Development of a cylindrical ultrasound applicator for Intracavitary Hyperthermia

Rena J. Lee, Hyunsuk Suh

Department of Radiation Oncology, Ewha Womans University Hospital, Seoul, Korea

In this study, a cylindrical ultrasound applicator is developed for the treatment of vagina and rectum in combination with high dose rate brachytherapy.
A cylindrical transducer (PZT-8, l=1.5 cm, thickness=1.5 mm, OD=2.5 cm) was used as an energy source for induction of hyperthermia. Three single-element applicators were constructed to examine the performance of the PZT material. Vector impedance was measured to determine driving frequency. The efficiencies of the elements were determined using a radiation force technique to evaluate the feasibility of using the applicator as a hyperthermia source. A multi-element ultrasound applicator was designed using the PZT-8 material for the treatment of vagina.
Results from the vector impedance measurements showed maximum magnitude at 1.78, 1.77, and 1.77 Mhz for applicator 1,2, and 3, respectively. The radiation force measurements showed that the acoustic power of 40 watts was obtained in all three elements. The average efficiencies of the elements were 61.4, 65.2, and 54.0% for element 1, 2, and 3, respectively.
The designed ultrasound hyperthermia applicator could be used in combination with high dose rate brachytherapy for the treatment of vagina and rectum. The use of this applicator with intracavitary brachytherapy could offer improved tumor control by increasing radiosensitivity of the tumor.

Key words: Ultrasound, Intracavitary Hyperthermia, Vagina, Rectum, High Dose Rate Brachytherapy

INTRODUCTION

Intracavitary application of high dose rate brachytherapy has promising potential for improving therapeutic outcome of vaginal and rectal cancer when it is combined with other modalities such as external beam radiation therapy, chemotherapy, and brachytherapy.[1-6] Although those treatments have demonstrated improved local control and long term survival for the patients treated with combined modalities, local recurrence is still well known pattern of failure.[7] The persisting failure stimulated interest in the development of other modalities, such as hyperthermia.

Studies of hyperthermia, which increases tumor temperatures above 42 C for 30-60 min, have shown both in vitro and in patients that it can significantly enhance the effect of radiation therapy by producing local tumor regression and prolonging the duration of regression.[8-12] Several different modalities of intracavitary hyperthermia are developed and currently used to treat patients with prostate, vaginal, and rectal cancers. These include microwave, radiofrequency capacitance, radiofrequency current, ultrasound, and hot water.[13-18] Studies with ultrasound probes showed that ultrasound applicators have the potential to provide an improved spatial localization and control of heating distribution over the other intracavitary hyperthermia techniques. Thus several advanced intracavitary ultrasound transducers with linear array applicators were developed and used for the treatment of prostate.[19-21]

For the treatment of cervical cancer, intracavitary brachytherapy applicators are used because it is easily accessible via body cavity. Despite the fact that com-

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Corresponding Author : Rena Lee, 서울시 양천구 목동 911-1
이대목동병원 방사선종양학과
Tel : (02) 650-5337, 5331
Fax : (02) 654-0363

bined application of hyperthermia and radiation improve the treatment outcome, no intracavitary ultrasound applicators are designed and constructed.

This study describes the design and construction of a clinical ultrasound hyperthermia applicator for the patients with locally recurrent rectal and cervical cancer who underwent radical hysterectomy.

MATERIALS AND METHODS

1. Array design and Construction

For the treatment of entire vagina with high dose rate brachytherapy, a cylindrical applicator was designed and constructed. In the single element applicators, the ultrasound was generated by a cylindrical crystal of PZT-8 material (lead zirconate-titanate, outer diameter: 25 mm, wall thickness: 1.5 mm, and length: 15 mm, EDO, Salt Lake City, UT). Two electrodes were soldered on both inside and outside walls and the tube was sealed at one end for air backing and the other end was connected to the PVC body (Fig. 1). The cylindrical PVC body tube allowed for mounting of the element and a dead space for the RF (radiofrequency) driving lines and cooling tubes. The electrical impedance of the element was matched to a 50 ohm load by a standard LC (Inductance-Capacitance) matching network.

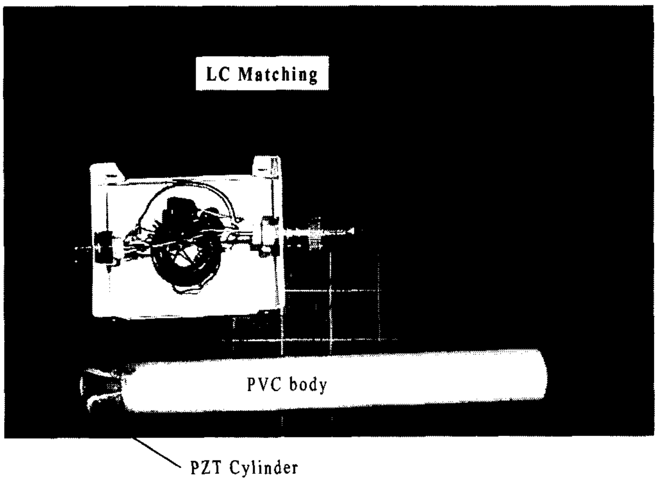

Fig. 1. A picture of the single-element intracavitary ultrasound applicator.

Fig. 2 shows the schematic diagram of the multi-element cylindrical array that was designed in this study. Four-element array consisted of four of the above elements mounted end to end. A silicone rubber was used to glue the elements and provide mechanical and electrical isolation. The outside electrodes were connected together and inside electrodes were connected to separate RF power lines. An applicator body was custom-made to provide both platform for the array and a means of implementing the cooling water bolus. The power line of the each element was passed through the lumen of the other cylinder and connected to coaxial cable. The portion of the applicator that would be in the cervix has the following dimensions: 70 mm in length, 23 mm in outer diameter. Slots for O-ring provide mounting of a latex membrane that can be used in conjunction with water inflow and outflow for array cooling. In addition to cooling tubes, an air-flow tube is added to prevent water leakage by maintaining positive pressure and remove any moisture that could corrode electric components.

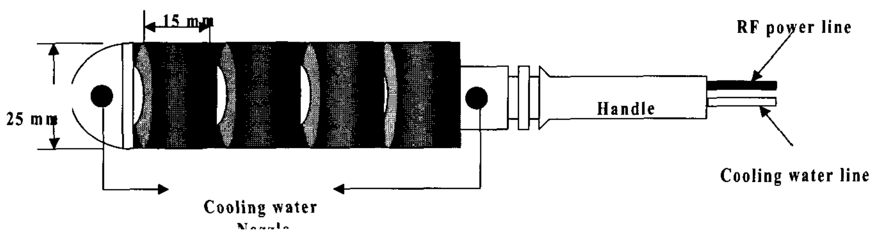

Fig. 2. A diagram of the Four-element intracavitary ultrasound applicator.

2. Electrical impedance measurements

To obtain electrical impedance of the three single-element applicators, a vector impedance meter was used (HP 4193A). For this measurement, the applicators were inserted in degassed water and the phase and magnitude of the applicator was measured by varying driving frequency from 1.0 to 1.8 MHz.

3. Ultrasound power measurements

The acoustic power of the cylindrical transducer was measured using a radiation force method developed by Hynynen.[22] In this technique, the force produced on the absorbing target is proportional to the total ultrasonic power intercepted by the target surface. In this study, the absorbing material was connected to microbalance. The applicator was then inserted into a reflector and fixed. The funnel shaped reflector with walls at 45 degree angle was used. Applicators were matched to zero phase and 50 ohm and the operating frequency was 1.8 MHz. The ultrasonic beam emitted radially from the cylindrical applicator propagates to the reflector and change its direction to be parallel with the array surface. The radiation force was then obtained from the weight change observed by the balance and the ultrasound power was calculated. The applied electric power was measured using a standard RF power meter (HP Model 438). Three single element applicators were used to determine maximum acoustic power that could be produced from the applicators. Each measurement was repeated three times and the average acoustic power was calculated. The transducer efficiency was then calculated as the fraction pf electric power that is converted to acoustic power.

RESULTS

Three single-element applicators were designed and constructed. Table 1 shows the results for the impedance measurements of the three applicators. Operating frequencies of 1.57 and 1.76, 1.57 and 1.75, and 1.55 and 1.75 gave zero phase values for applicator 1, 2, and 3, respectively. The frequencies with maximum magnitude were 1.78, 1.77, and 1.77 for applicator 1, 2, and 3, respectively.

The output acoustic power as a function of applied electric power for the applicators is plotted in Fig. 3. The ultrasonic power obtained from the applicator was, as expected, linearly increased as the electric power increased from 10 watts to 75 watts. There was no degradation of the elements at the electric power level of 75 watts. The maximum acoustic power of 47.0, 48.9, and 39.9 were obtained for the applicators 1, 2, and 3 in this study. At a given electric power, there was slight difference in acoustic power among various applicators.

In Fig. 4 the average electric to acoustic power efficiencies of the transducer elements from the appli-

Table 1. Electric impedance characteristics of the three applicators studied

Applicator	Frequency (MHz) at 0 phase		Frequency (MHz) at maximum magnitude
1	1.57	1.76	1.78
2	1.57	1.75	1.77
3	1.55	1.75	1.77

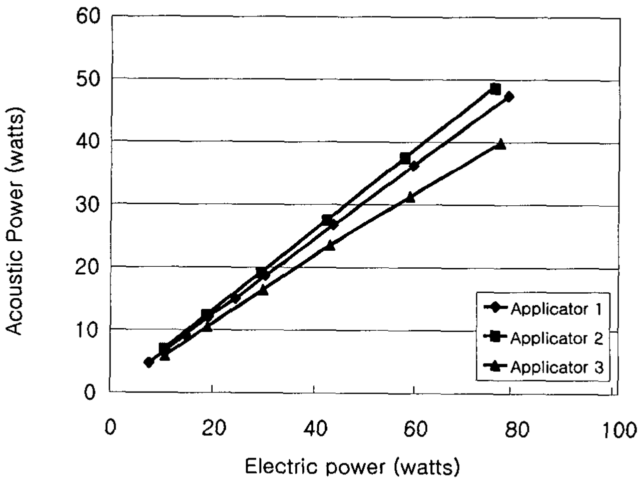

Fig. 3. Acoustic power of the applicators as a function of applied electric power.

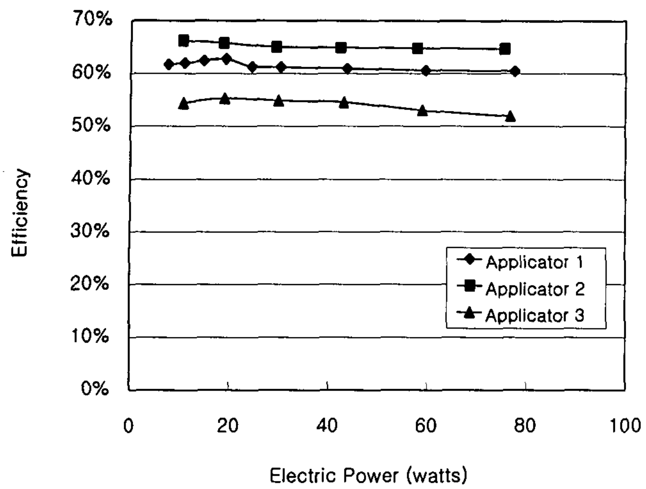

Fig. 4. The efficiencies of three single-element applicators as a function of net electric power.

cators are shown as a function of applied electric power. The efficiencies were fairly constant as a function of applied electric power at the power value plotted. For applicator 3, efficiency was reduced slightly at high power value.

DISCUSSION AND CONCLUSION

For the treatment of entire vagina with high dose rate brachytherapy, a cylindrical applicator is designed and the feasibility of the transducer as a hyperthermia source was examined. A cylindrical crystal of PZT-8 material was used in this study because it facilitates insertion of the applicator into vagina and, because it permits treatment of the tumor through 360 (in the azimuthal direction and along the vagina. The size of the applicator was determined from the cylindrical applicator used in high dose rate brachytherapy. Although three different size of cylindrical applicators (diameter=2.5, 3, 3.5, 4.0 cm) are used for the high dose rate brachytherpy, it was not necessary to use several crystals with various size because the outer dimension of the ultrasound applicator could be varied by increasing the amount of cooling water, thus increasing the diameter of the latex membrane. Thus, a cylindrical piezoelectric tube (outer diameter: 25 mm, wall thickness: 1.5 mm, and length: 15 mm) was used. Operating frequency was determined from the impedance measurements. Since maximum efficiency is achieved close to the peak magnitude value, 1.8 MHz was used as operation frequency.

As shown in Fig. 3, the cylindrical transducer was capable of producing acoustic power over 40 watts. This indicates that the ultrasound source could be used for hyperthermia treatment because it could produce enough power to increase tissue temperature above therapeutic range.

Based on the single element data, a multi-element applicator was designed. As shown in Fig 2, our elements were connected to build an applicator because it allows treatment of vagina with variable length. By powering all four elements, it is possible to treat vagina with maximum length of 60 mm. An applicator body was custom-made to provide both platform for the array and a means of implementing the cooling water bolus.

The results presented here indicate that cylindrical ultrasound applicator may be used for intracavitary hyperthermia in combination with brachytherapy because the physical dimension of the device is same as the high dose rate brachytherapy applicator. In addition, the designed multi-element applicator could provide individual power control, thus allowing temperature control in all directions. Thus, the designed ultrasound applicator is better in controlling temperature as compare to other intracavitary hyperthermia system such as current source and capacitive heating source.[23] Further characterization of the applicator is required including radiation field measurements and temperature measurement both in vivo and vitro before clinical use.

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강내온열 치료를 위한 원통형 초음파 치료기 개발

이화여자대학교 의과대학 목동병원, 방사선종양학과

이 레 나 · 서 현 숙

항문암 및 자궁경부암 치료시 사용되는 고선량률 강내 근접치료기와 병행하여 사용할 원통형 초음파 온열치료가 개발되었다.
온열치료를 위한 에너지원으로 원통형 트랜스듀서가(PZT-8 물질, 길이=1.5 cm, 두께=1.5 mm, 외경= 2.5 cm) 사용되었다. PZT-8 물질의 특성을 측정하기위해 세 개의 단일 엘리멘트 어플리케이터가 제작되었다. PZT 물질을 작동하기 위한 주파수를 결정하기 위하여 벡터 임피던스가 측정되었다. 선택된 물질이 온열치료에 사용될 수 있는지 가능성을 타진하기위해 방사능력을 측정하는 방법으로 각 엘리맨트의 초음파 발생 효율을 입력한 전기량과 발생한 초음파량의 비로 계산하였다. 마지막으로 질암의 온열치료에 사용할 수 있는 다채널 초음파 치료기가 디자인 되었다.
임피던스 실험결과 각 엘리맨트 1, 2, 그리고 3에 대해 1.78, 1.77, 그리고 1.77 MHz의 주파수에서 최대 임피더스 값을 얻었다. 방사능력 측정 실험결과 본 연구에서 사용된 에너지 소스는 40와트 이상의 초음파량이 방출되었다. 또한 각 엘리맨트 1, 2, 그리고 3의 평균 효율은 61.4, 65.2, 그리고 54.0% 이다.
본 연구에서 디자인되어진 원통형 초음파 치료기는 질 또는 항문 치료 시 고선량 강내근접치료와 더불어 사용할 수 있음이 증명되었다. 따라서 본 연구에서 개발된 온열 치료기구가 고 선량 강내 근접치료와 함께 사용하여 병변조직의 방사능 민감도를 증가시켜 암 치료효율을 높일수 있다.

중심단어 : 온열치료, 원통형 초음파 치료기구, 고 선량 근접치료, 자궁암