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Original article

Location-allocation model for external beam radiotherapy as an example of an evidence-based management tool implemented in healthcare sector in Poland

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A B S T R A C T

Background and purpose: External beam radiotherapy (EBRT) is one of three key treatment modalities of cancer patients. Its utilisation and outcomes depend on a plethora of variables, one of which is the distance a patient must travel to undergo the treatment. The relation between distance and utilisation is clearly visible in Poland. At the same time no strategic investment plan is observed. This work proposes a method of resolving these two issues.

Materials and methods: We propose a mixed-integer linear programming model that aims to optimise the distribution of linear accelerators among selected locations in such a way that a patient's journey to the nearest EBRT is as short as possible. The optimisation is done with observance of international guidelines concerning EBRT capacity. With the use of proposed theoretical framework, we develop a national, strategic plan for linear accelerator investments.

Results: According to model assumptions decentralisation of EBRT, together with new equipment purchases, is required to ensure optimal access to EBRT.

Conclusions: The results were incorporated into Healthcare Needs Maps for Poland. The plan based on the results of this study, implemented by 2025, should deal with the most pressing concerns of Polish EBRT.

External beam radiotherapy (EBRT) is an essential procedure in the treatment of many cancer patients. It is estimated that around 50% of all patients with cancer are indicated for EBRT [1–3]. Access to EBRT depends on many factors, including financial resources, human resources, quality and amount of equipment. It also depends on a geographic factor, namely the distribution of providers, which determines the distance a patient must travel in order to undergo EBRT. It has been shown that distance may negatively impact on EBRT utilisation [4–8], the treatment of choice [9–11], and survival outcomes [12]. Expanding access to radiotherapy can also be financially justified [13]. The existence of such correlations leads to the decentralisation of EBRT and suggests that new facilities in new locations should resolve the distance issue and therefore improve access to EBRT.

Decentralisation itself will have little effect on access if the demand for EBRT significantly exceeds the supply. No good will come from short distances, if waiting times are long. On the other hand, overcapacity will generate excessive expenses. That is why, in order to assure efficient EBRT services, not only should the location of new facilities be considered, but also the amount of equipment each facility needs. International guidelines set out the appropriate level of EBRT infrastructure (e.g. ESTRO-QUARTS [14], IAEA [15], EORTC [16]).

Given that distance is a major factor influencing EBRT utilisation and assuming that compliance with the guidelines assures equality between supply and demand, we formulated an optimisation model using mixed-integer linear programming. Its aim is to simultaneously locate EBRT providers and assign linear accelerators (linacs) to these providers in such a way that a mean distance a patient must travel to undergo EBRT is minimal. It is also assumed that no facility provides more courses per linac per year than it should according to the international guidelines. Linear programming is often applied to locate medical facilities or resources [17], and was recently used to find optimal radiotherapy centre locations in British Columbia, Canada [18].

This paper is constructed as follows. First, we present the idea behind the mathematical model (a formal specification can be found in the appendix). We also explain further assumptions. Second, we present the model solution, which was incorporated into

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Healthcare Needs Maps for Poland (HNM) and is to serve as national strategic plan for EBRT development and investment.

Materials and methods

We addressed the problem of optimising facility location and equipment allocation in Poland by 2025. The model is set at 2025 as its results are meant to serve as a basis for EBRT development plans in Poland and sufficient time should be provided to implement the changes. There are several reasons why applying the suggested model in Poland is justified.

First, there has been no strategic plan for EBRT investment in Poland. As a result, private and public investors have created an EBRT network that has been primarily focused on financial profits, and not on equitable access or efficiency.

Secondly, it has been shown that in Poland distance to the nearest EBRT facility is negatively correlated with EBRT utilisation and positively with the length of stay of EBRT patients [8].

Moreover, according to the ESTRO-HERO survey, access to EBRT in Poland is lower than in other European countries. Poland is ranked 24th out of 27 countries, with respect to Megavoltage units per population [20] and 20th out of 24 in terms of the number of EBRT courses per machine [21]. ESTRO-HERO reveals as well that among large European countries Poland is characterised by having one of the most centralised EBRT infrastructures [20]. Poland's catching up with other European countries in terms of equipment and access should be based on an objective and evidence-based plan.

Finally, private expenditure on EBRT is virtually non-existent in Poland. Hence, a countrywide EBRT development plan, that aims at improving the population's health and reducing health inequalities in the whole population, should be fully conducted by central and local governments.

p-median problem

The mixed-integer linear programming model we formulated can be viewed as an extension of a capacitated p-median problem. The p-median problem considers how to locate p facilities in n candidate facility sites in such a way that the sum of distances between each demand node (patient location) and every facility location site is minimal when weighted with demand values of demand nodes. The model's properties and variations are broadly discussed in the literature [17,22,23]. In the p-median problem only one facility can be located at a certain candidate site and the number of facilities to be located is given. In our extension we are more concerned about linacs and it is their quantity that is given and their capacity that is considered. As the model is discrete, it does not return the distribution of linacs between providers in the same location. A mathematical formulation of the model can be found in the appendix.

Potential facility sites

In our application the set of patient locations comprises 380 Polish counties. This set of candidate facility sites was created during several meetings between the representatives of the Polish Ministry of Health, provincial consultants in radiation oncology, and a national consultant in this speciality. A final set of 51 cities was selected. This set comprised all locations where in 2016 EBRT services were being provided (31 locations), as well as 20 new locations (Fig. 1). Only locations with well-developed oncology services were selected as potential facility sites. In these sites there must have been a provider who treated most cancer patients from its region and provided relevant services that should be co-localised with radiotherapy, for example surgery, chemotherapy, imaging, radiology, pathology. During the process we relied on the expertise of the consultants, with the casting vote given to the national consultant in case of discrepant opinions.

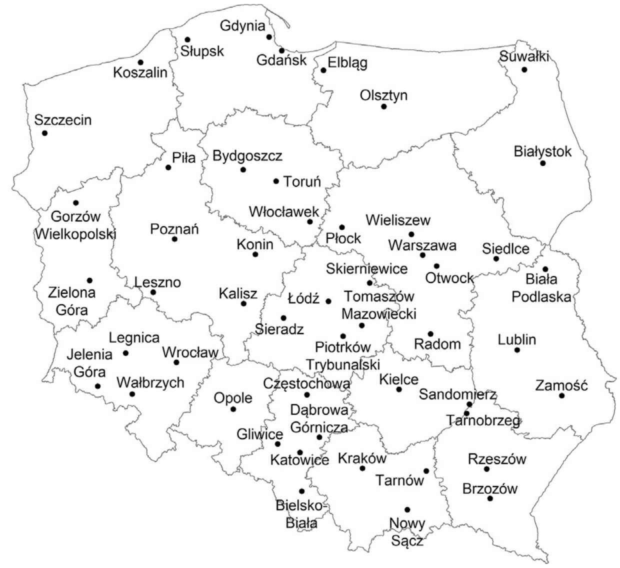

Fig. 1. Cities selected as potential facility locations.

As the results of our model are to serve as a national plan for EBRT investments, and not as a theoretical solution, we considered the current location and allocation of linacs as the starting point of the model. In other words, we did not allow for a reduction in the number of linacs in currently operating centres. During the aforementioned meetings with radiotherapy consultants we established that changing localisations was not economically sound. With the use of the Polish radiotherapy status report [24] and linac purchases by the National Cancer Control Programme in 2015 we established the number of linacs for every city. In the case of Lublin we also considered Council of Ministers resolution No. 197/2015 from the 3rd of November 2015, which commissioned the installation of two additional linacs in Lublin for 2019, that is, for Lublin the starting point was set to 8 and not 6, the current number of linacs. We did not take into account specialist equipment, such as cyberknife or gammaknife, nor linacs that can be used only for intraoperative radiation therapy (IORT), as their capacity and utilisation significantly differs from standard linear accelerators. In three locations (Otwock, Dąbrowa Górnicza, Katowice) there are providers without a contract with the public payer (National Health Fund). In the cases of Otwock and Dąbrowa Górnicza where there was only one provider, the cities were considered in the model, yet the starting number of linacs was set to 0. In the case of Katowice, where two providers (one with and one without a contract) with three accelerators each were located, the starting number of accelerators was set to 3. The aim of this procedure was to verify whether private providers without contracts should be incorporated into the public payer's scheme.

Polish atomic law requires a minimum of two or three units depending on the procedure [25], however reducing this to two without further conditions is being advocated. In our calculations, we considered two as the minimum number of linear accelerators needed in a centre.

Distances between demand nodes and potential facility sites were calculated in a straight line between the county capital city and the city where a facility is or may be located. We use straight line distance (Euclidean) as it is constant over time. Other distance measures, especially travel time, could be better suited if we were to describe the present, as they express patients' discomfort more

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