awareness of your competition, the likelihood of cooperation, and the potential payoff with each decision. Although the rational choice may seem for a player to confess to avoid getting the longer sentence, the best overall outcome would be if both players cooperated. The dilemma focuses on the importance of knowing what is individually advantageous vs. what is best for the group as a whole. This concept is used in business to market appropriate prices depending on local competition or in farming by increasing cooperation between local farmers to prevent overfishing or over-cultivation.

John Nash advanced game theory by introducing the concepts of cooperative and non-cooperative games. In the former, players are assumed to form coalitions and can make binding



	B Stays Silent	B Confesses
A Stays Silent	-5, -5	-20, 0
A Confesses	0, -20	-10, -10

Figure 1. Payoff matrix for prisoner's dilemma.

agreements to cooperate with each other. The focus is on how players can work together to achieve a collective outcome that maximises the total payoff for the coalition. In non-cooperative game theory, players act independently and do not form coalitions or make binding agreements. The emphasis is on individual decision-making, where each player chooses their strategy without direct cooperation with others. In non-cooperative games, a fundamental concept is the Nash equilibrium. It represents a collection of strategies where each strategy serves as the optimal response to the strategies employed by others. Consequently, no individual participant has a unilateral incentive to deviate from their chosen strategy. Determining the Nash equilibrium in a non-cooperative game can offer valuable insights into potential unintended consequences that may arise due to changes in policy.

Games can be categorised based on their fundamental characteristics. Figure 2 highlights the three ways by which games can be split: game of chance, game of chance and strategy, and game of strategy, which is then further sub-divided into four formal classifications. Cooperative and non-cooperative games include when players either collaborate towards a shared goal or act independently out of self-interest. Normal form games aim to portray strategies whereby multiple players have to make multiple decisions, whereas extensive form gains aim to depict sequential decision-making with information sets. Constant sum, zero sum, and non-zero games offer payoffs based on players strategies; the former maintains a fixed total payoff, zero sum entails one players' gain offsetting another's loss, and non-zero games allow for variable total pay off. Last, similar or sequential games are where players anticipate and react to opponents' moves in a sequential manner, as seen in games such as chess. By understanding these formal classifications, players gain insight into the diverse landscape of games ranging from pure chance to strategic complexity.

Game theory has recently been used successfully in various medical areas including transplantation, opioid addiction, and antibiotic resistance, to name but a few[5–7] Surgical uses include managing waiting times[8] strategic surgical planning[9] and modelling patient engagement postoperatively.[10]

This paper seeks to examine the utility of game theory in providing patients with CHD. Adding to excellent framings of decision theory for clinical decision-making in CHD [1,2,3], we will discuss how game theory can be applied in various clinical settings, risk assessment and decision-making, research and development, and bridging the gap in service provision between high-income countries and low-to-middle-income countries.

Congenital cardiac care as a strategic interaction

Congenital cardiac care is a high-stakes clinical environment where, relative to other specialties, patients carry a high medical burden through anatomical and physiological complexity, and complications.[11,12] Many stakeholders are involved in service provision. This includes doctors, surgeons, patients, families of patients, operating department staff, healthcare providers, insurance providers, and instrument manufacturers. In this section, we aim to illustrate the applicability of various game theory principles to the different facets of interaction within congenital cardiac care. We have highlighted a detailed hypothetical model in the *appendix*, which evaluates contradictory objectives.

Mismatching perspectives: a prisoner's dilemma

At the forefront of CHD care lies the patient–medical team interaction. This may not be straightforward given the high complexity and resource-intensiveness of congenital cardiac treatments. In an ideal situation, this interaction is defined by the principles of mutual trust, mutual respect, and shared decision-making to determine the ideal management and follow-up.[13] However, more recently, mismatches between patient preferences and values, especially from a parental perspective, and clinician priorities in perioperative management and monitoring frameworks in cardiac surgery have become an area of interest.[14,15] The prisoner's dilemma can be applied to model the possible interactions and outcomes between the clinicians and patient based on competing priorities, preferences, and assumptions—where each party could be a "prisoner" depending on the dominant decision-maker.[16] In the joint cardiology cardiac surgery conference, a point of equilibrium is reached whereby the clinical group is able to make recommendations based on the best understanding of the situation at the time. The role of the clinicians is to advocate for the different options available to the patient, give expert knowledge on the advantages and disadvantages of each procedure, and advocate for the patients' own priorities with their health requirements. Indeed, there must exist an optimal state where both parties' expertise and experience consolidate for a shared decision to be made.

It is a given that surgeons and interventional cardiologists offer options whereby the benefit of a procedure is higher than the disadvantage of not having the procedure. However, these decisions could be influenced by various factors including the clinician's own expertise in operating on complex patients. For example, children born with congenital aortic stenosis are provided with several options: balloon or surgical valvuloplasty or various forms of valve replacement, including the Ross procedure. If patients and doctors assign different values to different outcomes, or if all treatment options are not available, then shared decision-making may not take place on a level playing field. Further decisions include what intervention the patient will benefit most from, what the patient prefers and the implications on long-term care, mechanical versus tissue prosthesis, and so forth. Game theory can influence common binary and non-binary clinical choices that we make regularly. The complexity of the framework should not be underestimated. Mc Mahon et al. showed how, even within decision theory, unpredictable situations can arise, for example, different decisions for patients with near identical characteristics.[1–3]

The monitoring of surgical outcomes in the postoperative follow-up period represents a related area. Congenital cardiac surgery may confer significant and long-lasting impacts to the patients' quality of life. From the surgeons' perspective, the monitoring of outcomes may serve multiple roles in informing on the success of a procedure, technical ability, and objective parameters for subsequent follow-up and management decisions.

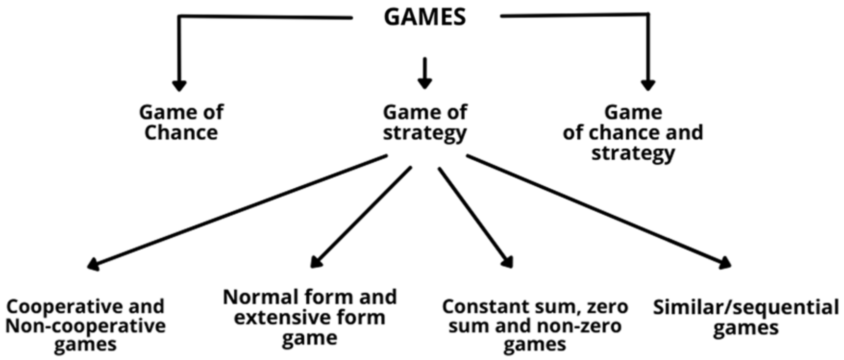


Figure 2. Formal classification of game theory paradigms.

From the patient's perspective, however, family members and patients themselves may choose to prioritise the impact on subjective quality of life and mental health, factors which may not be immediately clinically apparent. Patient-reported outcome measures address this conflict in providing a multifaceted instrument to assess outcomes more holistically. However, existing Patient-reported outcome measures may not be effectively applicable to congenital heart surgery.[14] The situation represents a prisoner's dilemma between the clinicians' priorities and desired outcome metrics versus the priorities and expectations of patients and family members during follow-up. The dilemma implies that each party will act within their own self-interest; clinicians may defer towards prioritising objective signs and symptoms in clinical follow-up discussions. However, from the patients' perspective, they may desire a more holistic assessment of the impact of surgery on quality of life. The best collective outcome from an ideal patient–doctor partnership model would be for the surgeon and all clinicians involved spending time discussing and acknowledging the impact of the surgery on the patient's quality of life. The worst overall outcome would be a brisk follow-up discussion to ensure clinical stability, resulting in the absence of a holistic consultation. Ultimately, we can establish the clinical priorities for research in CHD by involving patients, clinicians, and all other involved stakeholders in accordance to the James Lind Alliance CHD methodology.[17] Patient-reported outcome measures can address patient perspectives but using the methodology seen in James Lind Alliance, by offering the perspectives of multiple groups of people to the patient may help overcome the role of prisoner's dilemma.

This Nash equilibrium point may stem from the patients' tendency to defer to clinicians' decisions regardless of circumstances and needs.[18] In the surgeon's perspective, resource and time constraints may suggest a lesser need to spend time with postoperative counselling, provided there were no adverse clinical outcomes. Mutual discussion and cooperation may not be the default rational behaviour. Studies have highlighted that patient care should extend past surgical skill as patients value human characteristics highly and, within them, rank communication skills as a major contributing factor to an ideal surgeon.[19] The theoretical possibilities demonstrated by the prisoner's dilemma can be used to address and shape a more patient-focused counselling framework. Perhaps an objective follow-up tool could be utilised to address both clinical and non-clinical outcomes to decipher the success of an operation or transcatheter intervention. Patient-reported outcome measures could identify aspects of a child's life such as incorporation within school life, or relationships with peers, areas less familiar to the clinical teams delivering CHD treatments.

Previous studies have explored a game-theoretic signalling model to investigate patient engagement dynamics. For example, game theory was utilised to model the interaction between doctors and patients' engagement. Doctors understanding game theory concepts can adapt their interactions with patients, tailoring responses and demeanour to address patient-specific circumstances and barriers to engagement, which will inevitably increase patient engagement with health outreach programmes.[10] Additionally, healthcare providers are incentivised to maintain high-quality standards to attract patients, whilst regulatory agencies aim to ensure compliance with quality standards and protect patient safety. This creates a strategic game where providers may engage in strategic behaviour such as selective reporting or gaming the accreditation process to appear more favourable, whilst regulators must devise effective monitoring and enforcement mechanisms to detect and deter such behaviour. Game theory analysis can help identify equilibrium strategies that promote transparency, accountability, and quality improvement in healthcare delivery. By understanding the incentives and motivations of both providers and regulators, policymakers can design regulatory frameworks and accreditation processes that encourage collaboration, foster continuous quality improvement, and enhance patient outcomes in the healthcare system.

Ultimately, the prisoner's dilemma serves as a framework to highlight the potential barriers to mutual collaboration due to individual utility or self-interest. Further examples have been highlighted by other specialities where Brown et al. suggested the lack of academic collaboration during training out of self-interest[20] as modelled by the prisoner's dilemma may lead to a resultant Nash equilibrium of competition and burnout. McFadden et al. also stated that multidisciplinary collaboration in the operating theatre[21] would promote safety and synergy, but a culture of self-interest may be a common barrier to this.

Team dynamics and the Stackelberg game

Interpersonal and multidisciplinary team dynamics are the foundation of service delivery in congenital cardiac care. Some critical settings in cardiac care include the operating room, catheter lab, and the ICU. The interplay between procedural, technological, and multidisciplinary complexities confer a high risk of adverse events.[22] The surgeon or the interventional cardiologist are often assumed to bear the ultimate responsibility of the procedure, and their role as the leader is crucial in delivering favourable outcomes, the successful delivery of highly technical fields such as minimally invasive valve surgery, and also contributing to ICU work.[23–27]

A game theory model that can provide insights into the hierarchical interactions between the leader and the follower is called the Stackelberg game.[28] This is a sequential game where one player (the leader) assumes the role of the decision-maker and makes the first move. The other player (the follower) subsequently makes the second move in response to the leader's actions, which is adapted to derive an outcome favourable to the follower. The leader's goal in this game is to obtain the "Stackelberg equilibrium," a point at which the leader's losses from the follower's optimal response are minimised. This can be used to analyse the dynamic interaction between the cardiac surgeon or the interventionist and the multidisciplinary team.

Leadership in congenital cardiac care extends beyond decision-making to encompass collaboration and coordination within the joint cardiology cardiac surgery conference to leverage the diverse expertise to tailor treatment plans for each patient. Intra-operatively, surgeons acting as a Stackelberg leader may have to adapt their approach should they enquire technical difficulties or anatomical anomalies. Although the surgeon or the cardiologist may provide the initial directive, operating members should remain adaptable in response to evolving technical complexities. Ultimately, the Stackelberg game emphasises the importance of patient-centred care in CHD—the clinician as the leader should always prioritise the safety and outcome of patients by ensuring the team is focused on delivering the best possible care specific to each patient. With this approach, the team are constantly adjusting their strategies in response to continual changes perioperatively. The clinician can encourage a collaborative environment where there is information exchange between all members, which fosters a better decision-making process. Previous studies have used game theories to analyse surgical decision-making. For example, a study in India tested a stochastic game of imperfect information to ascertain if surgery is indicated for those with epilepsy.[29] The stochastic game focuses on the involvement of random factors and probabilities in decision-making, alongside the unavailability of all relevant information for the decision-makers. These diverse scenarios illustrate the multifaceted role of the clinician as a strategic leader and the importance of the different team members within the joint cardiology cardiac surgery conference and their cooperation.

Additionally, the very nature of developing guidelines stems from formulating key questions, retrieving and appraising the evidence to provide holistic patient-centred care. Game theory can contribute to developing guidelines by grasping the dynamics of stakeholder interactions. For example, the equilibrium strategy can be used to allocate medical resources during public health emergencies. Guidelines for the dissemination of materials will be based upon the urgency of medical equipment, prognosis, and chances of survival. Leveraging game theory allows evidence review to becoming a dynamic process whereby integrating stakeholder feedback and periodic reassessment can foster a guideline framework that remains responsive and effective over time. Additionally, understanding how linguistic content influences decision-making, such as in sentiment analysis in economic games like the dictator game, highlights the importance of language-based preferences in patient interactions and guideline formulation and potential leverage from artificial intelligence.[30]

Resource allocation: a tragedy of the commons

Congenital cardiac care is highly resource-intensive.[8] Resource allocation requires extensive involvement of several stakeholders in the organisation, distribution, logistic, and economic aspects of its provision.[31] With the ongoing advances in treatment scope and modalities, the interplay between resource consumption and allocation has become crucial. The "tragedy of the commons" game theory provides an effective model of the possible outcomes and approaches. This theory was developed from a scenario of shared resources (a common grazing land for livestock in a community) and emphasises the tendency for individuals to act in their self-interest for individual benefit (farmers allowing their livestock to overgraze beyond allotted portions), potentially resulting in a collective disequilibrium and deficit (overgrazing leading to depletion of food).[32]

An example of this is given by surgical site infections, which has been previously applied in orthopaedic surgery.[20] Surgical site infections confer detrimental effects on postoperative recovery and outcomes, and this is a particularly high-risk area for invasive CHD treatments owing to the already pre-existing complexities of postoperative management.[33] The use of prophylactic antibiotics in congenital heart surgery was demonstrated to affect the risk of postoperative surgical site infections, but prolonged courses may increase the risk of antimicrobial resistance. This is a common dilemma in resource utilisation where the finite pool of available antibiotics is shared amongst all specialties and patients. The appropriate practice of appropriate prescribing and antimicrobial stewardship would maintain resource equilibrium. However, inappropriate perioperative antimicrobial prescribing practices in this case would be representative of an act of self-interest, leading to a potential disequilibrium through increased antimicrobial resistance and reduced antibiotic choice.[20] The tragedy of the commons highlights the importance of stewardship in ensuring the appropriate segmentation and sharing of resources.[5,34]

This is of additional relevance in the distribution and coverage of congenital cardiac services as a high-cost, high-resource asset through a network model. In the United Kingdom, there are 10 congenital cardiac centres with four surgeons per centre. Ireland shares the same model and regulatory framework. Between 2022 and 2023 in England and Wales, 11,407 CHD procedures were performed on children and adults of which 4,212 were surgical and 3,758 were interventional cardiology procedures.[35] The distinct locations and distributions of centres ensure that each of the surgeons and cardiologists is skilled in operating on congenital patients. This geographical distribution ensures that resources are evenly shared and that the tragedy of the commons does not occur. This is evidenced in the United Kingdom by the National Institute for Cardiovascular Outcomes Research [35] periodic reports where no unit has a mortality significantly above the "expected" rate.

Despite this, the staffing levels amongst UK consultants who provide congenital cardiac care to patients are at an all-time low. A total of 64 consultants joined the service from 2010 to 2020, during which 91 consultants had left giving a staff turnover rate of 42%, with surgeons accounting for 56% of leavers.[36] Various reasons exist why individuals in the congenital cardiac services are leaving, but the exodus of experts in the field highlights the tragedy of the commons in retaining existing staff, adversely affecting the quality and continuity of congenital cardiac care. This situation underscores the urgent need for a concerted effort to address the systemic challenges and cultivate an environment that safeguards the vital human resources essential for the well-being of CHD patients. Using game theory may allow policymakers to increase individual payoff to improve retention rate as this would be mutually beneficial to both the staff member and the healthcare system.

Organisational structure and training needs: a chicken game

The interplay between service delivery and training needs is another area of strategic interaction. The potential mismatch in priorities and needs may be explored through the "chicken game." This classical game theory example involves a scenario of two players in cars accelerating toward each other. Players are faced with the decision to either turn away from the oncoming car and be the loser (the chicken) and let the opponent win or risk the possibility of death from collision if neither player swerves. Each player's decision relies on their assumption of the opponent's strategy. Procedures in cardiac surgery and interventional cardiology are technically demanding with steep learning curves, particularly in rare and complex operations.[26,37] Competency in this context may be difficult to attain owing to low caseloads, mentorship opportunities, or organisational barriers in terms of cost and risk management.[26] Changing landscapes in training opportunities in cardiac care may exacerbate this problem where, for instance, in the United Kingdom, the introduction of the European Working Time Directive imposed a 48-hour average work week limit, which caused great controversy and concern on the reduction of emergency and elective operating experience and, ultimately, overall training quality.[38,39,] Although measures such as curriculum outcome changes and simulation training modalities have been introduced to address such impacts, it has been reported that a significant proportion of trainees resort to utilising personal out-of-work time to pursue further operating opportunities.[40,41]

Consider the negotiation between the trainee and the service director in determining working patterns. The trainee aims to maximise their educational and operative opportunities within the constraints of their working hours. The service director may however prioritise maintaining service provision shifts within budgetary constraints over the trainee's educational needs. If neither player concedes, the worst possible outcome occurs where the trainee loses out on developmental opportunities, whilst the service may risk retaliation from the trainee in reputational damage, which has implications on future recruitment to the centre, or loss of the trainee altogether. Should the trainee and service director accept partial educational opportunities to be complemented by part-time recruitment of service provision staff and pursuits of further educational opportunities out of hours (both players swerve), no clear winner or loser is established. This interaction emphasises the mismatch between collective best interest and personal interest. Each player assumes the other's strategy, which may not result in the optimal outcome. To overcome this, a clear exchange between the service and the clinician is paramount to the exploration of goals and expectations to adequately plan the service and implement accommodations to training. This may be key to the long-term sustainability of skills and competencies in CHD where theatre or cath-lab experience strongly predicts long-term outcomes.[37]

CHD care at the regional centre

How can these complex uncertainties and interactions find their way into our everyday direct clinical care? In the decision theory framework, the Dublin group emphasised the importance of bias awareness as the first step to improve the decision-making process and its outcomes. More formal management algorithms can be generated and evaluated in the form of standardised clinical assessment and management plans.[42–44] McMahon et al. showed that even for common and relatively simple scenarios, the complexities of decision-making can become almost overwhelming.[1] They eloquently make the case for leveraging multidisciplinary collaboration on large data sets and the nascent benefits of artificial intelligence. We advocate the same. Our example (appendix) makes an entry-level comparison with vaccination utilities as the parallels with CHD are quite compelling. More complex examples are beyond the scope of this introductory review. A game theory approach to CHD problems could input existing data from the literature and enhance decision-making in common scenarios: for example, balloon versus surgical aortic valvotomy in neonates with severe aortic stenosis, device versus surgical closure of ventricular septal defects in larger infants, and so on. Diamant and Obolski illustrated the complexities of the mathematical framework in addressing multi-dimensional uncertainty in the game theory context.[5] Only by bringing domain and mathematical experts together we could begin to tackle these scenarios with new tools.

Global cardiac surgery

Twenty-eight percent of all major congenital abnormalities are heart defects, for which there are 15 million child deaths worldwide, most of which occur in low- and middle-income countries.[45] Reasons for such disparities include lack of insurance, inadequate resources or trained professionals, and insufficient infrastructure.[46] Even with high disease burdens, low-income countries only have 0.07 paediatric cardiac surgeons per million paediatric population, compared with 9.51 per million in high-income countries.[47] In low-to-middle-income countries, more than 90% of children lack access to treatment they require or receive suboptimal treatment. Access to cardiac centres can be extremely difficult for a cost-constrained family despite economic analysis showing that providing basic surgical interventions globally can be as cost effective as oral rehydration solution for dehydration or anti-retroviral therapy for human immunodeficiency virus.[48] We postulate that game theory can be of crucial use in global cardiac care, specifically in allocation in a limited-resource setting and supply chain management and for improved collaborative partnerships.

One branch of game theory that may be of relevance is mechanism design. This is when rules and mechanisms are designed to achieve a desired collaborative outcome, a framework used to distribute transplant organs depending on the health of the recipient and availability of donors.[7] In global CHD care, mechanism designs could allocate resources at a global scale rather than individual local scales as with centres providing care within their catchment area. A global pool of resources could be used to assess areas that are in dire need of cardiac services, logistics of transporting the visiting team should a humanitarian mission trip be required, and the optimal outcomes dependent on areas with high disease burden. Clinicians could act in their self-interest by increasing case volume within their centre to attract patients for specific pathologies. However, this would lead to an inefficient Nash equilibrium whereby surgeons and doctors around the country would expend more resources to outperform each other. A collaborative approach would be where cases are spread evenly to account for patient needs in each geographical location, training needs, and resource availability. This would incentivise participating countries to collaborate and share resources efficiently. Examples of strategies include operating on patients quickly should an urgent operation be required, allowing for a more suitable team to arrive if they are elective cases, or collaborating with neighbouring countries to collectively share and allocate resources efficiently. Whereas other game theory frameworks emphasise stakeholder interactions, mechanism design demonstrates an alternative outcome-based approach where, although individual behavioural patterns are considered, incentivising or regulative interventions can be identified and implemented to achieve a shared goal. A study conducted in India used population-based programme implementation to reduce mortality from CHD by identifying lesions early on and referring such patients to CHD centres.[49]

Game theory can be utilised in this scenario to model the strategic decisions made by countries and charities to allocate resources. With global cooperation, centres in low-to-middle-income countries can co-locate adult and paediatric cardiac care, particular to areas with high burden of rheumatic heart disease. With over 70% of CHD cases requiring medical or surgical treatment within their first year of life, we can see the value of early screening and proactive medical practice.[47] Above all, education and proactive investment in low-to-middle-income countries will allow for infrastructure to be built, quality of life improved, and more lives to be saved.[50]

Finally, game theory and implementation science offers a valuable insight into the complex operational decisions involved in global cardiac care. The reach, effectiveness, adoption, implementation and maintenance framework provides a framework for assessing intervention effectiveness by evaluating five domains: reach, efficacy, adoption, implementation, and maintenance.[51] Coupled with game theory, this framework enhances our understanding of strategic decision-making, cooperation dynamics, risk assessment, and behavioural influences with intervention implementation. For example, healthcare providers may prefer interventions that require minimal additional resources or time investment, whilst policymakers may prioritise interventions that demonstrate cost-effectiveness and political feasibility. By applying game theory, we can identify potential conflicts of interest or cooperation opportunities amongst stakeholders and design incentive structures that align their interests with the objectives of the intervention. Modelling strategic interactions between stakeholders can provide a holistic approach to evaluating and optimising public health interventions.

Conclusion

The use of game theory in CHD care has potential to further improve the landscape of decision-making, resource allocation, and ultimately patient care. It may provide innovative solutions to the challenges of delivering care in resource-limited settings. However, the interactive possibilities demonstrated by game theory models may be overwhelming; there may be no clear guidance on the appropriateness of possible behaviours or whether the equilibrium points may represent contextually appropriate outcomes. Nonetheless, it provides a comprehensive framework to derive well informed decision-making in complex systems from an interpersonal to a health economic scale. Multidisciplinary collaboration is imperative.

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Appendix

Vaccination Game

We chose a theoretical example of vaccination as it shows best several facets of contradictory objectives, with complexity illustrated by modelling the spread of infection. Some parallels with CHD treatments are possible, noting that specific scenarios require tailored models with reasonable assumptions. The decision to vaccinate can be the decision to offer active treatment in the most severe forms of CHD. Another layer can be added by introducing antenatal diagnosis and the possibility to terminate the pregnancy based on individual and societal norms and utilities.[52] Serial treatments may come in with different levels of efficacy. The patient and their family may have, rarely, misaligned objectives resulting in emotional and economic strain and sometimes ethical mediation to prolong life or withdraw support. Disutility is the multitude of known complications, with the possibility to add economic dimensions to reflect quality adjusted survival in relation to resource utilisation.

Consider the decision of an individual as to whether or not to get vaccinated. We explain how to model this decision as a game. We simplify the situation by assuming that there are only two players, the index individual E (for ego) and society (S). The individual E has two available actions: to get vaccinated (V) or to decline the vaccine (NV). The only action available to society is to decide how large an incentive (if any) to provide individuals who choose to take up the vaccine.

If E chooses not to get vaccinated, then they become infected with probability (p) and, if they become infected, incur a cost A_{NV}. Here, cost should be interpreted not as a direct financial cost but as a subjective measure of disutility converted into monetary units for the purposes of aggregation and comparison. Thus, the expected cost to the individual of not getting vaccinated is pA_{NV}, and we take the payoff associated with action NV to be the negative of this cost. Note that the probability (p) of becoming infected will depend on the choices of other individuals; it is thus an endogenous equilibrium of the game rather than an exogenously determined constant.

If E chooses to get vaccinated, then they suffer side effects whose expected cost we denote by A_V, which is obtained by averaging overall possible side effects, weighted by the probability of suffering that side effect. Again, costs are to be interpreted as subjective disutilities, expressed in monetary units. In addition, a vaccinated individual may still become infected. We assume that this happens with probability (1-a)p, where $0<a<1$ is a measure of the efficacy of the vaccine; a perfect vaccine would have $a = 1$, whilst $a = 0$ would correspond to a vaccine that offered no protection. We further assume that the cost of becoming infected is $(1\text{-}b)A_{NV}$, where b is again a measure of vaccine efficacy, now of reducing the severity of symptoms rather than the infection probability. Thus, the total expected cost of action V is $A_V+(1\text{-}a)(1\text{-}b)pA_{NV}$. The payoff is the negative of this. We could also consider a scenario in which society, or the state, provides an incentive for vaccination (or the individual derives moral reward from doing so). If we denote this incentive by B, then the payoff for getting vaccinated is $B\text{-}A_V\text{-}(1\text{-}a)(1\text{-}b)pA_{NV}$.

Notice that we have made a number of simplifying assumptions in the model. We have assumed that individuals are identical in the risk and cost of infection and likewise for side effects. In practice, individual, demographic, and lifestyle characteristics will all have an effect on both risks and costs. As the purpose of this example is primarily illustrative, we do not burden the model with additional parameters to take these factors into account.

We now make a couple of further assumptions that the population is well-mixed (an infected individual is equally likely to be in contact with every other individual) and that a vaccinated individual does not infect anyone else. With these assumptions, we can readily calculate the equilibrium infection probability (p) as a function of the fraction q_V of the population who chooses to take up the vaccine. In game-theoretic terms, q_V is the probability that an individual player will choose the action V.

We shall use the standard susceptible-infected-recovered/removed model from epidemiology. Let R0 denote the mean number of secondary infections caused by a single primary infective in a healthy population. In a large unvaccinated population, the fraction of the population that ever becomes infected at equilibrium is zero if $R0 < 1$ and is equal to (R0-1)/R0 otherwise. We henceforth assume that $R0 > 1$, as a disease with $R0 < 1$ would not cause a pandemic and there would be no need to vaccinate against it. Now, if a fraction q of the population takes up the vaccine and become non-spreaders, then it can be shown that the proportion of the unvaccinated whoever become infected is zero if $(1\text{-}q)R0 < 1$; otherwise, it is $p=((1\text{-}q)R0\text{-}1)/(1\text{-}q)R0$ otherwise. Rearranging this equality, we get $q=((1\text{-}p)R0\text{-}1)/(1\text{-}p)R0$.

It is socially desirable that $q>(R0\text{-}1)/R0$, so that $(1\text{-}q)R0 < 1$ and the disease is not endemic in the population. However, this outcome will not be a Nash equilibrium of the game if $B = 0$. We now show how to calculate the equilibrium value of q in this game. Notice that, at equilibrium, individuals have to be indifferent between the two actions, V and NV. Otherwise, if individuals prefer V, then the proportion vaccinated, q, will increase, whereas if they prefer NV, then q will decrease. For them to be indifferent, the payoffs from the two options must be identical, i.e., $\text{-}pA_{NV} = B\text{-}A_V\text{-}(1\text{-}a)(1\text{-}b)pA_{NV}$.

If follows from the above equation that $p=(A_V\text{-}B)/(1\text{-}(1\text{-}a)(1\text{-}b))A_{NV}$, which holds if $B < A_{NV}$; otherwise, $p = 0$ as everyone will get the vaccine if the incentive is larger than the expected cost of side effects. Substituting this expression for p in the displayed formula for q above yields the fraction of people opting for the vaccine.

Notice that in order to reach the socially desirable equilibrium in which q is high enough to push p all the way down to zero, the incentive B (whether monetary or derived from altruistic principles or a combination of the two) should at least equal A_V, the expected disutility from side effects.

The analysis that we have presented above is of what is known as a mean-field game; here, the number of players is large, and an individual player sees the averaged effect (here, the probability of becoming infected) derived from the choices of individual players. For a more detailed analysis of a very similar model, see. [53]