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Short Review

Postoperative Cognitive Dysfunction and Virtual Reality for Cognitive Rehabilitation in Cardiac Surgery Patients: A Short Review

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Abstract

Postoperative cognitive dysfunction (POCD) has been observed as a complication after cardiac surgery consistently. The ineffectiveness of current treatments for POCD is causing a search for non-invasive alternatives. The present review aims to consolidate the current understanding of how VR methods effectively facilitate the recovery of cognitive functioning in cardiac surgery patients. To obtain information about the effects of VR technology on cognitive functions, we investigated the PubMed, Scopus, and Web of Science Core Collection databases. Our research has shown that VR systems effectively provide feedback, adapt to individual needs, and provide high-intensity and meaningful exercise to promote cognitive and motor learning. Previous studies have demonstrated that multisensory and multidomain stimulation of cognitive functions is possible through VR technology. Thus, the cognitive rehabilitation of cardiac surgery patients can be significantly enhanced using virtual reality (VR) technologies.

Keywords
Postoperative cognitive dysfunction; cognition disorders; cognitive and motor training; cardiac surgery; virtual reality

1. Introduction

The number of older adults in the world has been increasing every year. The aging of the population has created new and complex challenges for health professionals, not only in increasing life expectancy but also in maintaining its quality. Preserving a person's intellectual functions is crucial for achieving a high quality of life. Cardiovascular diseases, primarily associated with atherosclerosis, are the leading causes of death worldwide, as reported by the World Health Organization [1]. The vascular basins of the brain and heart are often affected simultaneously by atherosclerosis. Cognitive impairments associated with vascular brain damage and coronary artery disease are more severe and have a high prevalence in the older population [2-5]. Coronary artery bypass grafting (CABG) is one of the most effective ways to correct coronary atherosclerosis [6] surgically. However, cardiac surgery as a complex invasive procedure is associated with local (stroke) or diffuse brain damage (postoperative delirium, postoperative cognitive dysfunction (POCD)) [7]. The development of POCD is associated with a decrease in surgery effectiveness and an unfavorable long-term prognosis (including dementia and death) [8-10]. It is vital to differentiate POCD from related concepts, such as postoperative delirium (POD). POD is an acute mental syndrome characterized by a transient fluctuating disturbance of consciousness, attention, cognition, and perception [8]. POCD is a less pronounced deficit affecting verbal, visual, language, visuospatial, attention, and concentration functions [7]. These cognitive impairments may have long-term implications as a progression from mild cognitive impairment to dementia over a 5-7-year period [11, 12].

Given that there is no prospect of pharmacological treatment, it is crucial to consider using different rehabilitation programs for cardiac surgery patients. Cognitive reserve concepts, such as neuroplasticity, are frequently viewed as working hypotheses for preventing pathological changes in the brain [13-15]. In this regard, increasing cognitive reserve or stimulating plastic processes in the brain through any methods and training will benefit cognitive rehabilitation [16, 17]. Multimodal training in virtual reality (VR) could be a possible approach [18]. Preliminary data show that training interventions using a multimodal approach can provide effective cognitive recovery in cardiac surgery patients, optimize cognitive and physical functions, and improve quality of life [19, 20].

This short review will address the application of multimodal and VR training programs in patients with cognitive decline and uncover the potential of VR technologies in preventing postoperative cognitive decline in cardiac patients. The focus will be on current limitations and future solutions in clinical practice.

2. Methods

IVT and OAT conducted an independent search of the PubMed, Scopus, and Web of Science Core Collection databases for all literature written in English and published until August 2023. The medical subject heading (MeSH) terms used were postoperative cognitive dysfunction, cognitive disorders, cognitive and motor training, cardiac surgery, and virtual reality. A systematic search methodology was not employed for the available literature in this brief narrative review. Evidence derived from animal data was partially considered.

3. Postoperative Cognitive Decline in Cardiac Surgery: Effects and Treatment

3.1 Definition and Assessment Tools

A decline in cognitive functions such as memory, attention, executive control, and thinking characterizes POCD. It is diagnosed based on neuropsychological testing data in the postoperative period [21]. Various neuropsychological tests are utilized to diagnose postoperative cognitive decline in current studies, thereby making direct comparisons of their results challenging [7, 8, 20]. The best possible results are obtained by an extended neuropsychological examination using specialized neuropsychological tests assessing memory, attention, psychomotor, and executive functions [8, 20]. To enable cross-study comparisons, postoperative cognitive decline should be defined by established criteria, such as a 20% reduction in cognitive scores compared to baseline on 20% of neuropsychological tests or a decline of 1-2 standard deviations in a specific domain, with the standard deviation calculated as the cross-sectional standard deviation of the baseline scores [8, 20, 22]. The assessment tool and criteria commonly affect POCD epidemiological data, such as POCD frequency. According to previous studies, the POCD frequency after cardiac surgery is 50-80% at the time of hospital discharge and remains present in 20-50% of patients in the long-term period after surgery [22, 23].

3.2 POCD Risk Factors and Clinical Effects

POCD is commonly associated with factors related to surgery and anesthesia. The patients may experience cerebral consequences due to a combination of embolism, hypoperfusion, and inflammatory response after surgery [24, 25]. Evered et al. have posited that the effects of anesthesia and surgery are difficult to separate because the two factors are always present in humans [11]. The recent study by Glumac et al. [26] showed the close relationship between POD and POCD. POD occurs in the first few postoperative days and may be considered a significant factor in early and long-term cognitive decline. Also, patient-related factors, including age and cardiovascular risk factors, have been associated with POCD [27]. All these contributing factors together may diffusely impair cerebral hemodynamics, thereby contributing to multi-domain cognitive decline for a long period after surgery.

Several studies have found that anesthesia and surgery not only lead to POCD but also increase the risk of Alzheimer's disease (AD) [11, 28, 29]. A prospective longitudinal study of older cardiac surgery patients found that the prevalence of dementia 7.5 years after interventions was significantly higher than the population prevalence [12]. Animal studies also indicate that surgery and anesthesia contribute to cognitive decline and AD-associated neuropathologic changes, including neuroinflammation, Aβ aggregation, and tau hyperphosphorylation [30, 31].

POCD is associated with a decrease in surgical effectiveness and impaired daily functioning and is a reliable indicator of unfavorable long-term prognosis (e.g., dementia and death) [9, 10]. A previous study assessed postoperative cognitive decline in patients 3 months after aortic valve replacement and demonstrated the impact of POCD on daily living functions. The main findings included that close relatives noticed cognitive deficits more often than the patients themselves [32]. Therefore, to identify and prevent POCD, evaluating patients' baseline cognitive status is crucial. Before and after surgery, neuropsychological tests are necessary [33].

With no current prospect of pharmacological treatment, clinicians pay attention to modifiable risk factors. Diabetes, hypertension, obesity, smoking, depression, and lack of cognitive and physical activity are some of the key modifiable risk factors that have been identified previously [7, 21, 34]. The study conducted by Pérez-Belmonte et al. identified smoking, diabetes mellitus, and obesity as risk factors that can predict POCD [34].

Long-term cognitive and behavioral impairments of various degrees will persist in most patients with ischemic brain injury even after active treatment. Factors associated with cardiac surgery can impact brain functions, with their effects being particularly pronounced during the early postoperative period following CABG. It was found that cognitive deficit is accompanied by morphological changes in brain tissue and the rearrangement of the background brain activity in the long term after CABG [35].

3.3 POCD Prevention

Rehabilitation technologies can promote neural function reorganization and stimulate the residual brain cells to replace the damaged cells and activate their function so that patients can achieve maximum functional improvement and self-care ability. Therefore, the need to search for effective rehabilitation training for the recovery of motor and cognitive functions and the prevention of the progression of motor and cognitive deficits is clear and no doubt.

Clinicians recognize physical activity as the basis of cardiovascular prevention and recovery, including structured aerobic exercises to reduce readmissions and improve patient's quality of life. Recent studies have shown the beneficial effects of physical exercise on neurophysiological functioning in cardiac surgery patients [36, 37]. Trubnikova et al. [37] conducted a study involving 97 CABG patients aged 45-70, and 47 had aerobic physical training before CABG. Cognitive and electrical cortical activity indicators showed improvement in patients who underwent physical training. The meta-analysis performed by Doyle et al. revealed that the early start of aerobic exercise after cardiac surgery results in significant improvements in functional and aerobic capacity following cardiac surgery [36]. Other studies have demonstrated that cognitive training contributes to the preservation of cognitive resources and enhances neuroplasticity processes, which can mitigate the negative consequences of surgery [38-40].

However, some studies have demonstrated that routine cardiac rehabilitation (including medical evaluation, exercise, cardiac risk factor, education, and counseling) has not improved cognitive functions and quality of life in cardiac surgery patients [19, 41, 42]. Combined cognitive and physical training programs are becoming increasingly common in treating cognitive and motor disorders. It is reported that cognitive functions have improved after training based on a combination of physical and cognitive exercises compared to any of them separately [43, 44]. Applying the multitasking approach with the simultaneous execution of motor and cognitive tasks requires considerable control by the attention and executive functions [45]. Preliminary data has shown that multitasking training can provide effective cognitive and motor recovery in patients with ischemic brain damage and optimize cognitive and physical functions [19, 20]. The positive impact of training on cognitive functions shortly after CABG is significant in promoting medical adherence and optimizing rehabilitation procedures overall.

Thus, correcting modifiable risk factors, early detection, and non-pharmacological approaches such as physical and cognitive training seem to be the best way to address POCD.

4. Potential Benefits of Virtual Reality for Cognitive Rehabilitation

Digital technologies are now greatly assisting in reforming the mental health system worldwide. New technologies may offer new medical research and practice opportunities, including virtual reality (VR) [46]. VR is a valuable addition as a safe and controlled environment for user interaction and monitoring physical activity and cognitive tasks [18, 47]. The manipulation of experimental parameters in VR software has great potential for new forms of intervention and treatment of cognitive and motor disorders in patients with different pathologies, including ischemic brain damage. The virtual environment created with computer graphics and 3D screens offers potential solutions to problems arising from traditional cognitive and motor training studies. Recent innovations have made VR technology portable, inexpensive, and easily accessible. This technology is safe for stimulating motor and cognitive function, as the virtual environment consists of graphics, and users are not exposed to physical risks. VR can be used for learning, examination, and rehabilitation [48, 49]. Unlike the real world, the virtual world can be customized to suit the abilities and requirements of each individual, thereby offering greater flexibility in the tasks to be trained. The training specialist's analysis and control of all virtual elements of the activity allows the observation of individual progress, increasing the motivation and commitment to the rehabilitation process [50]. The levels of immersion can be used to categorize virtual reality into non-immersion, semi-immersion, and full immersion [51]. Non-immersive or augmented reality (AR) differs in that virtual objects are superimposed onto the real-world environment through smartphones, tablets, heads-up displays, or AR glasses [52]. In the case of mixed reality (MR) or semi-immersion, the user can interact with both real and virtual objects within their environment, which are visible through MR glasses [52]. Full immersion virtual reality is more commonly used in medicine and rehabilitation [18, 47-50].

Therefore, neurotechnologies such as virtual and augmented reality have great potential for medical research and practice. Furthermore, digital technologies that are more accessible and less expensive, particularly for low-income or elderly individuals, can extend the reach of rehabilitation interventions. Digital healthcare innovations and their active integration into clinical practice are essential to provide quality, efficient, and timely care, emphasizing a personal approach to each clinical case.

VR technology creates multisensory and multidomain stimulation of cognitive functions [53-55]. Specially designed VR immersion scenarios and commercial video games use VR technologies that allow training attention, memory, spatial orientation, problem-solving, and flexibility of thinking [56]. However, the development of such information technologies by older people does not proceed so quickly due to insufficient skill and a frequent reluctance to master new types of activities, especially if success is not immediately noticeable. Nevertheless, training in VR environments is a safe and non-invasive method of rehabilitation of older persons. Liao et al. [57] conducted a 12-week physical and cognitive training program based on VR technology. They showed significant improvements in walking and performing dual tasks, possibly due to improved executive control.

Hassandra et al. [18] conducted an assessment of the possibilities of developing a VRADA program (VR dual task) among older adults with a mild form of Alzheimer's disease. A positive attitude towards VR dual-task training has been demonstrated, as it allows older individuals to engage in exercise. The high level of novelty experienced in VR programs also enhances their treatment adherence.

It is particularly noteworthy that studies aiming to develop complex intellectual systems for conducting dual-task training with simultaneous execution of motor and cognitive tasks in VR are currently lacking. However, this approach may be a promising and effective way of non-pharmacological treatment of reduced cognitive function in a special group of patients - with ischemic brain damage. Recently, there has been an increasing number of studies investigating the impact of VR technologies on the recovery of motor activity of patients after stroke. A systematic review of Saeedi et al. [58] showed that VR training is one of the most advanced motor rehabilitation methods for patients with stroke. The training was mainly aimed at balance and mobility of limbs and demonstrated their effectiveness.

Conventional rehabilitation has a limitation in that stroke survivors often find the exercises to be monotonous and tiring. The lack of engagement in their rehabilitation program may result from decreased motivation to perform the exercises. Consequently, the individual frequently loses interest in the frequency and intensity of their rehabilitation exercises, or they stop altogether. Their functional recovery can be impacted by their lethargy, resulting in no improvements or, in some cases, deterioration in their upper limb mobility. Much research has been undertaken over the last few years, investigating how VR and games can increase people's engagement and motivation to maintain stroke rehabilitation [48, 58, 59]. A recent Cochrane review found evidence that VR and games might be beneficial in improving upper limb function and activities of daily living as an adjunct to usual care or when compared with the same dose of conventional therapy [60].

However, it should be noted that the studies that aimed to develop VR systems for performing multitasking training with simultaneous execution of motor and cognitive tasks are currently insufficient [61, 62]. This is especially true for the recovery of cognitive functions in the postoperative period of surgical interventions. However, this approach may be a promising and effective non-pharmacological treatment of reduced cognitive function in cardiac surgery patients.

5. Virtual Reality's Potential for Cognitive Rehabilitation in Cardiac Surgery Patients

It had been previously identified that brain tissue lesions associated with cardiac surgery exhibit a diffuse nature. VR multitasking training may be the most effective method for cognitive rehabilitation in patients after coronary surgery, as these patients are characterized not only by a decrease in information processing speed, executive control, and memory but also by anxiety and a lack of positive emotions [63]. In this regard, it is desirable to include in the VR program the tasks that require the selection of objects according to the instructions, such as counting or memorization, motor activity, and immersion of this activity in a natural virtual environment. Such VR programs are useful in rehabilitating cardiac surgery patients to activate their cognitive reserves. A high level of cognitive reserve can be conducive to better effects of VR exposure. It is known that the cognitive reserve is a protective factor contributing to less pronounced pathological reorganization of cognitive functions [64, 65].

Cognitive rehabilitation programs using VR technologies and multimodal tasks should involve targeting particularly vulnerable areas of the brain during surgery. The frontal and parietal brain regions are particularly vulnerable to cerebral hypoperfusion and microemboli associated with cardiac surgery [23, 66]. These brain regions are known as "cerebral watershed areas," they are perfused by the most distal branches of two major cerebral arteries [67, 68]. Furthermore, the frontal brain areas play a key role in cognitive control and executive function [69, 70], whereas the parietal cortex has a significant role in task switching [71]. Using a multitasking approach and VR with various tasks can expand cognitive resources, including more brain regions. On the other hand, it activates neuroplasticity processes and initiates a compensatory restructuring of brain resources in response to the increased load.

The meta-analysis conducted by García-Bravo and colleagues revealed that using VR may enhance motivation and adherence in cardiac rehabilitation programs [72]. There are few studies describing the impact of VR technology on cardiac procedure-related anxiety and pain management [73, 74].

The use of VR for the rehabilitation of cardiac surgery patients is still very rare. The study by Cacau et al. [75] demonstrated that cardiac surgery patients exhibited improved functional performance following VR motor exercises. The authors believe that the main reason for the use of treatment strategies with VR is based on the necessity of adding a motivation factor, which helps patients in the recovery process. Cardiac surgery patients frequently have a lower functional reserve and a risk of complications in the early postoperative period. Choosing an approach for cognitive recovery is challenging due to the physical state of cardiac surgery patients. It is crucial to include tasks appropriate for their physical condition during the early postoperative period.

Rousseaux et al. randomly assigned 100 cardiac surgery patients to four groups: control, hypnosis, virtual reality, and VR combined with hypnosis. Each patient performed one of the techniques for 20 minutes the day before and the day after surgery. However, the outcome measures (anxiety, pain, fatigue, relaxation, physiological parameters, and opioid use) were not significantly different [76]. After cardiac surgery, Gerber et al. employed VR immersive nature scenes to treat 33 critically ill patients. Most patients reported that VR was more accepted than the rest of the intensive care unit stay. A decreased respiratory rate during stimulation indicated a relaxing effect of VR [77].

Thus, we can observe by analyzing today's information that VR is commonly used to enhance motivation, increase adherence to therapy and rehabilitation programs, and relieve anxiety and stress in cardiac surgery patients. Meanwhile, VR technologies can have excellent recovery potential for cognitive rehabilitation in cardiac surgery patients.

Our preliminary research has revealed the positive effects of multitasking training on cognitive functions in cardiac surgery patients. Compared to a more manageable task, the training with a complex motor task resulted in better figurative memory, psychomotor speed, and attention indicators [20]. This study used a short course (5-7 training sessions) for multitasking training. The data obtained indicated that cognitive functions were improved within 11-12 days following CABG. This effect is crucial for patients in establishing adherence to treatment and optimizing rehabilitation procedures.

Further studies are needed to examine the sustainability of multitasking cognitive training's positive effects on preserving the patient's overall intellectual functions. Improving postoperative training methods that involve multitasking with an intense load and individual support for cardiac surgery patients in the long-term postoperative period is essential. VR technologies could present new possibilities for medical research and practice. The VR interface requires additional research to adapt successful multitasking training to effectively train memory, executive functioning, and attention.

6. Limitations of study

A systematic search methodology was not employed for the available literature in this brief narrative review. Only a preliminary estimate of virtual reality in cardiac surgery can be derived by analyzing the available information in scientific databases such as PubMed, Scopus, and Web of Science Core Collection. For a fuller understanding of VR technology's medical and psychophysiological aspects, it is necessary to continue the research, expand the database of sources, and involve more experts - neurologists, cardiologists, technicians, and other scientists.

7. Conclusions

Using virtual environments to create new cognitive and motor rehabilitation approaches has excellent potential for treating broad-spectrum cognitive disorders. VR training is one of the actively developing rehabilitation methods for patients suffering from stroke and vascular cognitive disorders after cardiac surgery. The programs to restore cognitive functions using VR technologies and multitasking approaches can be used in cardiac surgery patients, providing an effect on particularly vulnerable brain regions during surgery. The development of a personalized approach in the cognitive rehabilitation of cardiac surgery patients is promising, with the assessment of the initial level of cognitive reserve as an indicator of the possible activation of neuroplastic processes associated with VR multitasking training.

Author Contributions

IVT and OAT both contributed to the writing a manuscript.

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Competing Interests

The authors have declared that no competing interests exist.

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