

OBSTETRICS

Fear of the unknown: ionizing radiation exposure during pregnancy

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Ionizing radiation during pregnancy can negatively impact a fetus. In light of the Fukushima nuclear plant disaster in Japan, we discuss existing knowledge on the health effects of radiation and preventive measures for pregnant women. Overall, the risk of exposure to radiation is limited but severe defects can result from fetal radiation exposure >100 mGy equivalent to 10 rad (>1000 chest x-rays). While such high-level exposure rarely occurs during single medical diagnostic procedures, caution should be exercised for pregnant women. As a protective public health measure in light of a disaster, evacuation, shielding, and elimination of ingested radioactive isotopes should all be considered. Detailed radiation reports with health effects and precautionary measures should be available for a population exposed to more than background radiation.

Key words: lactation, nuclear, pregnancy, protective measures, radiation

The disaster at the Fukushima Daiichi nuclear plants in Japan has led to renewed fear around the world of the negative health effects of ionizing radiation.¹ Media reports of pregnant women fleeing Fukushima highlight the particularly disconcerting risk perceived for pregnant women and infants.²

In times of nuclear disasters or radiation exposure it is crucial for medical professionals to be well informed and to understand the nature and characteristics of radiation and its potential hazardous effects on health and, especially, pregnancy. This article provides guidance to understand the types of radiation and units of dose measurements, health

impact of high-dose radiation from disasters and on pregnancy and lactation, and measures that may be taken in the event of radiation exposure.

Radiation and measurement in dose units

Radiation, ie, any “energy that comes from a source and travels through some material or through space,”³ can be categorized as either ionizing or nonionizing. Nonionizing radiation “has enough energy to move around atoms in a molecule or cause them to vibrate, but not enough to remove electrons”⁴; examples include ultrasound waves, visible light, microwaves, and magnetic resonance imaging.

Ionizing radiation “has enough energy to remove tightly bound electrons from atoms, thus creating ions”⁴ and consists of either particulate or electromagnetic energy. Examples of particulate energy include alpha particles, which have a short travel range and cannot penetrate more than a single layer of skin, and beta particles, which have moderate penetrating power but can still only traverse a few millimeters of skin.⁵ While alpha and beta particles generally do not pose a significant health threat due to their lack of penetrating power, when inhaled, ingested, or injected, they may act as carcinogens or initiate other adverse health effects.⁶

Electromagnetic energy includes gamma rays and x-rays, both of which can travel thousands of meters in air and penetrate many materials, including human tissues. As a result, exposure to these types of radiation can result in significant damage to organs.⁵

The International System of Units (SI) has 4 unit measures (Table 1).^{7,8} Generally, the dose equivalent, ie, sievert (Sv), is used to measure the public exposure to radiation as it accounts for factors such as the type of radiation, amount of time exposed, level of protection, and distance from the radiation source. In describing the potential radiation exposure from medical diagnostic equipment, gray (Gy) is the SI unit, but radiation absorbed dose (rad) is the predominant measure used. In this article, we adhere to the SI unit gray (Gy) or milligray (mGy) for readability and will provide the rad-converted amount in brackets for readers’ convenience.

When interpreting ionizing radiation exposure, “background” radiation should be considered. Ionizing radiation originates from space and natural resources, and exists everywhere including soil, water, and air. On average, a person is exposed to 2.4 mSv of background radiation every year.⁹ This background radiation translates into 1 mSv of background radiation for the fetus for a full-term pregnancy. The precise amount of background radiation exposure varies in different parts of the world, depending on the altitude and the quality of the atmosphere.¹⁰ Table 2¹¹⁻¹⁷ illustrates the estimated fetal radiation absorption dose for various events potentially experienced by pregnant women.

Health impact of high-dose radiation from a nuclear disaster

The International Atomic Energy Agency developed the International Nuclear Events Scale to measure the health significance and environmental impact of all events associated with the transportation, storage, and use of radioactive materials (Table

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TABLE 1

Commonly used measurements for ionizing radiation and their units^{7,8}

Variable	Commonly used units	SI units	Conversion
Radio activity ^a	Curie (Ci)	Becquerel (Bq)	1 Ci relates to 37 gigabecquerel (GBq)
	1 Ci = 1g of radium	1 Bq = 1 decay/s	1 GBq relates to 27 mCi
Exposure ^b	Roentgen (R)	Coulomb (C)/kg	1 R relates to 258 μ C/kg
			1 C/kg relates to 3876 R
Absorbed dose ^c	Radiation absorbed dose (rad)	Gray (Gy)	1 Gy = 100 rad
		1 Gy = 1 J/kg	1 rad = 0.1 Gy
Equivalent dose ^d	Roentgen equivalents man (rem)	Sievert (Sv)	1 Sv = 100 rem
		1 Sv = 1 Gy \times radiation weighting factor (Wr)	1 rem = 0.1 Sv

SI, international system of units.

^a Radio activity is measurement for source of radiation and depends on type and amount of material and distance from where measurement is taken. Conversion from curie to becquerel is not the same for every material, but this equation is commonly cited; ^b Exposure is only used for gamma and x-ray. Alpha, beta, and neutrons cannot be calculated in roentgen. Measurement of exposure can be done by Geiger counters (or other survey meters) that will give information on radiation per time period in a certain location. Dosimeters will calculate accumulative dose of exposure over time;

^c Absorbed dose is energy deposited by radiation (J/kg). Since tissue differs in density, same amount of radiation will give a different absorbed dose to different tissue, calculated using tissue-weighting factor; ^d Equivalent dose is dose calculated as if a body is homogeneously exposed to radiation, taking into account that tissues have different density and taking into account the impact factor of different radiation types. Impact factor is sometimes called radiation weighting factor (Wr). For x-ray, the gamma and beta radiation impact factor is 1 and therefore 1 Gy = 1 Sv. For alpha radiation, the impact factor is 20. Alpha radiation is more harmful for the human body. In medical practice, radiation exposure is mostly related to x-ray. Therefore, equation of 1 R = 1 rad = 1 rem is often accepted, although not totally reflecting reality.

Groen. Ionizing radiation and pregnancy. *Am J Obstet Gynecol* 2012.

3).¹⁸ Using the International Nuclear Events Scale, radiation exposure events are classified on a scale ranging from 1–7. Both the Chernobyl and Fukushima disasters were classified as a 7, the highest possible rating.

In a radiation disaster, the nature and intensity on health will depend on which areas of the body were exposed and what intake pathways were used for absorption. The most common health effect of high-dose radiation exposure is cell death; an effect that is positively used for cancer treatment. However, high-dose ionizing radiation can also alter the DNA of normal cells and cause uncontrolled cell divisions, thereby inducing cancer. In addition, uncontrolled and excessive exposure to high-dose radiation can damage organs and result in acute radiation sickness (including coagulopathy and immunity disorders), diarrhea, fever, burns, and coordination and equilibrium disturbances.^{19,20}

During the Chernobyl disaster, where the peak radioactivity reached 14 exabecquerel approximately 150 on-site emergency workers developed acute radiation sickness and 28 of them died as a result within a year.²¹ In addition to acute illness, many survivors of the initial exposure at Chernobyl, Nagasaki, and Hiroshima suffered long-term negative health conse-

quences that included leukemia; thyroid, breast, and skin cancers; and cataracts.^{22–29}

When looking specifically at the effects of radiation on a fetus, it is important to first note that the radiation dose that a pregnant woman is exposed to or absorbs may not directly transfer to the fetus. A fetus is partly protected from radiation injury by a pregnant woman's surrounding soft tissues and uterus, both of which generally stop alpha and beta particles from penetration if they are not ingested, injected, or inhaled;^{30,31} however, gamma and x-rays directed toward the abdomen of a pregnant woman who is not appropriately shielded can reach and harm a fetus. Of note is that the placenta can transfer radioactive ions ingested, injected, or inhaled by a pregnant woman and radioactive material that accumulates in the bladder of a pregnant woman may cause internal radiation exposure to the nearby fetus.³²

Effects of radiation in pregnancy

The effects of ionizing radiation on an embryo and fetus can include: pregnancy loss, malformations, neurobehavioral abnormalities, fetal growth retardation, and cancer. The first 4 categories of adverse pregnancy outcomes have a deterministic effect whereby a threshold or No-Adverse-Effect Level (NOAEL) ex-

ists; however, once the radiation amount exceeds a certain level, all individuals will be affected. After exceeding the NOAEL, a deterministic effect typically shows a gradient relationship with the absorbed dose—the larger the absorbed dose, the more severe the effect. Pregnancy loss does not show this gradient relationship, but due to the NOAEL it is considered a deterministic effect. On the other hand, cancer appears to have a stochastic effect whereby the more radiation given, the greater the chance of the disease. There is no defined threshold and the amount of radiation does not predict the severity of the disease.³³

The nature and extent of deterministic effects of radiation on pregnancy depends on the radiation dose and the trimester of the pregnancy. Pregnancy loss is most likely a result of high-dose ionizing radiation in the first trimester. Animal studies show that, during the first 2 weeks after conception (gestational age 3–4 weeks), a dose as small as 100–200 mGy (10–20 rad) can be lethal for an embryo.³⁴ Shortly thereafter, the threshold for fetal death increases to 250–500 mGy (25–50 rad), with the fetal death threshold increasing throughout gestation as the fetus develops.³⁴ The estimated radiation dose necessary to kill all embryos or fetuses <18 weeks' gestation is 5000

TABLE 2
Estimated fetal radiation absorption per procedure or event¹¹⁻¹⁷

Clinical suspicion	Procedure	Estimated fetal absorption (mGy) per procedure	Estimated fetal absorption (rad) per procedure
Pneumonia	X-ray chest	<0.01	<0.001
Pulmonary embolism	CT scan	0.06-0.96	0.006-0.096
	VP scan	0.1-0.37	0.01-0.037
Appendicitis	Ultrasound	Nonionizing radiation	Nonionizing radiation
	CT scan abdomen	8-49	0.8-0.49
	MRI	Nonionizing radiation	Nonionizing radiation
Nephrolithiasis	Ultrasound	Nonionizing radiation	Nonionizing radiation
	X-ray abdomen	1-4.2	0.1-0.42
	Pyelogram	1.7-10	0.17-1
	CT scan abdomen	8-49	0.8-4.9
	MRI	Nonionizing radiation	Nonionizing radiation
Breast nodule	Ultrasound	Nonionizing radiation	Nonionizing radiation
	Mammogram	0.07-0.2	0.007-0.02
Colon pathology	X-ray abdomen	1-4.2	0.1-0.42
	Barium enema	7	0.7
Trauma			
Spine injury	X-ray lumbar spine	6	0.6
	X-ray thoracic/cervical spine	<0.01	<0.001
	X-ray skull	<0.01	<0.001
Pelvic injury	X-ray pelvis	1.1-4	0.11-0.4
	CT scan pelvis	20-79	2.0-7.9
Abdominal injury	Ultrasound (FAST)	Nonionizing radiation	Nonionizing radiation
	CT scan abdomen	8-49	0.8-4.9
	MRI	Nonionizing radiation	Nonionizing radiation
Background radiation	None	1 mSv	0.1 rem ^a
Commercial flight	Round trip Toronto-Frankfurt	0.1 mSv	0.01 rem ^a
	100 h of commercial flying	1 mSv	0.1 rem ^a

General considerations: (1) All estimates have wide variation of estimation due to more exposure in more advanced pregnancies and different scanning techniques. (2) Procedures have different sensitivity and specificity, and therefore, estimated fetal exposure of ionizing radiation is not the only consideration to undertake an imaging procedure. The clinical maternal condition indicates the appropriate mode of examination for the pregnant patient. (3) MRI might have some fetal health hazards based on thermal and acoustical effects of MRI. These effects seem more theoretical and are not proven by limited available studies on MRI and pregnancy outcome.¹⁴ American College of Radiology states, however, that answers to the following questions should be documented before proceeding with MRI in pregnancy: (a) MRI will give information that cannot be acquired via other proven harmless means (ultrasonography). (b) Information given by MRI will affect care of patient or fetus during pregnancy. (c) Referring physician does not think it is prudent to wait until patient is no longer pregnant to obtain these data.⁷⁹

CT, computed tomography; FAST, focused assessment with sonography for trauma; MRI, magnetic resonance imaging; VP, ventilation perfusion scan.

^a 1 rem is comparable but not equivalent to 1 rad; see Table 1 for further explanation.

Groen. Ionizing radiation and pregnancy. *Am J Obstet Gynecol* 2012.

mGy (500 rad).³⁵ At term, the fetal risk equals the pregnant woman's risk at 20,000 mGy (2000 rad).^{34,36}

Malformation rates of a surviving fetus during the preorganogenesis stage are similar to nonradiated controls. This is not due to a lack of malformations, but rather that the radiation induces cell loss or chro-

mosome anomaly, which most likely inhibits the implantation of an embryo and results in a miscarriage. This all-or-nothing phenomenon has been confirmed by animal experiments^{34,37-41} and by observational studies of pregnant women in Europe who were exposed to the low-dose Chernobyl radiation fallouts.⁴²⁻⁴⁵

However, if a woman absorbs a radiation dose beyond the proposed NOAEL of 350-500 mGy (35-50 rad) during gestational weeks' 3-8, malformations such as microcephaly, microphthalmia, growth restriction, and cataract may occur.⁴⁶⁻⁴⁹

Neurobehavioral abnormalities are most likely to occur between gestational weeks

TABLE 3
International Nuclear Events Scale¹⁸

INES scale	Description	Implication
1	Anomaly	Unwanted exposure without noted harm; eg, lost or stolen radioactive transport package
2	Incident	Unwanted exposure >50 mSv/h or worker with nuclear material exceeding annual radiation exposure
3	Serious incident	Nonlethal unwanted radiation effects in population, eg, skin reddening or burns; exposure is >1 mSv/h
4	Accident with local consequences	1 death due to radiation; no need for public health countermeasures
5	Accident with wider consequences	>1 death and need for limited countermeasures
6	Serious accident	More deaths and possibly need for extensive countermeasures
7	Major accident	Widespread radioactivity causing negative environmental and health effects including radiation deaths; extensive countermeasures are needed

INES, International Nuclear Events Scale.

Groen. Ionizing radiation and pregnancy. *Am J Obstet Gynecol* 2012.

8-25 when a fetus develops its central nervous system. Studies have generally confirmed the negative impact of in utero exposure to high-dose radiation on neurological and mental development of the fetuses. According to these studies, a threshold level for severe mental retardation is 350-500 mGy (35-50 rad) <16 weeks of gestational age.^{48,50-52} After 16 weeks, the minimum dose for severe mental retardation is estimated to be 1500 mGy (150 rad).³⁶

The NOAEL for intelligence quotient (IQ) loss is difficult to define, due to the different ways IQ is measured. The current general consensus is that, for 8-15 weeks of gestational age, the NOAEL is around 100 mGy (10 rad), and for 16-25 weeks of gestational age, 500 mGy (50 rad). One study showed that radiation at the level of 1000 mGy (100 rad) resulted in the reduction of the fetus' IQ by as much as 25-30 points.⁵¹ Growth retardation can result from ionizing radiation during organogenesis at a level just below the lethal dose, but it is more frequently seen as a result of high exposure >1500 mGy (>150 rad) during midterm.³⁶

Radiation can cause cancer in the fetus; however, multiple studies have shown that in utero exposure to 1-time, high-dose radiation during a nuclear disaster does not necessarily lead to an increased risk of childhood cancer compared with normal controls.⁵³⁻⁵⁶ Another study compared pregnancy outcomes of nuclear disaster survivors and nonexposed controls and

noted that the childhood cancer risk was less for patients exposed in utero.⁵⁷

This is in contrast to the findings for low-dose radiation. Wakeford⁵⁸ compared results from 33 case-control studies that investigated the association between obstetrical radiography and the risk of childhood leukemia and calculated a relative risk of 1.32 (95% confidence interval, 1.19-1.46). This risk was not related to the gestational age, included a direct fetal exposure to radiation of ≥ 10 mGy (1 rad), and led to a 32% increase in the risk of leukemia.⁵³ However, given a baseline childhood cancer risk of 0.2-0.3%, the overall risk of cancer after in utero exposure to radiation still remains low.¹⁷

Controversy exists as to whether there is a radiation dose below which no deleterious effect on a fetus may occur, and if so, what that dose is. The International Commission on Radiological Protection stated that radiation exposure <100 mGy (10 rad) during pregnancy should not constitute medical grounds for termination of a pregnancy.¹⁷ While this seems to have been accepted by many,^{33,34,59,60} some researchers, including the American College of Obstetricians and Gynecologists, have indicated that the threshold for medical concern, particularly regarding congenital malformations, should be lowered to 50 mGy (5 rad).^{35,46,61} Exposure >1000 mGy (100 rad) seems to pose a serious risk to a fetus' central nervous system resulting in severe mental retardation as well as growth

retardation.³⁴ Table 2 gives further guidance on fetal exposure due to medical diagnostic procedures. In general, single exposure to these procedures is not likely to expose a fetus to a radiation dose >100 mGy (10 rad) or even the more conservative guideline of 50 mGy (5 rad).

Separate concerns need to be addressed with regard to radioactive iodine during pregnancy. The fetal thyroid is extremely active from ≥ 16 weeks and begins the uptake of iodine in increasing amounts. Radioactive iodine can have detrimental effects such as spontaneous abortion and hypo/hyperthyroidism, and can even lead to cretinism especially when the exposure occurs during gestational weeks 16-25.³⁵

Radiation exposure on infants and lactating women

Breast milk can become radioactive by a lactating woman's direct exposure to radiation on her breast or ingestion of radioactive pharmaceuticals or food. As with pregnancy, a lactating woman should be cautioned about the potential health effects before using medical diagnostics involving radiation. However, concerns about radiation exposure should not lead women to postpone or abandon critical medical treatment. X-ray exposure resulting from a single diagnostic procedure (eg, mammogram) is far below the threshold for adverse response.⁶² In fact, a mammogram is generally not consid-

ered a medical reason for cessation of breastfeeding.³²

When a woman has ingested, inhaled, or injected radioactive pharmaceuticals or food, the quantity of residual radioactive pharmaceuticals in breast milk can substantially vary depending on a woman's breast mass, milk production volume, and the half-life of the radiopharmaceuticals.⁶³⁻⁶⁵ Thus, to accurately assess the danger of radiation exposure resulting from lactation, an individual breast milk sample should be tested rather than relying on statistical information provided in the literature.

In most cases, the highest radiation concentration in breast milk is found 3-4 hours after administration of radioactive pharmaceuticals and the concentration level subsides afterward.⁶⁴ The residual radiation absorbed by a fetus through breast milk is generally not >3-10% of the total dose absorbed by a woman.⁶⁴ This is not a negligible dose, particularly because the health effects of radioactive substances in infants and children are more severe than in adults. An infant's exposure to 1 Gy (>10,000 chest x-rays) of the ionizing radiation increases the risk of thyroid cancer by a factor of 10, and the magnitude of this effect gradually decreases as a child grows older.⁶⁶

Research has not shown any conclusive relationship between lactating women's exposure to a low dose of radiation and diseases suffered by infants. On the other hand, a lactating woman's exposure to radioactive iodine, which has been found in the air, soil, and water around Fukushima after the nuclear explosion, raises serious health concerns because (radioactive) iodine is actively excreted in breast milk in concentrations as many as 30 times higher than the administrative dose.⁶⁴ In addition, the high metabolic rate of infants makes them more vulnerable to the negative health effects of radioactive iodine on the thyroid, such as development of thyroid cancer or noncancerous cysts/nodules. For these reasons, the Centers for Disease Control and Prevention recommend women who may have been exposed to radioactive iodine to stop breastfeeding.⁶⁷

Protection of pregnant women and fetuses from radiation exposure

Precautionary measures for pregnant women from the effects of radiation-related adverse health outcomes are essentially the same as those for the general public. These measures are based on the following 3 principles: maintaining a safe distance, shielding one's body from exposure, and avoiding ingestion of food and water contaminated with radioactive particles in the air, rain, or soil.⁶⁸

In case of a large-scale radiation disaster, such as the Fukushima incident, evacuation is the safest option. However, when such action is not feasible, all precaution should be taken to minimize the exposure to radioactive water, air, and soil. Windows and doors should be closed and sealed. Water and any food grown in the vicinity should be inspected for radiation contamination. Should outdoor movement be necessary, pregnant women should tightly shield their bodies to limit skin contact with radioactive air or rain. If there is concern of alpha particle exposure, they should cover their noses and mouths while outside to minimize inhalation.³⁰ In the event of exposure, immediately washing radioactive particles off the body with clean water is recommended to alleviate long-term radiation effects.^{5,69}

The potential harm to a fetus resulting from localized, limited exposure to radiation, such as the same received from an x-ray, is generally controllable through the use of lead-containing vests (0.35 mm of lead) shielding a pregnant woman's abdomen and pelvis from penetrating x-rays.^{70,71} Likewise, while it is advisable for pregnant health workers to avoid dealing with radioactive materials, it is nonetheless generally possible for them to safely operate radiotherapy equipment as long as they remain behind a shielding wall or make proper use of a lead vest. When workers fully comply with safety protocols, the radiation exposure of health care workers generally remains <1 mSv per year.^{20,72-74}

While x-ray imaging should only be used on pregnant women for vital health care needs, protective measures in the imaging setup, such as reducing the field

size, intensifying screens, limiting exposure times, and reducing the absolute dose, should be used to minimize potentially hazardous effects.⁷⁵

Interventions to enhanced elimination of radioactive materials

The decorporation process, which refers to elimination of radioactive materials from the body, involves prevention of radioactive ion uptake and/or enhanced secretion and excretion of radio nucleotides. The best known measures for decorporation of radioactive iodine is the ingestion of potassium iodine (KI). Once the thyroid is saturated with nonradioactive iodine, it will no longer absorb any more iodine, radioactive or not, even if it is available for uptake. The KI tablets, which contain nonradioactive iodine are thus used to block radioactive iodine from being absorbed into the thyroid gland and causing deleterious health effects.⁶⁷

KI ingestion is most effective when taken directly before or after the radiation exposure; a 4-hour delay in KI intake can reduce the protective effect by as much as 50%.⁷⁶ The recommended dosage for each individual differs depending on the age and health status. Generally speaking, 1 tablet is estimated to provide approximately 24 hours of protection.⁷⁶ As mentioned earlier, children's and pregnant women's thyroids are more active than those of other individuals. However, they should be cautious in ingesting more KI than the recommended dose—excessive KI intake could cause iodine-induced hypothyroidism in the neonate or the nursing infant. In addition, the fetus could be indirectly harmed by maternal iodine-induced hypothyroidism, causing long-term mental and neurological development problems.⁷⁷

Although breastfed infants are already exposed to KI through breast milk, the World Health Organization recommends providing an additional dose of KI to any infants at risk of being exposed to radioactive iodine to ensure that a sufficient level of KI is present in their thyroids.⁷⁸

It is important to note that KI is not helpful in preventing the negative health effects of any radionucleotides other than iodine. Moreover, KI protects only thyroids from radioactive iodine, not other

parts of the body. Thus, pregnant and/or lactating women should not rely on KI as a sole means of protection against radiation's health risks.⁷⁸

To protect the body from the harms imposed by radioactive caesium, ingestion of ferric hexacyanoferrate (Prussian blue/Berlin blue) is recommended. One tablet of ferric hexacyanoferrate, when accompanied by bowel movement that properly excretes radioactive materials, has been shown to reduce the uptake of caesium by a factor of 2-3.⁶⁹ The substance is also considered to be safe for pregnant women and fetuses.

For protection against radioactive radium or strontium, ammonium chloride can be used. However, it has a tendency to cause constipation and, in some cases, kidney/liver failure. In addition, there are not enough data to confirm the safety of ammonium chloride use during pregnancy or lactation.⁶⁹ Decorporation methods other than those mentioned above also exist, but they should be used only under close supervision of a radiospecialist.

Lastly, many of the radionuclide elimination methods rely heavily on kidney function as well as urination. Thus, in addition to medication, frequent hydration and voiding are critical for pregnant women to minimize the harm from radiation exposure to fetuses.¹⁶ Further, the public should keep in mind that, due to variations in individual situations and health conditions, one should consult with a radiospecialist before taking any precautionary or intervention measures.

Conclusion

In general, the risk of exposure to radiation causing health effects is limited, but can have a significant impact during disasters such as the recent incident in Fukushima, Japan. Public health departments should have detailed radiation reports available as soon as possible in case of a nuclear incident and inform the public of possible health effects and protective measures. Physicians and public health departments should be trained to give objective advice to concerned citizens on the health effects of radiation to their unborn children, which includes reassurance for levels of exposure <100 mGy (10 rad).

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