The Preliminary Prototype of Medium Dose Rate Brachytherapy Equipment

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ABSTRACT

A preliminary prototype of a brachytherapy equipment has been constructed. The work started by developing conceptual design, followed by basic design and detailed design. In the conceptual design, design requirements are stated. In the basic design, technical specifications for main components are determined. In detailed design, general drawings are discussed. The prototype consists of three main systems: a mechanical system, an instrumentation system, and a safety system. The mechanical system assures the movement mechanism of the isotope source position beginning from the standby position until the applicators. It consists of three main modules: a position handling module, a container module, and a channel distribution module. The position handling module serves to move the isotope source position. As shielding, the second module is to store the source when the equipment is in standby position. The prototype provides 12 output channels. The channel selection is performed by the third module. The instrumentation system controls the movement of source position by handling motor operations. It consists of several modules. A microcontroller module serves as a control center whose task includes both controlling motors and communicating with computer. A motor module serves to handle motors. 10 sensors, including their signal conditionings, are introduced to read the environment conditions of the equipment. LEDs are used to display these conditions. In order to facilitate the operators' duty, communication via RS232 is provided. The brachytherapy equipment can therefore be operated by using computer. Interface software is developed using C# language. To complete both mechanical and instrumentation systems performance, a safety system is developed to make sure that the safety for operator and patients from receiving excessive radiation. An interlock system is introduced to guard against abnormal conditions. In the worst case, a manual intervention by the operator is provided when all other means are failing to store the isotope source into the safe container. The tests showed good results. The prototype can send the isotope source to applicators. The isotope source can be positioned with an accuracy of ± 0.5 mm and with a speed of 550 mm/second. These characteristics meet the design criteria.

INTRODUCTION

One of the therapy techniques for cervical cancer is irradiation using brachytherapy equipment. Unfortunately, in Indonesia, only certain hospitals provide the necessary facilities. Additionally, most Indonesian cervical cancer patients are not familiar with this technique due to its high cost. To solve these problems, a brachytherapy equipment has been developed by emphasizing local contents. Coincidentally, it is helpful to this effort that the Multipurpose Siwabessy Reactor is capable of producing the iridium-192 isotope used as radiation source for the therapy.

The development of brachytherapy equipment for cervical cancer has been conducted especially in BATAN's Center for Nuclear Components and Engineering. In 2009, a low dose rate brachytherapy apparatus was introduced [1]. The apparatus was not promising since one therapy session needs about 5 hours for irradiating just one patient. Since 2010, the medium dose rate brachytherapy equipment has been developed by using iridium-192 isotope sources with activities of 5 to 10 Curies [2]. By using the equipment, a therapy takes only several minutes. On the other hand, patients and operators consequently face a greater risk from the radiation. To minimize the absorbed doses, the source should be handled as quickly as possible. Presently, a preliminary prototype of the medium dose rate

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brachytherapy equipment intended for use in cervical cancer therapy has been introduced. The paper discusses steps leading to the construction of the prototype.

EXPERIMENTAL METHODS

The preliminary prototype was developed step by step as follows: (1) design. The design is divided into three steps: conceptual design, basic design, and detailed design. In the conceptual design, a principle diagram shows how it works. The design requirements are also stated. In the basic design, technical specifications for main components are determined. It includes calculations needed for determining the technical specification. After all main components are determined, the next step is drawing the detailed design. All drawings should not need interpretation during the fabrication; (2) fabrication and construction. All components needed are fabricated. The components are then assembled into modules and these modules are assembled into a brachytherapy unit; and (3) testing. Tests are performed in order to check whether the prototype meets the design requirements.

RESULTS AND DISCUSSION

Conceptual design

The therapy uses afterloading method [3]. By this method, a set of three applicators are inserted to the patient's body. Irradiation is performed by sending the isotope source to inside the patient's body through the applicators. The source should stop at certain positions in the applicators. The number of stop position and how long it stops depend on both the cancer stages and patient body conditions.

Figure 1 shows the conceptual design of the brachytherapy equipment prototype. The prototype is designed to use an iridium-192 radiation source with an activity of about 5 to 10 Curries. The source is wrapped in SS-316 capsule and carried by a SS-316 wire. Both capsule and wire diameters are 1 mm and their total length is about 1800 mm. In stand-by position, the source is located in the middle of the lead container. The radiation emitted is then localized in this container. The source wire is rolled around a drum. When the source is applied during a therapy session, a motor rotates the drum and pushes the wire so as to move the source.

The conceptual design also includes the determination of design requirements or criteria. Those criteria state the characteristics which must be attained by the prototype resulting from the design, fabrication, and tests carried out in this work. The main design criteria are [4]: (1) the time to send the source from the standby condition to applicator tip and vice versa is less than 4 seconds. Since the wire length is 1800 mm, the source should be able to move with a speed of at least 450 mm/second; (2) the precision of the source position is ± 1 mm; (3) in standby condition, the radiation must be in accordance with the regulation; and (4) the equipment must provide a safety system preventing the malfunction of components.

Basic design

Referring to the conceptual design, the technical specifications for main components are determined. Presented here are calculations followed for determining the thickness of the radiation shielding. The calculations use the dose reduction factor method. Due to practical reasons and its easy manufacture, lead is used for shielding.

For a 10-Ci iridium-192 source, the radiation dose rate (**D**, in mR/hour) at 1 m is calculated by using the following equation:

$$\begin{aligned} \mathbf{D} &= (\mathbf{Q} \times \mathbf{K\gamma} \times \mathbf{t}) / \mathbf{R}^2 \\ &= (10\,000 \times 0.485 \times 1) / 1 \\ &= 4850 \text{ mR} \end{aligned} \quad (1)$$

where **Q** is the activity in mCi, **Kγ** is γ radiation constant for iridium-192 (equal to 0.485 according to Ref. [5]), **R** is the distance from the source to the point of observation, and **t** is the exposure time.

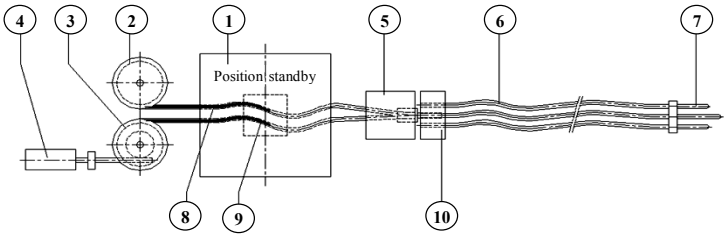


Fig.1. The concept design.

As stated by regulations, at distance of 1 m from the source equipment, the dose rate must be less than 0.05 mRem/hour [6]. Thus, the reduction factor **K** becomes:

$$\mathbf{K} = \mathbf{D} / \mathbf{Do} = 97000 \quad (2)$$

By using the reduction graph shown in Fig. 2 [6], it is obtained that the initial thickness is 7.5 cm. This value should be added to its half-value thickness. Iridium-192 has 13 energy levels [7]. For this shielding thickness calculation, only two energy levels are considered because of their most significant effects on radiation safety. The two levels are 0.468 MeV dan 0.604 MeV. According to Ref [8], their half-value thicknesses for lead are 0.33 cm and 0.51 cm, respectively. To compensate for other energy levels, one-half of the half-value thickness is added. Therefore, the final shielding thickness $\mathbf{t_h}$ becomes:

$$\mathbf{t_h} = (7.5 + 0.33 + 0.51 + (0.33+0.51) / 2) \text{ cm} = 8.76 \text{ cm}. \quad (3)$$

This value is rounded up to 9.0 cm and considered as design value.

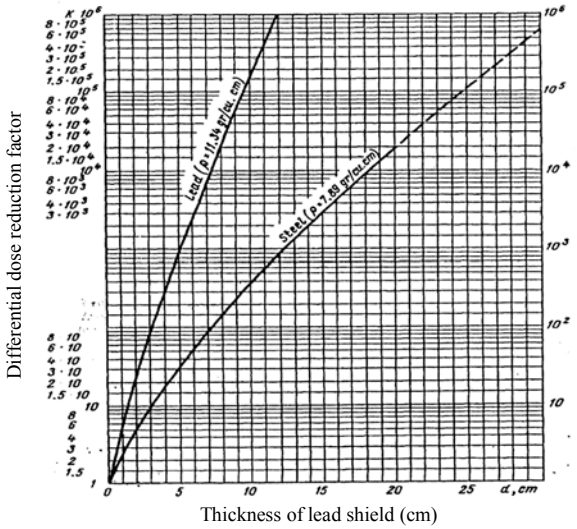


Fig. 2. Factor γ reduction versus lead thickness for Iridium-192 source [6].

Besides the above calculations, other calculations and engineering considerations were followed to obtain the technical specifications for other main components such as motors for handling source/check wires, motor for selecting output channel, ideal diameter of guiding tube, etc [9,10]. Table 1 summarizes the main components and their technical specification.

The main components were determined by considering the availability of the products in local market while adhering to the above minimum technical specification.

Table 1. Minimum technical specification for main components based on calculation and engineering justfication

No	Component	Minimum specification
1	Motor for handling source/checker wires	Type: stepper motor, torque: 3.2 Nm, resolution: 0.955˚, speed: 71.6 rpm
2	Motor for output channel selection	Type: stepper motor, torque: 0.15 Nm
3	Source/check wires	Stainless steel, diameter 1 mm, length: 1800 mm
4	Drum for rolling source/check wires	Cylinder, diameter 115 mm, width: 25 mm, material: polyacetal
5	Shielding	Lead material, thickness: 8 cm
6	Tube for guiding source wire	Rigid tube: stainless steel, 1/8", inside diameter 2.16 mm Flexible tube: teflon, inside diameter 2 mm, thickness 1 mm
7	Belt	Width: 20 mm, thickness: 2 mm

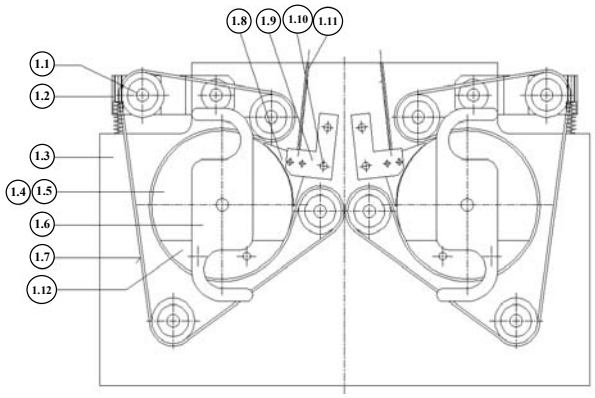
Detailed design

The prototype consists of three main systems: a mechanical system, an instrumentation system, and a safety system. The mechanical system assures the movement mechanism of the isotope source position beginning from the standby position until the aplicators. The instrumentation system controls the movement of source position by handling motor operations. The safety system ensures that, when a malfunction occurs, the equipment reaches a safe state which is safe not only for the equipment itself, but also for the operator and the patient.

Mechanical system

The mechanical system for loading and unloading the isotope source consists of three main modules: a position handling module, a container module and a channel distribution module. The movement of the wire is guided by a tube. When following a fixed trajectory, a stainless steel tube is used. However, in the region where the trajectory is potentially changed or dependent on certain condition, a teflon tube is used instead for flexibility reasons. The gap between the inside diameter of guiding tube and the source wire diameter should be acceptable. An excessive gap could lead to potential imprecision of the source position [11]. In the other hand, too narrow a gap could lead the source wire into getting locked [12].

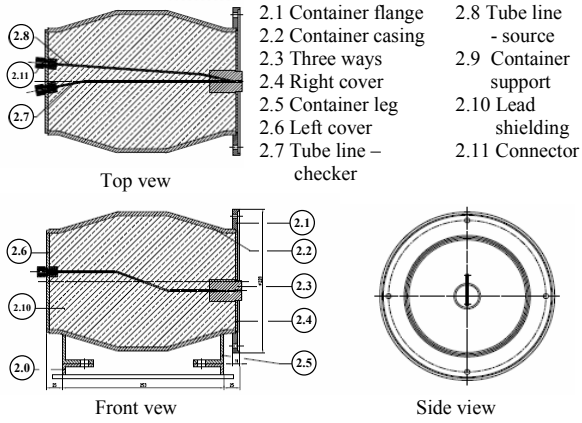
The position handling module serves to move the isotope source position. Figure 3 shows the general drawing for this module. The checker wire has the same dimension with the source wire, but it does not carry an Iridium source. Its function is to simulate the wanted trajectory. The actual source wire will be send to perform the therapy only and if only the checker wire encontours no problems. The main components of the module which perform this task are stepper motors for handling the source wire and the checker wire. Each motor rotates a drum wrapped with a belt. The source wire is rolled around the drum and pressed by the belt. The ideal belt tension is calibrated by dimensioning the spring. By rotating the drum, the isotope source position can be controlled.



1.1 Cam follower
1.2 Tensionner
1.3 Base plate
1.4 drum – source wire
1.5 Drum adapter
1.6 Manual source handle
1.7 Belt
1.8 Wire guide
1.9 Wire guide holder
1.10 Wire guide support
1.11 Guiding tube
1.12 Stepper Motor

Fig. 3. General drawing for the handling position modul (symetric configuration).

As shielding, the second module, called th container module, is to store the source whe the equipment is not in operation or is in standb position. According to the calculation, the minimun thickness of the shielding is 8 cm. Figure 4 shows the general drawing for this module. The module provides two lines for guiding both the isotope source wire and the checker wire. Both lines meet in one line. The guiding tubes are made of stainless steel and the body is made of carbon steel filled with lead.



2.1 Container flange
2.2 Container casing
2.3 Three ways
2.4 Right cover
2.5 Container leg
2.6 Left cover
2.7 Tube line – checker
2.8 Tube line - source
2.9 Container support
2.10 Lead shielding
2.11 Connector

Fig. 4. General drawing for the container module

The brachytherapy prototype provides 12 output channels. For cervical cancer therapy, only three channels are used for each applicator tube. Channel selection is performed by the third module using a stepper motor. This channel distribution module is divided into two sections, namely the rotating section and the static section. As shown in Fig. 5, the rotating section consists of a hollow stepper motor, an S-shaped tube, and a rotating disc. The static section consists of a body and a fixed disc providing 12 output channels. The rotating section should rotate accurately. Most of the channel distribution module material is aluminum alloy, except for the stainless steel used for the tube and the needle bearing used to guide the rotation.

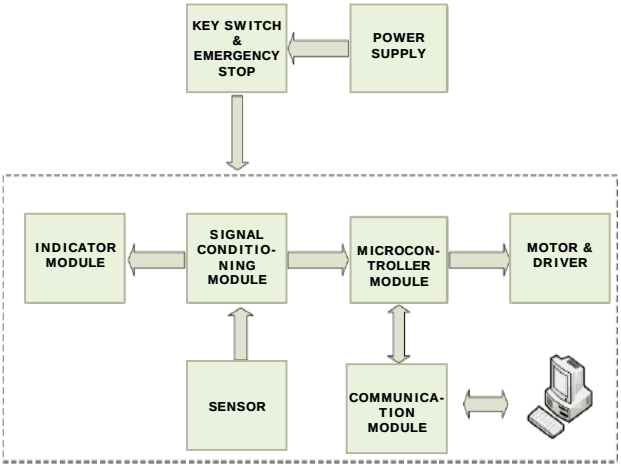


Fig. 5. Instrumentation diagram.

Instrumentation system

The instrumentation diagram for the brachytherapy equipment is shown in Fig. 5.

The instrumentation system consists of several modules: microcontroller module, motor module, sensor module, signal conditioning module, indicator module, key switch and emergency stop module, power supply module, communication module, and computer.

The microcontroller module serves as a control center which both controls the motors and communicates with the computer. An AT89S52 microcontroller is used. It has four ports. Port 0 is designed for controlling the motors. The port receives 6 signals. Each motor is connected to the microcontroller through two pins: one pin for the forward direction signal and another pin for the backward direction signal. In addition, 13 pins of the microcontroller are connected to the signal conditioning module: 4 through Port 1, 6 through Port 2 and 3 through Port 3. Port 3 is also used to receive trigger data due to emergency condition and to communicate with the computer. The RS232 is used to send the therapy data and to monitor the process during the therapy. The microcontroller provides 256 bytes of RAM. By allocating 128 upper bytes of memory to store data, it provides 25 therapy data stored for each channel. One therapy datum needs five bytes. If needed, by optimizing the memory allocation, the microcontroller can perform the therapy with 41 points for each channel.

The motor module serves to handle motors. There are three motors: one motor for handling source wire, one motor for handling the checker wire and other motor for selecting the output channel. All motors are stepper ones so that speed, rotation direction and rotation distance are able to be programmed.

Ten sensors are used to read the conditions of the equipment. They are classified into 3 types and therefore need three signal conditioning types: first type for optocouplers, the second type for door condition and emergency case, and the third type for limit switches. LEDs are used to display the equipment conditions. The indicator LEDs are marked such as to inform operators of the operating condition of the equipment.

The brachytherapy equipment is controlled and operated by the microcontroller module. To facilitate the work of operators, RS232-based communication is provided. The brachytherapy equipment can therefore be operated using the computer. An interface software is developed in the C# language.

Safety system

A safety system is developed to prevent the operators and patients from receiving excessive radiation. Table 2 lists all components related to the safety system [13].

Table 2. Safety-related components

No	Component	Safety related function
1	Shielding	To localize the radiation
2	Checker wire	To simulate the trajection before sending the isotope source
3	Limit switch	To limit the motor rotations
4	Interlock system	To prevent unwanted environment conditions (open door, absence of electricity network, keylock, emergency, cahnnel non-connection, etc)
5	Manual handle and mechanical limits	To store the source into the container manually
6	UPS	To supply electricity in emergency condition
7	LED indicator	To indicate warnings or errors

Fabrication and construction

Referring to the detailed design, all components needed were fabricated. Use of CNC machines is highly recommended due to the need for high precision. Due to the limited budget, some components were made manually or with manual machines. Some parts of the design had to be revised because of the unavailability of material in local market. After fabricating all needed components, the components were assembled into modules and those modules were then assembled into a prototype unit. The entire assembling process was performed by our technicians. The resulting preliminary prototype of medium dose rate brachytherapy equipment is shown in Fig. 6.

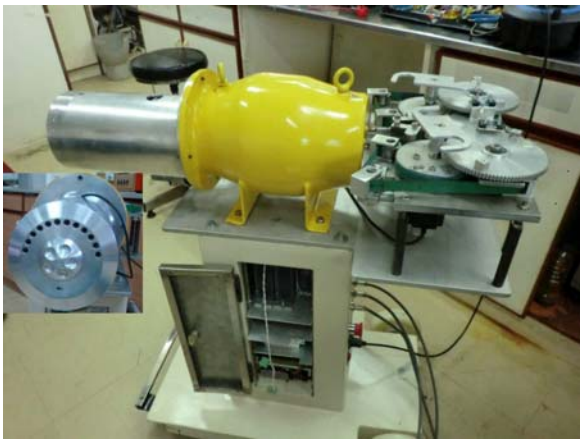


Fig. 6. The preliminary prototype of medium dose rate brachytherapy (inserted photo: 12 output channels).

Testing

Three types of tests were conducted: channel selection, precision, and speed. For channel selection, testing was performed by moving the appropriate channels as desired. Test results showed that all of the channels can be selected and passed by source wire or checker wire.

For positional precision, in accordance with the design calculations by considering the motor characteristics and geometrical dimensions, the stepper motor requires 14 pulses to move the source by 1 mm. Thus, one pulse corresponds to 1/14 mm. However, precision measurements encountered constraints due to small movement. By giving 7 pulses on the stepper motor, the wire tip was moved by exactly 0.5 mm. This suggests that the accuracy of the source position is ± 0.5 mm.

For varying speeds, the motor torque is indicated to linearly decreased with the speed. With the configuration as designed, the motor still rotates to pull and push the source wire up to the pulse speed of 7.6 kHz. This is equivalent with the speed of about 550 mm/second.

To determine whether the prototype functions as required, the testing results are compared with the design requirements. It is clear that the positional precision and speed meet to the design criteria. To determine complete conformance with other criteria, some further tests are required. Such tests include, for instance, performance tests of shielding and the safety system. However, some of those tests have not been conducted as until now all tests have only been conducted using dummy sources. Tests using an iridium-192 source has not been conducted yet.

CONCLUSION

The preliminary prototype of the brachytherapy equipment has been constructed. The prototype can send the isotope source to applicators. The source can be positionned with accuracy of ± 0.5 mm and with maximum speed of 550 mm/s. These characteristics meet the design criteria.

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