The first flammable halogenated volatile anesthetic gas was methoxyflurane which was used in Manhattan Project in 1948 during the 2nd World War. It has been withdrawn for use as an anesthetic agent due to the high rate of vasopressin resistant renal failure. Afterwards the attempts to find a new agent continued with the discovery of another fluoride agent. This agent was Sevoflurane and its conversion to haloalkenes by dehydrofluorination when it encountered CO₂ absorber to produce Compound A: trifluoro methyl vinyl ether, has shown a new concern in rats [1]. Although nephrotoxicity has not been established in clinical studies; according to the FDA recommendations, sevoflurane can only be used up to 1 h with a fresh gas flow of 1L/min. Moreover sevoflurane can be considered more than 1h with a flow of >2 L/min. As a result, desflurane gained popularity because of its structure being a fluorinated methyl ether and highly stable with sodalime. Desflurane has almost no metabolism even administered at 7 MAC values, and it has the least solubility among volatile agents. By this way the recovery time is almost 50% of isoflurane [2]. Like isoflurane, causes a dose-dependent increase in heart rate and blood pressure and a decrease in systemic vascular resistance with myocardial depression and peripheral vasodilation. On the other side, coronary vasodilatation also leads to a decrease in cardiac workload. The metabolism in liver is about 0.02%. The most unfavorable property is the stimulation of airway reflexes with irritant odor leading to cough and bronchospasm.

**Volatile agents and immune response**

The inflammatory response to surgery and changes in cell-mediated immunity may lead different results. Based on the current literature, changes in the immune system response were found to be more pronounced after a balanced volatile anesthesia compared to total intravenous anesthesia. It is clear that volatile agents can increase inflammation and cellular adhesion due to their high doses resulting with hypotension and transient hypoxia. They decrease Th1 phenotype, increase cell-mediated immunity and directly affect immune system by manipulating glucose control. For instance, isoflurane has been shown to inhibit normal insulin production and produce a hyperglycemic response. The NK cell activity is suppressed by volatile agents [3]. Besides they enhance angiogenesis through hypoxia inducible factor-1α activity. Moreover, volatile anesthetics suppress cell-mediated immunity and promote cancer cell proliferation [4,5]. In addition volatile agents induce T-lymphocyte
and glomerular capillaries as a response during reperfusion causes fibrin deposits and platelet aggregation. This is accompanied by a decrease in Glomerular Filtration Rate (GFR) due to the reduction of renal perfusion. Again, adhesion of erythrocytes and leukocytes to the vascular endothelium contributes to the obstruction of the renal microvasculature. And ultimately, all these events cause thrombosis in renal vasculature and graft loss.

Activation of toll-like receptors by expression of adhesion molecules, polymorphonuclear cells and neutrophil infiltration as a result of microvascular plug and local tissue destruction is also exacerbated. Activation of complement by an alternative pathway also contributes to this situation. Acute tubular necrosis is responsible for 75% of acute renal injury. These necrotic tissues cause more inflammation and a vicious cycle with danger signals [9]. Therefore, the inhibition of IRI is responsible for the development of all these processes by maintaining nephron support with reduced graft immunogenicity and renal microvasculature. Despite advances in immunosuppression, long-term graft survival rates remain ideal. There are studies showing that immune rejection and chronic graft failure are not only responsible reasons, but also the severity of IRI can affect graft function. There is a relationship between prolonged ischemia duration and delayed graft failure, and even the severity of IRI and the frequency of acute rejection episodes. So even short-term hypoxia episodes damage the kidneys. Almost half of donor kidneys are exposed to short-term hypoxia in renal transplantation and lead to a failure rate of 10% in transplanted primary grafts. Restoring perfusion can lead to recovery of injured tissues from the ischemic phase, but may also cause more damage paradoxically. A kidney graft should carry the workload of two previously existing kidneys. However, this workload should be performed in spite of an inflammation as well as a rapidly decreasing nephron pool due to ischemia–reperfusion injury. Workload is becoming more complicated in cadaveric donors. An autonomic response develops with the donor cytokine storm. Thus, the amount of circulating catecholamine increases and this rises the level of the microvascular and parenchymal damage. Continuous process reduces circulating catecholamines and develops vasodilation bradycardia and tissue hypoxia.

**Ischemic preconditioning**

In fact, the whole story was described in 1986 by Murry et al. and is based on the definition of ischemic preconditioning. The sublethal doses of ischemia periods become injury-resistant against the following episodes of lethal ischemia. Many studies have shown that the use of volatile anesthetics before ischemic injury increases the tolerance of cell against IRI damage in brain and heart. Moreover, the effects of isoflurane in favor of renal protection are also reported.

To date, the choice of anesthetic agent in renal tx was only performed according to the personal preference of the anesthesiologist. However, the renoprotective effect of isoflurane by preconditioning has been shown after 24–72 hours and this protective effect of volatile agents has been mentioned. This effect is known to occur by signaling molecules.
such as hypoxia-inducible factor–1α (HIF–1α) and hypoxia inducible factor. Adenosine–producing, ecto–5'-nucleotidase (CD73), sphingosine–1–phosphate (SIP) via Sphinogine Kinase (SK) and IL–11 molecules such as transforming growth factor–β1 (TGF–β1) have been identified. The relation between sevoflurane and heat shock proteins including ERK, AKT and TGF–β1 has been revealed. The protection mechanism formed by volatile in the kidney is formed by different paths from the heart, liver and brain. Volatile agents affect on calcium haemostasis in heart, activate myocardial protection pathways with their immunomodulatory effects. The depletion of ATP stores causes an increase in intracellular free calcium, and it has been shown that volatiles inhibit the IR in the heart by inhibiting the Na–Ca exchanger. Renal protection of volatile anesthetics is based on the inhibition of renal tubular, endothelial and interstitial inflammation by secretion of cytoprotective and anti–inflammatory molecules.

Volatile agents interact with the plasma lipid membrane in renal tubular cells and induce TGF–β1 production by exogenous phosphoditylserin. Volatiles have antinecrotic, antiinflammatory and antiprotective effects in renal tubule cells with SK and SIP signaling and TGF–β1–induced CD73 increase. In addition, Toll–like receptor–mediated T–cell immune response occurs. They increase megakaryocyte maturation by inducing IL–11 release and inhibiting endothelial cell death. The regulatory T (T reg) cells protect the kidney from IR damage by suppressing inflammation damage. Preventing the opening of pores with changes in mitochondrial permeability after ischemia, which causes the release of proapoptotic factors and necrotic cell death, is another advocated mechanism [10]. Volatile agents also suppress natural immunity, by the effects on NK, monocyte, neutrophil and macrophages. They also suppress T lymphocytes of CD4, CD 8 with B lymphocytes. Clinically effective concentrations of volatile agents also reduce the activation of mitogen–activated protein kinases with a reduction in inflammation and apoptosis [11].

Ideal volatile agent

The inorganic fluoride amount formed by isoflurane and halothane biodegradation was found to be 3 – 5 and 1 – 2 μmol/L, respectively. These levels are below the renal toxic threshold however desflurane is not even metabolised. And compared to intravenous anesthetic agents, volatile decreases plasma creatinine, neutrophil and macrophage migration in kidney, decrease expression of proinflammatory and adhesion molecules, decrease necrotic and apoptotic damage [12]. Ham, et al. [13], conducted a study in human kidney cells. A 16 h of 1.25–2.5% isoflurane exposure followed 30 min renal ischemia and 4 h period of reperfusion. In contrast with pentobarbital, there was an increase in the synthesis of IL 11 in 1.2% isoflurane post–conditioning. This proves the cytoprotective effects of isoflurane. In a retrospective study, the records of 200 renal transplant patients were examined [14]. Postoperative creatinine levels of patients treated with Isoflurane (n= 103) and sevoflurane (n= 97) were evaluated at the 1st, 3rd and 6th months. There was no statistically significant difference between the isoflurane and sevoflurane groups in terms of postoperative serum creatinine, urea nitrogen and creatine clearance. The incidence of rejection was 4.9% in the isoflurane group and 9.3% in the sevoflurane group (P= 0.22), although not statistically significant. Postoperative dialysis requirement was also found to be higher in sevoflurane than isoflurane group (8.7% vs 13.4%, respectively). However, in a meta–analysis, the studies between 1995 and 2016 were evaluated and the main outcome was a change in plasma creatinine, urine protein and glucose excretion at 24th and 72nd h [15]. Sevoflurane and isoflurane were compared in terms of nephrotoxic potentials and no statistically significant difference was found in 6 studies.

Researchers have begun to study whether an almost non–metabolized inhalation agent, such as desflurane, would be more useful in the IRI. In an experimental study, in the first 15th minutes of reperfusion, post–conditioning was performed using desflurane and found protective on both renal function and tissue perfusion [16]. Guye, et al. [17], investigated tubular cell damage in rabbits, with desflurane preconditioning. Three hours of reperfusion phase was observed following a 45 min bilateral renal ischemia period. The histopathological damage score was found to be the lowest in desflurane and sham groups. Karadeniz, et al. [18], divided renal transplant donors into two groups: sevoflurane (n= 35 pairs) and desflurane (n= 30 pairs). Preoperatively and on postoperative 1st and 7th days, GFR, creatine, NGAL, IL–18 levels were analysed. No difference was found between the two groups. In another retrospective study, the effects of sevoflurane (n= 73) and desflurane (n= 71) were compared at postoperative 1st year [19]. Creatinine, BUN levels and glomerular filtration rate didnot differ between groups.

However, in several studies, the opposite results were obtained. The effects of desflurane and sevoflurane (n= 37 in each group) on hepatic and renal functions were evaluated in live donors undergoing right hepatectomy [20]. In sevoflurane group, there was an increase in BUN and creatine levels at 30th day with a reduction in GFR [20]. In a study comparing IV and inhalation anesthetics, it was shown that mRNA coding for chemokines with ICAM 1 and proinflammatory cytokine in the renal cortex was less in the volatile group and renal necrosis was rarely detected after 24 – 72h [21]. Another study included renal transplant patients from live donors and desflurane has been shown to provide better preconditioning of renal IR injury than sevoflurane and isoflurane [22]. In another study comparing the effects of volatile agents on neutrophil migration in reperfused organ, it has been shown that Sevoflurane and Desflurane reduce the neutrophil transmigration induced by IL–8 expression of CXR1 and CXCR2, which are ELR + receptors [23]. In addition, inhibition of CD11b (17% for sevoflurane and 27% for desflurane) has been shown to reduce the adherence of neutrophils to the endothelium.

Volatile Anaesthetic Protection of Renal Transplants–1 study aimed to compare the biochemical and clinical effects of propofol vs sevoflurane–based anaesthesia. Sixty pairs of patients were divided in 3 groups: PROP (donor and recipient received propofol), SEVO (donor and recipient received sevoflurane), and PROSE (propofol for donor and sevoflurane for recipient) [24]. No difference was found between the groups in terms of the amount of first–line renal injury molecule-1.
(KIM–1), N–acetyl–b–D–Glucosaminidase (NAG), and heart-type fatty acid binding protein (H–FABP). On the second day KIM–1 was higher in SEVO than PROP. However, the acute rejection rate in the second year was 35% in the PROP group and 5% in the PROSE group.

In a murine model, desflurane was found to be related with higher creatinine levels in comparison with halothane, isoflurane and sevoflurane [25]. This was consistent with renal tubular edema, dilatation, and necrosis in histopathological sampling. According to the results of this study, desflurane was found to be weaker in renal preservation than other anesthetic agents, however this was an experimental study and it was also stated that clinical trials are needed [25]

Conclusion

As a result, according to the information obtained from the literature, isoflurane has the most severe effects on hemodynamic variables. It has been shown that sevoflurane has less effect on renal blood flow, GFR and urinary output with less stable hemodynamics, including a reduction in mean arterial blood pressure. Moreover the nephrotic side-effect of inorganic fluoride and compound A, which is associated with the deflation of desflurane, is still under discussion and there is no clinical evidence. In renal transplantation the main goal should focus on preserving the kidney and maintain the optimal postoperative renal functions.

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