Original Article

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Customized 3D Printed Bolus for Breast Reconstruction for Modified Radical Mastectomy (MRM)

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We aim to develop the breast bolus by using a 3D printer to minimize the air-gap, and compare it to commercial bolus used for patients undergoing reconstruction in breast cancer. The bolus-shaped region of interests (ROIs) were contoured at the surface of the intensity-modulated radiation therapy (IMRT) thorax phantom with 5 mm thickness, after which the digital imaging and communications in mdicine (DICOM)-RT structure file was acquired. The intensity-modulated radiation therapy (Tomo-IMRT) and direct mode (Tomo-Direct) using the Tomotherapy were established. The 13 point doses were measured by optically stimulated luminescence (OSLD) dosimetry. The measurement data was analyzed to quantitatively evaluate the applicability of 3D bolus. The percentage change of mean measured dose between the commercial bolus and 3D-bolus was 2.3% and 0.7% for the Tomo-direct and Tomo-IMRT, respectively. For air-gap, range of the commercial bolus was from 0.8 cm to 1.5 cm at the periphery of the right breast. In contrast, the 3D-bolus have occurred the air-gap (i.e., 0 cm). The 3D-bolus for radiation therapy reduces the air-gap on irregular body surface that believed to help in accurate and precise radiation therapy due to better property of adhesion.

Key Words: Modified radical mastectomy, Breast radiation treatment, 3D printing, Bolus

Introduction

The electron beam that applies compensator has been applied for treating patients with skin diseases.[1)] Furthermore, bolus is applied to patients undergoing modified radical mastectomy (MRM) for breast, which is the tissue equivalent for patients undergoing breast reconstruction after surgery and radiation treatment.[2)]

For increase the skin dose, the bolus needs to be in contact with the skin surface of the patient. The bolus generally consist of tissue-equivalent materials such as paraffin wax, polystyrene, Lucite, super Stuff and super Flab.[3)] However, due to the anatomical structure of patients and after effects of breast surgery, various irregularities were seen on the surface, such as the deformation, dent and protrusion. Commercialized-bolus also resulted in formations of air-gaps between the skin and bolus, which resulted in the reduction of the surface dose and central axis depth dose during the treatment.[4-6)] Various studies were undertaken to minimize the air-gap formation.[7,8)]

Three-dimensional (3D) printing technology has been utilized in various fields and development of customized geometric structures for individual patients. In particular, treatment of the scarp in brain, MRM in breast, patient organ-shaped phantom and dedicated phantom for evaluation of medical imaging were developed in the field of radiation therapy and medical physics.[9-14)] Kim et al.[11)] analyzed dosimetric parame-

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ters of the 3D printed customized bolus, and reported that it provided a good dose escalation and contact with the irregular surface of the RANDO phantom.

In this study, we propose to develop the bolus by using 3D printer (i.e. 3D bolus) for minimizing the air-gap. We further compare the 3D-bolus to the commercialized-bolus for patient undergoing reconstruction for breast cancer.

Materials and Methods

1. 3D-bolus production

The 3D printer (CubeX, 3D system, USA) applied the fused deposition modeling (FDM) technique to dissolve the poly lactic acid (PLA) inside the nozzle and fabricate the customized object from the bottom. 3D printing modeling process for production of 3D-bolus was performed based on computed tomography (CT) images of thorax phantom (IMRT thorax phantom, CIRS, USA), with breast-shaped phantom to simulate the same condition as the patient with MRM. The acquired phantom image was exported to the MIM system (MIM version 6.5.8 MIM software, USA) which created the 3D-bolus structure. Using the MIM system software, the bolus-shaped regions of interest (ROIs) were contoured in the surface of the IMRT thorax phantom with 5 mm thickness, after which the digital imaging and communications in medicine (DICOM)-RT structure file was acquired. The CT DIMOM files were converted to STL files by 3D Slicer (3D Slicer, open source software, USA) and Blender (Blender, v2.77a, open source software, USA) programs, which were then used to produce a 3D-bolus (output speed: 30 mm/s; Layer thickness: 0.5 cm). Finally, the 3D-bolus file converted to output type by using the KISSlicer program (KISSlicer, open source software, USA), and printed material as the PLA. Fig. 1 shows a 3D printer and the 3D-bolus created.

2. Treatment planning

A water-equivalent gel was inserted into the space between the 3D-bolus and phantom for complete removal of air and CT image of 3D-bolus with thorax phantom was acquired. All contouring in this study followed the reference 'Radiation Therapy Oncology Group (RTOG) 0319'[15] and were as defined in the MIM system. The planning target volume (PTV) was outlined with an expansion of 10 mm from the Clinical target volume (CTV). The intensity-modulated radiation therapy (Tomo-IMRT) and direct mode (Tomo-Direct) by using the Tomotherapy (Accuray, Hi-art II, USA) were established. Field width, pitch, and modulation factor were 5.02 cm, 0.430, and 2.0, respectively. A prescription dose of 50.4 Gy in 28 daily fractions of 1.8 Gy covered to 95% isodoses of PTV daily.

3. Evaluation: the applicability of the developed 3D-bolus and dosimetric comparison

To demonstrate the applicability of the developed 3D bolus, the air-gap of the right angle between the bolus and flexion breast phantom surface, as shown in Fig. 2 was calculated by using two different CT image sets, for both the commercial-bolus and 3D-bolus. And the volume of air-gap was obtained by MIM. For dosimetric comparison, treatment planning of a Tomo-IMRT and Tomo-Direct for each application of commercialized and 3D-bolus was evaluated by analyzing the dose volume histogram (DVH) to the PTV, and to normal organs such as the breast, lungs and heart. The delivered dose to right

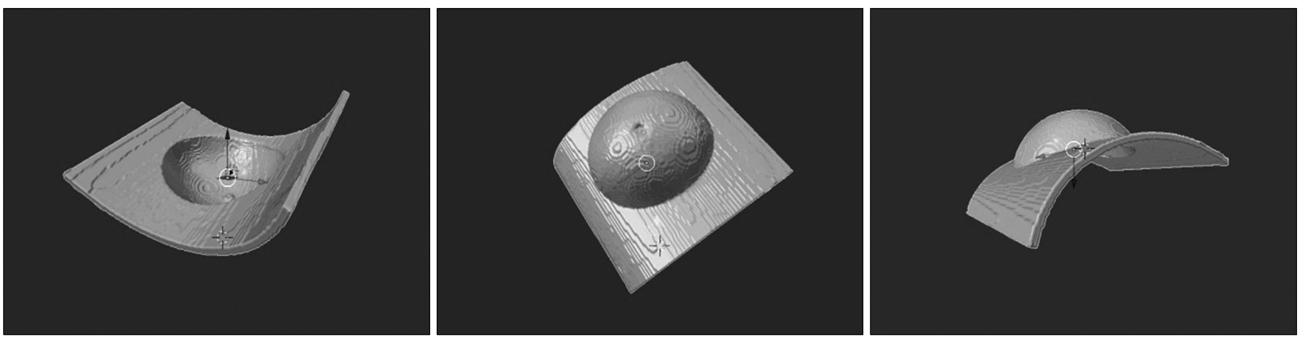

Fig. 1. 3D-bolus file converted output type by using KISSlice program.

lung was calculated for the maximum, minimum and mean dose (Gy). In addition, total 13 point doses, as shown in Fig. 3, were measured by using the optically simulated luminescence dosimetry (OSLD, InLight® nanoDot™, LANDAUER, USA).

Results

1. The applicability of the developed 3D bolus

The magnitude of the air-gap in the commercialized-bolus was greater than that in 3D-bolus. The air-gap of commercialized-bolus was 0.8 cm of the minimum and 1.5 cm of the maximum, at the points L1, M3, S1 and I3, located at the periphery of breast. And the air-gap volume of commercialized-bolus was 107.45 cm^3 at the same point. Commercial bolus are also known to have large air-gaps during breast radiation treatment. The air-gap for 3D-bolus could not be verified (i.e., 0 cm^3), since 3D-bolus were well contacted with the phantom surface (Fig. 4).

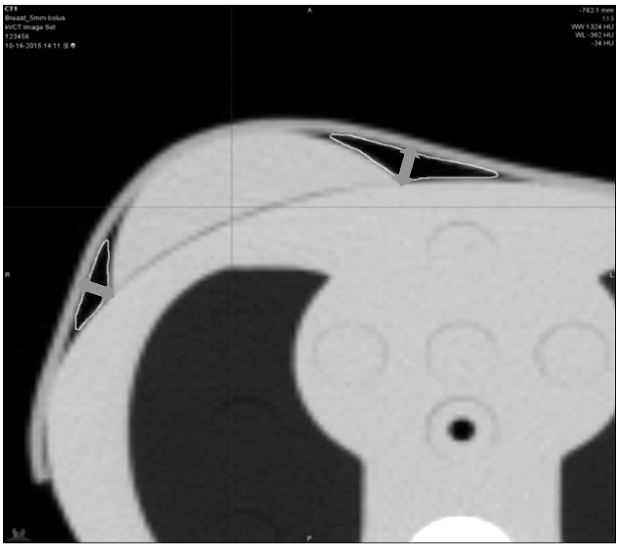

Fig. 2. Air-gap measurement of distance and volume.

2. Dosimetric comparison

The mean dose for 13 point measured dose with 3D-bolus was well matched with the planning dose, but higher than the mean dose with commercialized-bolus for both treatment techniques. Tables 1 and 2 show the planning dose and measurement dose with OSLD for 13 points at the phantom surface in Tomo-IMRT and Tomo-Direct, respectively. For mean dose for 13 point as evaluated by Tomo-IMRT, the measured dose was 160.0 cGy and 161.4 cGy, and planning dose was 162.0 cGy and 163.2 cGy, for commercialized-bolus and 3D bolus, respectively. Evaluating the mean dose for 13 point for Tomo-Direct, the measured dose was 174.5 cGy and 178.7 cGy, and planning dose was 173.5 cGy and 177.0 cGy for commercialized-bolus and 3D bolus, respectively.

To quantitatively evaluate the applicability of 3D bolus, we analyzed the measurement data. The percentage change of mean measured dose with commercial bolus and 3D-bolus was 2.3% and 0.7% for the Tomo-direct and Tomo-IMRT, respectively. Also, the maximum difference dose was 22.2 cGy for Tomo-direct and 16.6 cGy for Tomo-IMRT.

Table 3 shows the delivered dose to right lung for the two treatment plans with each bolus (Tomo-IMRT versus Tomo-Direct). In Tomo-IMRT, a mean dose of right lung was 10.02± 7.59 Gy and 8.68±7.31 Gy for commercialized- and 3D-bolus, respectively. In Tomo-Direct, mean dose was 2.98±7.56 Gy

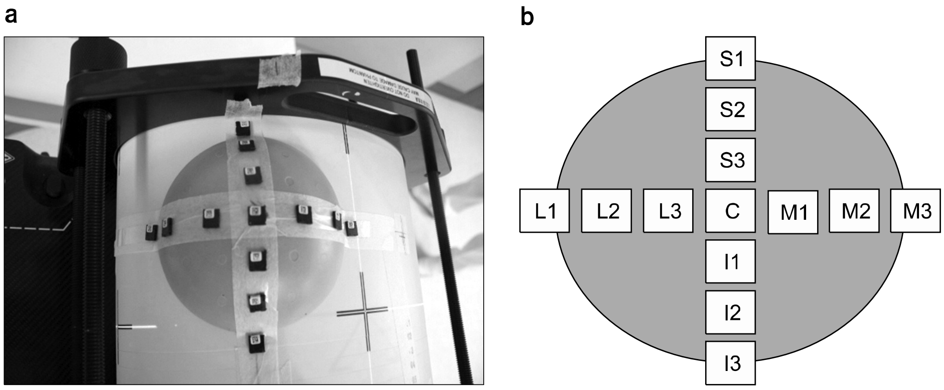

Fig. 3. The IMRT thorax phantom with OSLDs (a) and total of 13 points in horizontal, vertical and central location in breast phantom (b) (L: Lateral, M: Medial, C: Center, S: Superior, I: Inferior).

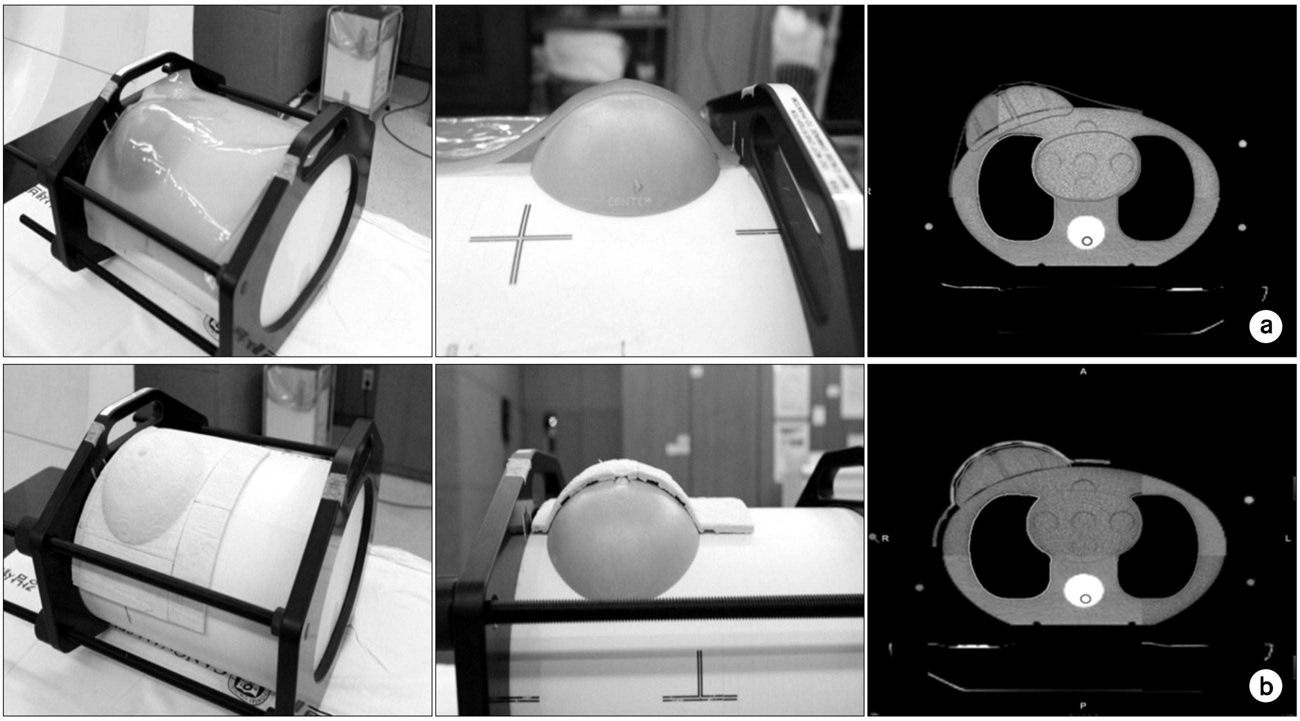

Fig. 4. MVCT image after applying (a) commercialized-bolus and the (b) 3D-bolus.

Table 1. OSLD measurement at 13 points for Tomo-IMRT treatment planning.

Point		Commercialized-bolus			3D-bolus		
		Planning (cGy)	Measure (cGy)	Difference (%)	Planning (cGy)	Measure (cGy)	Difference (%)
Lateral	L1	171.0	167.8	−1.9	181.0	190.0	5.0
	L2	163.0	168.3	3.3	176.0	167.5	−4.9
	L3	179.0	175.2	−2.1	182.0	191.7	5.4
Medial	M1	171.0	173.4	1.4	181.0	174.6	−3.6
	M2	166.0	177.5	6.9	178.0	171.0	−3.9
	M3	174.0	171.0	−1.7	185.0	186.8	1.0
Center	C	186.0	195.3	5.0	183.0	185.1	1.1
Superior	S1	171.0	166.4	−2.7	157.0	155.0	−1.3
	S2	181.0	191.7	5.9	182.0	177.8	−2.3
	S3	182.0	178.4	−2.0	181.0	186.3	3.0
Inferior	I1	177.0	174.7	−1.3	181.0	185.8	2.7
	I2	172.0	171.8	−0.1	182.0	191.8	5.4
	I3	163.0	157.2	−3.6	153.0	160.0	4.6
Mean±SD		173.5±7.2	174.5±10.0		177.0±10.0	178.7±12.2	

L: Lateral, M: Medial, C: Center, S: Superior, I: Inferior.

and 2.66±6.71 Gy for commercialized- and 3D-bolus, respectively. Overall, the dose with 3D-bolus was smaller than with commercialized-bolus (Fig. 5).

Discussion

In recent times, patients of breast reconstruction are increasing because of insurance coverage. Their purpose is not about

Table 2. OSLD measurement at 13 points for Tomo-Direct treatment planning.

Point		Commercialized-bolus			3D-bolus		
		Planning (cGy)	Measure (cGy)	Difference (%)	Planning (cGy)	Measure (cGy)	Difference (%)
Lateral	L1	140.0	135.3	−3.4	139.0	145.0	4.3
	L2	169.0	175.1	3.6	171.0	168.2	−1.6
	L3	173.0	170.3	−1.6	171.0	170.8	−0.1
Medial	M1	162.0	166.7	2.9	177.0	183.3	3.6
	M2	167.0	168.7	1.0	170.0	183.1	7.7
	M3	113.0	110.0	−2.7	109.0	105.0	−3.7
Center	C	169.0	155.8	−7.8	160.0	141.7	−11.4
Superior	S1	164.0	158.2	−3.6	159.0	155.0	−2.5
	S2	179.0	182.4	1.9	183.0	175.8	−3.9
	S3	173.0	172.7	−0.2	171.0	165.2	−3.4
Inferior	I1	169.0	164.7	−2.5	176.0	159.5	−9.4
	I2	173.0	167.0	−3.5	186.0	189.0	1.6
	I3	155.0	157.3	1.5	150.0	157.3	4.8
Mean±SD		162.0±17.7	160.3±18.9		163.2±20.8	161.4±22.3	

L: Lateral, M: Medial, C: Center, S: Superior, I: Inferior.

Table 3. Evaluation treatment planning of comparison between commercialized- and 3D-bolus with 5 mm thickness for right lung.

Mode	Measurement (Gy)					
	Commercialized-bolus			3D-bolus		
	Max	Min	Mean±SD	Max	Min	Mean±SD
Tomo-IMRT	37.0	0.4	10.0±7.6	41.4	0.4	8.7±7.3
Tomo-Direct	47.2	0.1	3.0±7.6	48.8	0.1	2.7±7.0

Max: maximum value, Min: minimum value, SD: standard deviation.

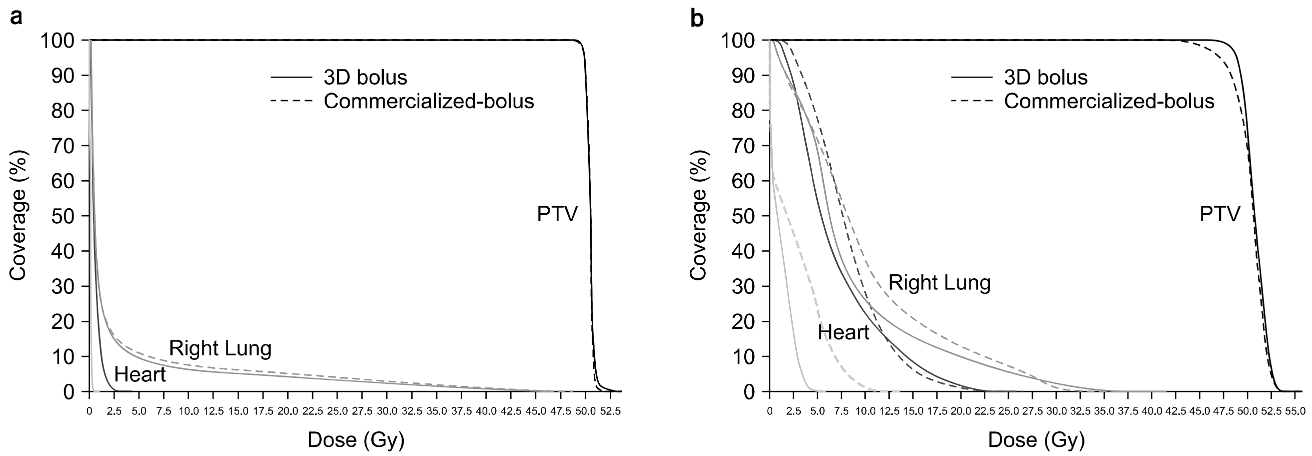

Fig. 5. DVH of (a) IMRT and (b) Direct applied for commercialized-bolus and 3D printed bolus.

cosmetic merit, but to relieve the emotional pain associated with breast resection of women. In addition, this surgery prevents other complications arising from an imbalance in the body due to breast asymmetry.[16,17] In this study, improvement in the advantage of the 3D printing technology has been used for customizing the bolus.

Applying the bolus to minimize the air-gap in breast cancer treatment has a very significant role. As shown in Fig. 4, the ir-gap could be minimized using 3D-bolus, as compared to commercialized-bolus. The air-gaps at locations L1, M3, S1, I3 were calculated since the most air-gaps were founded at the periphery of the breast and also because other locations are better attached. The minimum and maximum values of the air-gap using commercialized-bolus were 0.8 cm and 1.5 cm. On the other hand, the CT image set with 3D-bolus above the phantom showed minimal space for air. This diminished air-gap could be interpreted as a follows. First, the customized 3D-bolus is well matched with phantom, as compared to a universal bolus. Commercial bolus also has the flexibility to be well matched with patient skin, but the highly customized 3D-bolus was produced based on patient CT data set and to be tailored to the patient skin. Second, the layer occurs according to the CT slice thickness during the production of the 3D bolus. As the slice is thicker, more of the layer occurs, making flexion compensation difficult. In order to correct the layer, a thin and smooth slice (thickness 1.5 mm) should be used when produced by CT scan, to enable making the final surface even. Lastly, a water-equivalent gel is inserted into the space between the 3D-bolus and phantom for complete removal of air.

In specific point with commercialized-bolus, higher skin dose was delivered than 3D-bolus (13.9 cGy for S2 with Tomo-Direct and 14.1 cGy for C with Tomo-IMRT). On the other hands, the treatment with a same dose resulted in a greater difference (22.2 cGy for L1 with Tomo-Direct, and 16.6 cGy for M1 with Tomo-IMRT) with 3D bolus than commercialized-bolus. According to the research by Yousaf Khan, in case of 1cm air-gap and a small field size of 5 cm×5 cm, the variation of the surface dose and Dmax appears greater, whereas at 10 cm×10 cm, the variation of the surface dose appears lesser. In case of approximately 2 cm air-gap, it is reported that the skin dose reduced by about 7%. This study concluded that the cause in variation is not considerable in a wide field, such as the whole breast. Also, Tomo-IMRT and Tomo-Direct of the right lung mean dose entering the OAR, was 10.7% and 13.3%, respectively. In our study, we researched the thorax phantom of the right breast. However, in a similar study of the left breast, including the heart or with MRM, the dose entering the OAR would decrease.

The recent technological advances and the decline in price of a 3D printer have resulted in a significant development in this treatment technique, with a corresponding expansion in the range of its applications. However, areas such as the production cost, time, personnel expenses, and assembly cost, still need to be resolved. Advancement of the 3D printer has resulted in improving its utilization in radiation therapy, along with achievements in various other fields. Customizing 3D-bolus using 3D printers will be beneficial to many, especially in the field of medicine. As the study shows, the need for precision manufacturer 3D-bolus and OLSD calibration, accurate dosimetry in high doses or electrons is possible, but the OSLD limit was confirmed in photon (180 cGy). These precise corrections are required. The radiation emitted should be minimized in radiation therapy when applying the bolus to head and neck cancer with many flexions, to high protrusions and the depressions due to surgery, and if the region includes critical organs. Thus, using customized 3D-bolus for radiation therapy would serve to reduce the air-gap on irregular body surfaces, and is believed to help in accurate and precise radiation therapy because of a better degree of adhesion. The study of the 3D-bolus used for radiotherapy of the treatment area, including the critical organ, needs to be further understood.

Conclusion

To minimize the air-gap of breast cancer patient with bolus, a customized 3D printed bolus has been developed and the dosimetric evaluation performed. We suggest minimizing the slice thickness of CT image for 3D printing modeling, flattening the surface of 3D printed bolus, and application of water equivalent gel into the space between patient and 3D bolus. It may be appropriate to treat various anatomy cases for customized 3D printed bolus, including extremities and head and neck.

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