ABSTRACT

Nowadays, cancer presents a serious health problem worldwide. Oxidative stress has an important role in a variety of pathologies, and the search for an effective and well-tolerated antioxidant agent continues. Although cancer radiotherapy confers significant benefits, it causes remarkable tissue damage and subsequent apoptosis as a result of ionizing radiation by hydroxyl radicals (•OH) that follow the radiolysis of water. There is evidence, but inconclusive indicating that antioxidant capabilities of molecular hydrogen (H₂) ameliorate this oxidative stress and subsequent cancer complications and decrease death rates. This article discusses current knowledge on the implications of H₂ in the reduction of radiation therapy-induced adverse effects in cancer. It also highlights the outcomes of recent clinical trials. Relevant articles were identified through an up-to-date online search of PubMed, Medline, Scopus, Science Direct, PsycINFO, registered clinical trials, Google Scholar, and WHO database. The available evidence shows that H₂ as a therapeutic antioxidant selectively reduces the cytotoxic oxygen radicals, in particular, •OH, and may improve cancer conditions. Despite the non-specific mechanism of H₂, researchers have reported several positive effects of H₂ in cancer therapy, including delayed cancer progression, alleviation of radiotherapy and chemotherapy complications, and improved efficacy of conventional therapy when used in combination with H₂. It seems that H₂ has protective effects in the radiotherapy of many cancers. Nonetheless, there is a general scarcity of controlled human studies that investigate direct and longitudinal clinical and biochemical effects of H₂ on key cancerous changes. Thus, further research is required.

Key Words: Antioxidants, Carcinoma, Hydrogen-rich water, Radiation therapy, Oxidative stress

INTRODUCTION

Cancer is an abnormal growth of cells that tend to proliferate in an unrestrained manner and, in some cases, to metastasize to other areas of the body. It is the second leading cause of death globally, accounting for an estimated 9.6 million deaths. The most common types of cancers in men are the lung, prostate, colorectal, stomach, and liver, whereas, in women, they are cancers of the breast, colorectal, lung, cervical, and thyroid. Over the past half-century, progress has been achieved in basic and clinical research, resulting in a decrease in the incidence and death rates of some types of cancer, due, largely, to primary prevention and early detection of the disease, rather than the effectiveness of any drug.

Cancer often necessitates multimodal therapy which includes surgery, radiotherapy (RT), and chemotherapy, or a combination. RT deposits high-energy radiation and thus destroys cancerous tissues and provides a significant survival benefit. The opinion that cancerous cells are more sensitive than normal cells to radiation constitutes the basis of RT. The ability of cancerous cells to repair damaged DNA is limited as they tend to divide rapidly, while normal cells surrounding tumour lesions can withstand RT and recover. Despite efforts to deliver a maximum radiation dose to the target cancerous area and simultaneously protect the nearby normal tissues from radiation injury, there remains significant toxicity of RT to the latter tissues; a matter that leads to several side effects such as fatigue, irritation of skin and bladder, nausea, diarrhoea, constipation, painful bowel movements, sexual problems, scarring, fibrosis, and reduced quality of life. RT also increases long-term risks of cancer, central nervous system disorders, cardiovascular disease, and cataracts. Local treatment of a primary tumour with RT has produced unpredictable systemic effects on tumour growth, such as enhanced growth of distant metastases or inhibition of distant tumour growth that is known as the abscopal effect. Moreover, enhanced tumour...
Several radioprotectors and mitigators have received ROS represents the imbalance between the production of oxidants especially free radicals and ROS and the capacity of disposing of them through antioxidants. Several findings have implied that RT can paradoxically enhance tumour recurrence and metastasis via multiple pathways.

It is believed that most RT-induced symptoms are associated with increased oxidative stress (OS) and inflammation. Ionizing radiation produces toxic reactive oxygen species (ROS) and free radicals. ROS represents the imbalance between the production of oxidants especially free radicals and ROS and the capacity of disposing of them through antioxidants. Several radioprotectors and mitigators have received substantial interests to eliminate or reduce these side effects and thus improve therapeutic efficiency; however, their role in cancer treatment is unclear.

Molecular hydrogen (H₂) is a novel and safe medical gas. It can be dissolved in water and administered through drinking, inhalation, baths, and intravenous drip infusion of H₂-rich saline. Moreover, H₂ is a new antioxidant that scavenges free radicals and reduces oxidative load. In contrast to other antioxidants, gaseous H₂ can effectively enter the cell, organelle membranes, and diffuse ROS because of its neutrality and small size. Therefore, H₂ is recommended as an appropriate candidate for or contributor to the therapeutic strategies for many metabolic diseases, such as certain types of cancer, especially liver carcinoma. This article discusses the current literature addressing the role of H₂ in the reduction of RT-induced adverse effects in cancer and evaluates the findings of recent human clinical trials.

LITERATURE SEARCH

An up-to-date literature review was conducted on the role of H₂ in the reduction of RT-induced adverse effects in various types of cancer. The search was limited to recent English publications. Relevant articles were principally identified through an up-to-date online search of the PubMed, Medline, Scopus, Science Direct, Google Scholar, PsyINFO, registered clinical trials, WHO site, and other available databases. The search was performed using the following keywords or their combinations: hydrogen-rich water, gaseous molecular hydrogen, cancer, radiotherapy, radiotherapy-induced adverse effects, antioxidants, oxidative stress, reactive oxygen species, and free radicals. Included articles were mainly original observational, experimental, and clinical, case study, intervention, and cross-sectional researches in humans or animals. For further search accuracy, the reference lists of works were checked for additional publications from the major databases.

OXIDATIVE STRESS IN CANCER

OS is an imbalance between the production of free radicals and reactive metabolites, the so-called oxidants or ROS, and the protective mechanisms which involve their elimination referred to as antioxidants. This imbalance causes damage to cells and biomolecules with a potential effect on the entire organism. ROS are the products of oxygen-derived small molecules that play a role in normal cellular metabolism including oxygen radicals, such as superoxide anion (O²⁻), hydroxyl (•OH), peroxyl (RO₂•), and alkoxyl (RO•), as well as non-radicals. The latter can be transformed into radicals or serve the purpose of an oxidizing agent and include hydrogen peroxide (H₂O₂), hypochlorous acid (HOCI), ozone (O₃), and singlet oxygen (1O₂). ROS enhances DNA synthesis, cellular proliferation and survival, cellular migration and invasion, tumour metastasis, and angiogenesis. In aerobic cells, endogenous metabolic processes produce O₂•-, H₂O₂, and •OH. The continuous exposition of mitochondria to high levels of ROS leads to mitochondrial DNA damage and increase O and •OH levels in cellular apoptosis. The generation of ROS in cells exists in equilibrium with a large variety of antioxidant defence mechanisms that include enzymatic scavengers such as superoxide dismutase (SOD), catalase, glutathione peroxidase and peroxiredoxins, and non-enzymatic scavengers like vitamins C and E, glutathione, lipoic acid, carotenoids, and iron chelators.

Tumour cells produce ROS in larger quantities than normal cells elevating OS in these cells. ROS damages DNA in many chronic inflammatory diseases and a wide variety of cancer types. ROS can initiate tumorigenicity and subsequent tumour promotion and progression by damaging DNA. ROS also produces and introduces respectively gene mutations and structural alterations into the DNA during the initiation stage of cancer. Furthermore, ROS plays key roles in the stimulation of cell signalling pathways in intra- and extracellular environmental conditions, regulation of gene mutations, and balance of cell proliferation and apoptosis. Peroxisome proliferator-activated receptor-γ, nuclear factor-xB, β-catenin/Wnt, activator protein 1, nuclear factor erythroid 2-related factor 2, tumour protein p53, and hypoxia-inducible factor-1-alpha are among the many transcription factors that can be activated by OS. ROS controls and mediates the effects of C-radiation and various chemotherapeutic agents used to treat cancer. It is known that chronic inflammation caused by long-term ROS activates the effector molecules. ROS also alters the malignant transformation and the expression of genes involved in immune, inflammatory responses, carcinogenesis, and metastasis. The hypermetabolic state is one of the characteristics of malignant carcinomas that results in a persistent OS state in a cellular microenvironment. As a result, the utilization of antioxidants that antagonize ROS seems to be a feasible strategy in cancer therapy.

OXIDATIVE DAMAGE OF RADIATION

Radiation energy in the exposure pathway causes direct detrimental biological effects by targeting several biomolecules,
mainly DNA, proteins, and lipids.\textsuperscript{26,27} Hydroxyl radicals target DNA forming 8-hydroxydeoxyguanosine (8-OHdG), a biomarker of carcinogenesis, from deoxyguanosine.\textsuperscript{28} The initial formation of ROS, a result of H$_2$O radiolysis, intervenes in the radiation-induced DNA lesions, which leads to indirect detrimental biological impacts.\textsuperscript{28} The generation of HO$^\cdot$, ionized water (H$_2$O$^\cdot$), hydrogen radicals, and hydrated electrons are the quick result of exposure of water to ionizing radiation. The reaction of the initially produced radicals generates hydrogen peroxide (H$_2$O$_2$) and superoxide anion (O$_2^-\cdot$). The radiation-induced increase of ROS could damage cellular constituents and induce OS; this is because ROS is produced endogenously, and its level is regulated by several antioxidant defence mechanisms.\textsuperscript{29}

Free radicals target the lipid layer of cell membranes.\textsuperscript{28} ROS reacts with membrane polyunsaturated fatty acids.\textsuperscript{30} The process involves the abstraction of the bis-allylic position of these fatty acids either by HO$^\cdot$ or by a thyl radical (RS$^\cdot$) forming peroxyl radicals. The latter can abstract a hydrogen atom from another fatty acid, inducing the so-called peroxidation reactions.\textsuperscript{29} Malondialdehyde (MDA), acrolein, and 4-hydroxy-2-nonenal are some of the break-down products of hydroperoxides that are considered chemical indicators of lipid peroxidation reactions or even indices of defective permeability and fluidity of cell membranes.\textsuperscript{29,31}

**RADIOThERAPY IN CANCER**

Cancerous cells have a degree of self-sufficiency that causes them to not respond to the signals which activate the normal cell cycle leading to uncontrolled growth and proliferation of transformed cells.\textsuperscript{1,12} If the proliferation of cancerous cells continues, it can be fatal.\textsuperscript{32} It is estimated that metastasis is responsible for about 90% of cancer deaths.\textsuperscript{33} The type of cancer, its locality, and stage of progression determine the selection of treatment of cancer and its progress. Some of the traditional and most widely used treatment methods are surgery, RT, and chemotherapy, or a combination.\textsuperscript{4} Hormone-based therapy, anti-angiogenic modalities, stem cell therapies, and immunotherapy are some of the modern modalities.\textsuperscript{32} More than half of the cancer patients receive RT during their illness; RT is of prime importance, especially in patients with untreated tumours or incompletely resected tumours and for those with recurrent disease.\textsuperscript{34} RT can be used to downstage primary tumours, to reduce the risk of recurrence in the adjuvant setting, and in the palliative setting, to improve the quality of life at each stage of the disease.\textsuperscript{10} Treatment with surgery, often followed by RT is used in most breast cancer patients in stages I, II, or III. About half of women (49%) with stage I or II breast cancer undergo breast-conserving surgery followed by RT.\textsuperscript{35} Women (56%) diagnosed with metastatic disease (stage IV) most often receive radiation and/or chemotherapy alone.\textsuperscript{35}

Before surgery, RT is often applied to disrupt the ability of cancer cells to grow and divide, slow their growth, and shrink tumour areas.\textsuperscript{5} The use of RT is based on the theory that cancerous cells are more sensitive to radiation than normal cells as the former cells have a limited ability to repair damaged DNA and tend to divide more quickly, while the latter cells surrounding tumour lesions can withstand RT and recover.\textsuperscript{36} The mechanism underlying this theory lies in the fact that the damaged DNA is unable to replicate, and thus cell division is halted, resulting in the death of cells.\textsuperscript{36} Targeting normal cells that lie in the peripheries of the main tumorous mass is the main adverse effect of RT. Nevertheless, improved imaging techniques for accurate targeting of the cancer mass, in addition to the ability of normal cells to regain normal function faster than cancer cells, could minimize the damage caused by RT.\textsuperscript{32} Fatigue, nausea, diarrhoea, and dry mouth, loss of appetite, hair loss, sore skin, and depression are some of the acute radiation-associated side effects. The probability of radiation-generated complications is linked to the size or area of the radiation treated body parts, the given dose of radiation and its fractionation and rate of application, and individual radio-sensitivity.\textsuperscript{7}

RT remains the most effective non-surgical technique to achieve control of malignant tumors.\textsuperscript{32-35} The past two decades have witnessed a rapid rise in technological advancement aimed at improving endurance, accuracy, and efficacy through RT used more than a century ago. On the other hand, there is evidence to suggest that the various changes caused by radiation in the tumour environment can also pose a metastatic risk that may offset the long-term effectiveness of treatment. Several theoretical mechanisms have been largely suggested by which radiation exposure can increase the risk of metastases. These include the direct release of tumour cells into the circulatory system, systemic effects of the tumour, irradiation of normal tissues, and changes caused by radiation in the phenotype of tumour cells.\textsuperscript{37} It is a new scientific topic for radiologists to examine highly effective low-toxic radiation protectants. The focus has always been on deploying ideal radiation protectants in the radiation field.\textsuperscript{28,38}

**ANTIOXIDANT ACTIVITY OF MOLECULAR HYDROGEN**

The oxidants in ROS are reduced by H$_2$. When selectively dissolved in the cultured medium, H$_2$ reduces the strongest oxidants, such as OH and ONOO$^-\cdot$, in cell signals.\textsuperscript{29} However, H$_2$ does not disturb the cellular levels of O$_2$, NO$^\cdot$, or H$_2$O$_2$.\textsuperscript{27} ROS is also involved in metabolic oxidation-reduction reactions in cell-free systems. Because OH is strong enough to interact with H$_2$, it can be a sign of the oxidative strength of ROS. Hydroxyl radicals (·OH) produced by radiolysis or photolysis of H$_2$O significantly reduced by H$_2$ treatment leading to decrease levels of OH in cultured cells, thus protecting the mitochondria from OH.\textsuperscript{21}
H₂ has promising physical-chemical properties as a therapeutic antioxidant. It is smaller than molecular oxygen and is electrically neutral. It allows it to easily penetrate cell membranes and spread into cellular organelles, mainly the nucleus and mitochondria. Moreover, H₂ has a very mild reactivity so that it does not interact with important physiologically relevant ROS that is involved in cell signaling. It also does not affect physiology, temperature, blood pressure, pH, or pO₂, nor has it been reported to be toxic at much higher levels than clinically effective doses. H₂ excess simply expires across the lungs when much is delivered. H₂ treatment enhances endogenous antioxidant enzymes and thus contributes to improved OS. Catalase, SOD, and glutathione peroxidase are the important cellular antioxidant enzymes. Table 1 summarizes the physical-chemical properties of H₂ that determine its antioxidant therapeutic benefits.

Table 1: Physical-chemical properties and therapeutic features of molecular hydrogen

| Physical-chemical properties | Therapeutic features |
|-----------------------------|---------------------|
| Low molecular weight        | Easily diffuses across cellular membranes to reach subcellular compartments |
| Small size and high diffusivity | Can cross the blood-brain barrier |
| Strong covalent bond between H atoms | Stability at room and body temperature |
| H₂ molecule is non-polar | Slightly soluble in water at atmospheric pressure |
| Gas at room temperature | Multiple routes (oral, injection and inhalation) |
| Endogenous gas | Well tolerated |
| Reducing agent | Selective antioxidant effects |
| Selective reducing agent | No effect on redox homeostasis |
| Reaction with OH radicals and inhibition of lipopolysaccharide/interferon-γ-induced nitric oxide production | Anti-inflammatory |
| Reducing/eliminating ‘OH and ONOO’ | Anti-apoptotic |
| High level of H₂ is well tolerated | Biologically inert and safe |

**RAIOPROTECTIVE EFFECT OF MOLECULAR HYDROGEN**

Molecular hydrogen has appeared as a promising cancer treatment either as a preventive agent or in combination therapy with anticancer drugs. The consumption of hydrogen-rich water (HRW) may reduce the side effects of anticancer drugs by reducing OS and improving metamorphosis due to decreased apoptosis. H₂ also protects the immune system through radiation protection action. Moreover, H₂ may reduce radiation-induced blood injury, as well as save depletion of white blood cells and platelets. HRW causes telomere shortening in cancer cells, suppressing tumour angiogenesis by clearing intracellular ROS as well as suppressing gene expression and secreting vascular endothelial growth factors.

Several side effects of RT are believed to be associated with increased OS and inflammation due to ROS generation during RT. Daily consumption of HRW is a potential new treatment strategy to improve the quality of life after exposure to RT. It has been reported that the life quality of patients with liver carcinoma who were given a placebo decreased significantly during the first month of RT. One of the most common complaints in patients undergoing RT is symptoms of the digestive system. Compared to patients consuming placebo, patients consuming HRW had significantly less appetite loss and fewer taste disorders, with no significant difference in the average degrees of vomiting or diarrhoea. The biological reaction to RT-induced OS without compromising antitumor effects was reduced by HRW consumption.

It has been reported that OH was significantly decreased in cultured cells using H₂ treatment by radiolysis or photolysis of H₂O and thus protecting the mitochondria. H₂ also penetrates the biological membranes and diffuses into organelles, thereby reducing the cellular levels of ATP synthesized in the mitochondria and the nucleus. H₂ effectively reduces cyclooxygenase-2, a marker of OS, in immune-positive neurons due to its antioxidant and anti-inflammatory neuroprotective effects. Induction of inflammatory cytokines and inhibition of cell signalling factors activates the anti-inflammatory and anti-allergic properties of H₂. Moreover, H₂ has been shown to reduce the expression of several pro-inflammatory factors, including tumour necrosis factor (TNF)-α, interleukin (IL)-6, IL-1β, IL-10, IL-12, and chemokine ligand 2, intercellular adhesion molecule 1, nuclear factor-κB, high mobility group box 1 protein, and prostaglandin E. H₂-rich saline reduces serum diamine oxidase, TNF-α, IL-1β, IL-6, tissues MDA, protein carbonyl and myeloperoxidase activity, as well as discouraging pro-apoptotic players, including c-Jun N-terminal kinase and caspase-3. 44-45 IL-4 serum level decreased significantly after H₂ inhalation. H₂ gas inhalation upregulated SOD activity and significantly reduced the increased level of MDA and myeloperoxidase in allergic asthmatic mice. 21,46 The protective effect of H₂ against the development and invasion of the tumour enables it to act as an antitumor factor. Hence, the electrically neutral HRW was shown as an antioxidant to counteract ROS, inhibition of cancer cell proliferation, and invasion, together with the removal of intracellular oxidants.

Increased antioxidant capacity as indicated by decreased levels of oxidative products, increased activities of antioxidation-related enzymes and decreased early and late levels...
of pro-inflammatory cytokines in serum and tissues are the three main positive effects of the treatment with H₂ on organ damage. H₂ has also been used to treat many OS-associated diseases, such as cardiovascular disorder. Regardless of the form that is used, H₂ gas or H₂ water, treatment with H₂ improves the quality of life of patients receiving chemotherapy or RT. Energy metabolism, measured by O₂ consumption and CO₂ expiration, was stimulated by drinking HRW. These results indicate the potential advantage of H₂ in improving obesity, diabetes and metabolic syndrome. Consuming HRW can prevent arteriosclerosis more effectively than other antioxidants and may delay the development and progression of Parkinson’s disease. The brain OS was also reduced by continuous consumption of HRW. Oral HRW is an effective antioxidant and anti-inflammatory agent that reduces chronic allograft nephropathy. Accumulated data also show the possibility of H₂ as an anti-ageing solution and in wellness applications, especially sports and injuries.

H₂ therapy can work with cancer treatments such as surgical removal, chemotherapy, and RT, which often lead to systemic inflammation, to restore tissue function. H₂ rapidly spreads to reduce cytotoxic and inflammatory radicals in tissues. The antioxidant properties of H₂ gas or H₂ water have been shown to improve the quality of life of cancer patients during chemotherapy. Nephotoxicity, mortality, and body weight loss caused by cisplatin were reduced by inhaling 1% of H₂ gas or drinking H₂ water. The level of renal apoptosis was also reduced by drinking H₂. Most of the symptoms caused by radiation are believed to be associated with increased ROS and inflammation during RT significantly affecting the patient’s quality of life. HRW consumption reduces biological interactions with the radiation-induced OS without damaging antitumor activities. Inflammation in OS-related cancer can be protected by inhaling H₂ gas and giving H₂ orally. This improves the antitumor effect of cancer management. H₂ may act alone or in conjunction with another treatment to suppress tumour growth by inducing apoptosis, reducing proliferation, regulation of structural maintenance of chromosome 3, and inhibiting cell cycle-related factors.

Table 2 presents a summary description of some studies on the therapeutic potentials of molecular hydrogen in cancer.

| Cancer                          | Research design                | Study population                                      | Main findings                                                                                      | Reference |
|---------------------------------|-------------------------------|-------------------------------------------------------|-----------------------------------------------------------------------------------------------------|-----------|
| Tongue carcinoma                | In vitro human cell line models | Human tongue squamous carcinoma-derived cell line HSC-4 (RCB1902) | Pt-NC-supplemented HD-water is a novel agent against tongue cancer due to its cancer progression-regressive abilities | 49        |
| Liver cancer                    | A randomized, placebo-controlled study | 49 patients receiving radiotherapy for liver tumour | Hydrogen-rich water reduces radiation-induced oxidative stress without affecting antitumor action | 9         |
| Lung cancer                     | In vitro human cell line models | Human lung epithelial cell line A549 cells | Hydrogen protects against irradiation lung damage without toxicity | 50        |
| Lung cancer                     | In vitro human cell line models | Human NSCLC A549 cell line | Hydrogen-rich saline with a PI3K inhibitor, LY294002, reduces cancer proliferation and promotes apoptosis | 51        |
| Colorectal cancer               | Controlled, randomized, single-blind trial | Cancer A549 and H1975 and normal BEAS-2B cell lines | Hydrogen inhibits cancer progression through down-regulating SMC3 | 52        |
| Colorectal cancer               | Human clinical trial phase II  | 152 patients with colorectal cancer | Hydrogen-rich water alleviates mFOLFOX6-related liver injury | 53        |

Pt-nc= Platinum nano colloid; mFOLFOX6= A chemotherapy consisting of leucovorin calcium (folic acid), fluorouracil, and oxaliplatin; PI3K= Phosphatidyl inositol-3 kinase; LY294002= A morpholine-containing drug; SMC3= Structural maintenance of chromosome 3; PD 1+= A protein found on T cells.

The gastrointestinal tract ranks the second-most sensitive organ to irradiation injury during cancer RT after the bone marrow. Injection of H₂-rich saline before radiation in a mouse model protected the gastrointestinal endothelia from RT-induced injury, decreased plasma MDA and intestinal 8-OHdG levels, and protected plasma levels of endogenous antioxidant enzymes such as SOD and glutathione peroxidase.

Lungs are also radiosensitive to pneumonitis in acute and subacute settings and pulmonary fibrosis in chronic settings. Pretreatment of H₂ reduced OS products, mainly...
4-hydroxy-2-nominal and 8-OHdG. The levels of apoptosis-associated proteins, including Bax and active caspase 3 in irradiated A549 cells, after 24-hour incubation with H₂-rich solution, were significantly reduced by H₂. Five months after irradiation, lung fibrosis, Ashcroft scores, and type III collagen deposition were reduced by H₂ treatment.²⁸,⁵⁰

Due to their postmitotic state, cardiac myocytes are relatively resistant to radiation damage.⁵⁹ Endothelial cells are known to be sensitive to radiation, and their damage is associated with the pathophysiology of most forms of cardiac injuries, which may result from loss of alkaline phosphatase activity of capillary endothelial cells.⁶⁰,⁶¹ In addition to myocardial degeneration, perivascular and interstitial fibrosis are seen. H₂ pretreatment proved to have cardioprotective properties by decreasing MDA and 8-OHdG levels.²⁸

CONCLUSION

Collectively, the role of antioxidants in preventing and treating cancer has been well studied, but the majority of research has not paid much attention to molecular hydrogen. In this context, H₂ has antioxidant, anti-inflammatory, and antiinflammatory effects by its selective removal of free radicals. H₂ treatment can alleviate the harmful effects of chemotherapy and RT to improve the quality of life for cancer patients. H₂ treatment may also delay the development of cancer; combined use of H₂ with other anticancer drugs may enhance anticancer effects in treatment. H₂ is then included as a treatment, with highly reactive ROS, and effective diffusive action in cells. Characteristics of the strength of body temperature in mammalian cells, a virtually event-free tolerance profile, and the ability to administer therapy in a variety of ways to fit a patient or indication treatment, with minimal cost-effective surgical intervention. The expanded nature of the effects of H₂ means that it has therapeutic potential across a wide range of medical applications. The definition of H₂ as a type of antioxidant, cannot explain all its radioprotective effects. The exact mechanism and signal pathway involved in the protective role of H₂ in ionizing radiation injury needs further studies in the future. Only a few studies describe how H₂ exerted its effect not only as an antioxidant. For the first time, H₂ may become a gaseous signaling molecule like nitric oxide, carbon monoxide, and hydrogen sulfide. However, several randomized clinical trials are needed to confirm whether H₂ treatment is applicable in the clinical setting and whether it affects the efficacy of RT. Although the field is still relatively new, H₂ appears promising in preventive care and treatment of ROS-related diseases.

ACKNOWLEDGEMENTS

This study was supported by the University of Jordan, Amman, Jordan, Slovak Academy of Sciences, Bratislava, Slovakia, and Al-Quds University, Al-Quds, Palestine. The authors are also grateful to authors/editors/publishers of all those articles, journals and books from where the literature for this article has been reviewed and discussed.

Conflict of interest: The authors declare no conflict of interest.

REFERENCES

1. Blass BE. Editorial for cancer virtual issue. ACS Med Chem Lett 2017; 8 (12):1205-1257.
2. World Health Organization. Cancer. [cited 12 September 2018]. Retrieved from: https://www.who.int/news-room/fact-sheets/detail/cancer.
3. Chen JB, Kong XF, Lv YY, Qin SC, Sun XJ, Mu F, et al. “Real world survey” of hydrogen-controlled cancer: a follow-up report of 82 advanced cancer patients. Med Gas Res 2019;9(3):115-121.
4. Holman FA, Bosman SJ, Haddock MG, Gunderson LL, Kusters M, Nieuwenhuijzen GA, et al. Results of a pooled analysis of IOERT containing multimodality treatment for locally recurrent rectal cancer: results of 565 patients of two major treatment centres. Eur J Surg Oncol 2017;43(1):107-117.
5. Baskar R, Dai J, Wenlong N, Yeo R, Yeoh KW. Biological response of cancer cells to radiation treatment. Front Mol Biosci 2014;1:24.
6. Bergamo A, Sava G. Chemical and molecular approach to tumor metastases. Int J Mol Sci 2018;19(3):843.
7. Slezak J, Kura B, Babal P Barancik M, Ferko M, Frimmel K. Comparison of 3D CRT and IMRT treatment plans. Acta Inform Med 2013;21(3):211-212.
8. Lawrie TA, Green JT, Beresford M, Wedlake L, Burden S, Davidson SE, et al. Interventions to reduce acute and late adverse gastrointestinal effects of pelvic radiotherapy for primary pelvic cancers. Cochrane Database Syst Rev 2018;1:Cd012529.
9. Kang KM, Kang YN, Choi IB, Gu Y, Kawamura T, Toyoda Y, et al. Effects of drinking hydrogen-rich water on the quality of life of patients treated with radiotherapy for liver tumors. Med Gas Res 2011; 1(1):11.
10. Villalta M, Raffat M, Graves EE. Effects of radiation on metastasis and tumor cell migration. Cell Mol Life Sci 2016;73(16):2999-3007.
11. Vetrani C, Costabile G, Di Marino L, Rivellese AA. Nutrition and oxidative stress: a systematic review of human studies. Int J Food Nutr Sci 2013;64(3):312-326.
12. Citrin D, Cotrim AP, Hyodo F, Baum BJ, Krishna MC, Mitchell JB. Radioprotectors and mitigators of radiation-induced normal tissue injury. Oncologist 2010;15(4):360-371.
13. Slezak J, Kura B, Babal P Barancik M, Ferko M, Frimmel K, et al. Potential markers and metabolic processes involved in the mechanism of radiation-induced heart injury. Can J Physiol Pharmacol 2017;95(10):1190-1203.
14. Nakala U, Thakkar S, Krager KJ, Breen PJ, Compadre CM, Aykin-Burns N. Antioxidant tocols as radiation countermeasures (Challenges to be addressed to use tocols as radiation countermeasures in humans). Antioxidants 2018;7(2):33.
15. Kurokawa R, Seo T, Sato B, Hirano SI, Sato F. Convenient methods for ingestion of molecular hydrogen: drinking, injection, and inhalation. Med Gas Res 2015;5:13.
16. Slezak J, Kura B, Frimmel K, Zalesak M, Ravingerova T, Vizenczova C, et al. Preventive and therapeutic application of mo
lecular hydrogen in situations with excessive production of free radicals. Physiol Res 2016;65(1):S11-28.
17. Runtuwene J, Amitani M, Amitani M, Asakawa A, Cheng KC, Inui A. Hydrogen–water enhances 5-fluorouracil-induced inhibition of colon cancer. Peer J 2015;3:e859.
18. Ohsawa I, Ishikawa M, Takahashi K et al. Hydrogen acts as a therapeutic antioxidant by selectively reducing cytotoxic oxygen radicals. Nat Med 2007;13(6):688-694.
19. Ning Y, Shang Y, Huang H, Zhang J, Dong Y, Xu W, et al. Attenuation of cigarette smoke-induced airway mucus production by hydrogen-rich saline in rats. PLoS One 2013;8(12): e83429.
20. Reuter S, Gupta SC, Chaturvedi MM, Aggarwal BB. Oxidative stress, inflammation, and cancer: how are they related? Free Radic Biol Med 2009;49(11):1603-1616.
21. Yang Y, Zhu Y, Xi X. Anti-inflammatory and antitumor action of hydrogen via reactive oxygen species. Oncol Lett 2018;16(3):2771-2776.
22. Redza-Dutordoir M, Averill-Bates DA. Activation of apoptosis signalling pathways by reactive oxygen species. Biochim Biophys Acta.2016;1863(12):2977-2992.
23. Wang J, Yi J. Cancer cell killing via ROS: to increase or decrease, that is the question. Cancer Biol Ther 2008;7(12):1875-1884.
24. Takaki A, Kawano S, Uchida D, Takahara M, Hiraoka S, Okada H. Paradoxical roles of oxidative stress response in the digestive system before and after carcinogenesis. Cancers 2019;11(2):213.
25. Rojas V, Hirshfield KM, Ganesan S, Rodriguez-Rodriguez L. Molecular characterization of epithelial ovarian cancer: implications for diagnosis and treatment. Int J Mol Sci 2016;17(12):2113.
26. Kura B, Babal P, Slezk J. Implication of microRNAs in the development and potential treatment of radiation-induced heart disease. Can J Physiol Pharmacol. 2017; 95(10): 1236-1244.
27. Chuai Y, Qian L, Sun X, Cai J. Molecular hydrogen and radiation protection. Free Radic Res. 2012. 46(9):1061-1067.
28. Qian L, Shen J, Chuai Y, Cai J. Hydrogen as a new class of radioprotective agent. Int J Biol Sci 2013;9(9):887-894.
29. Pouget JP, Georgakilas AG, Ravanat JL. Targeted and off-target ( bystander and abscopal) effects of radiation therapy: redox mechanisms and risk/benefit analysis. Antioxid Redox Signal 2018;29(15):1447-1487.
30. Ayala A, Muñoz MF, Argüelles S. Lipid peroxidation: production, metabolism, and signaling mechanisms of malondialdehyde and 4-hydroxy-2-nonenal. Oxid Med Cell Longev 2014;360438.
31. Holley AK, Miao L, St. Clair DK, St. Clair WH. Redox-modulated phenomena and radiation therapy: the central role of superoxide dismutases. Antioxid Redox Signal 2014;20(10):1567-1589.
32. Abbas Z, and Rehman S. An overview of cancer treatment modalities. Neoplasms. 2018; 19: 139.
33. Seyfried TN, Huysentruyt LC. On the origin of cancer metastasis. Can J Physiol Pharmacol. 2017; 95(10): 1236-1244.
34. American Cancer Society. Cancer Treatment & Survivorship Facts & Figures 2019-2021. 2019; Available from: https://www.cancer.org/content/dam/cancer.org/research/cancer-facts-and-statistics/cancer-treatment-and-survivorship-facts-and-figures/cancer-treatment-and-survivorship-facts-and-figures-2019-2021.pdf.
35. Abuaawad et al.: Role of molecular hydrogen in cancer radiotherapy
36. Blyth BJ, Cole AJ, MacManus MP, Martin OA. Radiation therapy-induced metastasis: radiobiology and clinical implications. Clin Exp Metastasis 2018; 35(4):223-236.
37. Qian L, Li B, Cai J, Gao F. The hypothesis of an effective safe and novel radioprotective agent: hydrogen-rich solution. West Indian Med J 2010;59(2):122-124.
38. LeBaron TW, Kura B, Kalocayova B, Tribulova N, Slezk J. A new approach for the prevention and treatment of cardiovascular disorders. Molecular hydrogen significantly reduces the effects of oxidative stress. Molecules 2019; 24(11):2076.
39. Li S, Liao R, Sheng X, Luo X, Zhang X, Wen X, et al. Hydrogen gas in cancer treatment. Front Oncolo 2019; 9: 696.
40. Yang Y, Li B, Liu C Chuai Y, Lei J, Gao F, et al. Hydrogen-rich saline protects immunocytes from radiation-induced apoptosis. Med Sci Monit 2012; 18(4):144-148.
41. Shirahata S, Hamasaki T, Teruya K. Advanced research on the health benefit of reduced water. Tren Food Sci Technol 2012; 23(2):124-131.
42. Yang Q, Ji G, Pan R, Zhao Y, Yan P. Protective effect of hydrogen gas in cancer treatment. Front Oncolo 2019; 9: 696.
43. Kang KM, Kang YN, Choi IB, Gu Y, Kawamura T, Toyoda Y, et al. Effects of drinking hydrogen-rich water on the quality of life of patients treated with radiotherapy for liver tumors. Med Gas Res 2011;1(1):11.
44. Varga V, Nemeth J, Oláh O, Tóth-Szüki V, Kovács V, Remzsov G, et al. Molecular hydrogen alleviates asphixia-induced neuronal cyclooxygenase-2 expression in newborn pigs. Acta Pharmacol Sinica 2018;39(8):1273-1283.
45. Y Hattori, Kotani T, Tsuda H Mano Y, Tu L, Li H, et al. Maternal molecular hydrogen treatment ameliorates lipopolysaccharide-induced rat fetal lung injury. Free Radic Res 2015;49(8):1026-1037.
46. Zhang N, Deng C, Zhang X, Zhang J, Bai C. Inhalation of hydrogen gas ameliorates airway inflammation and oxidative stress in allergic asthmatic mice. Asthma Res Pract 2018;4:3.
47. Ohta S. Recent progress toward hydrogen medicine: potential of molecular hydrogen for preventive and therapeutic applications. Curr Pharm Des 2011;17(22):2241-2252.
48. Lemaire M, Barbier F. Hydrogen: therapeutic potential in wellness and medicine. J Aging Res Clin Practice 2017;6:14-22.
49. Saitoh Y, Yoshimura Y, Nakano K, Miwa N. Platinum nanocolloid-supplemented hydrogen-dissolved water inhibits growth of human tongue carcinoma cells preferentially over normal cells. Exp Oncol 2009;31(3):156-162.
50. Terasaki Y, Ohsawa I, Terasaki M Takahashi M, Kunugi S, De Dong K, et al. Hydrogen therapy attenuates irradiation-induced lung damage by reducing oxidative stress. Am J Physiol Lung Cell Mol Physiol 2011;301(4): L415-426.
51. Jiang Y, Liu G, Zhang L, Cheng S, Luo C, Liao Y, et al. Therapeutic efficacy of hydrogen-rich saline alone and in combination with PI3K inhibitor in non-small cell lung cancer. Mol Med Rep 2018;18(2):2182-2190.
52. Wang D, Wang L, Zhang Y, Zhao Y, Chen G. Hydrogen gas inhibits lung cancer progression through targeting SMC3. Biomed Pharmacother 2018;104:788-797.
53. Yang Q, Ji G, Pan R, Zhao Y, Yan P. Protective effect of hydrogen-rich water on liver function of colorectal cancer patients treated with mFOLFOX6 chemotherapy. Mol Clin Oncol 2017;9(5):891-986.
54. Akagi J, Baba H. Hydrogen gas restores exhausted CD8+ T cells in patients with advanced colorectal cancer to improve prognosis. Oncol Rep 2019;41(1):301-311.
55. Xiao HW, Li Y, Luo D, Dong JL, Zhou LX, Zhao SY, et al. Hydrogen-water ameliorates radiation-induced gastrointestinal toxicity via MyD88’s effects on the gut microbiota. Exp Mol Med 2018;50(1):e433.
56. Qian L, Cao F, Cui J, Huang Y, Zhou X, Liu S, et al. Radioprotective effect of hydrogen in cultured cells and mice. Free Radic Res 2010;44(3):275-282.
57. Para AE, Bezjak A, Yeung IW, Van Dyk J, Hill RP. Effects of genistein following fractionated lung irradiation in mice. Radiother Oncol 2009;92(3):500-510.
58. Simone II CB. Thoracic radiation normal tissue injury. Semin Radiat Oncol 2017;27(4):370-377.
59. Han X, Zhou Y, Liu W. Precision cardio-oncology: understanding the cardiotoxicity of cancer therapy. NPJ Precis Oncol 2017;1(1):31.
60. Donnellan E, Phelan D, McCarthy CP, Collier P, Desai M, Griffin B. Radiation-induced heart disease: A practical guide to diagnosis and management. Cleve Clin J Med 2016;83(12):914-922.
61. Khan M, Iqubal A, Joshi A, Ajai K. Role of antioxidants in prevention of cancer: a review. Int J Curr Res Rev 2014;06(09):80-88.
62. Purohit C, Jain S, Kaur J. Total antioxidant capacity- a biomarker in oral precancer patients. Int J Curr Res Rev 2014;06(20):21-24.