UNIVERSITAT DE BARCELONA

Final Degree Project

Biomedical Engineering Degree

Design and conception of new interventional radiology areas

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Author: Arnau Rovira Veciana

Director &Tutor: Mario Garcia Causapié

Abstract

The number of medical procedures performed through Interventional Radiology (IR) has increased considerably the last decades. As a result, new IR facilities are required to face the current and future challenges that the discipline could encounter. In front of this reality, the following project is proposed as a guide for the design of the novel IR areas, more specifically, for the design of those IR areas equipped with fixed fluoroscopy systems usually referred as Digital Intravenous Angiography Systems (DIVAS).

Apart from an initial review of the current design trends and the organizations involved in it, this report proposes the ideal design of an IR area to achieve safe, efficient and satisfactory procedures. The design is accompanied by a description of its technical and legal requirements, a brief analysis of the resources involved in its implementation, several proposals for the reinvention of common spaces, the key aspects that must be considered when designing any IR area and examples to demonstrate how to apply the concepts developed.

The whole project has been supported by Hospital Clinic de Barcelona and includes the necessities of all those individuals involved in IR, from hospital clinicians to patients or even technical engineers.

Acknowledgements

Before tackling the matter, I would specially like to express my sincere gratitude to Mario Garcia, the director and tutor of this final degree project. Its support during the whole project has been unconditional and its aid determining on several occasion.

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1. Introduction

As its name reveals, the following project is based on the design of Interventional Radiology (IR) areas. Among the broad scope of the discipline, this study is focused on the conception of those facilities in which fixed fluoroscopy equips play a central role, leaving apart, or in the background, those procedures performed through other imaging modalities. The foremost objective is to design an integral service to cover the increasing necessity of fluoroscopy guided procedures. Taking intervention suites as the main characters in IR, the intention is to conceptualize the ideal facilities that must accompany these suites to prioritize patient needs and maximize professional efficiency. Additionally, the project includes an analytical study of the current IR facilities of Hospital Clínic de Barcelona and Vall d'Hebron. The idea is to identify its weak points and suggest feasible changes.

The assignment is performed as the final degree project of the bachelor's degree in Biomedical Engineering held by University of Barcelona. In that respect, it is realized by a 4th year student. The presented work is born form an internship realized in the Infrastructures and Biomedical Engineering Direction of Hospital Clínic de Barcelona. During the mentioned experience, the immersion in the daily clinical activity, as well as the involvement in the conception and implementation on new IR areas, have enabled the writer of this report to know in a deep sense the particularities of the IR discipline. For this same reason, the proposed study is a combination of personal experiences and extensive research on the field.

Performed with the support of Hospital Clínic de Barcelona, the study presented in this document encompasses the opinion and participation of different healthcare professionals, clinicians but also engineers or technicians. The project is done with a divulgate scope intended to promote the improvement of current healthcare centers, present new patient-oriented design concepts and stablish the basis and the references for the future IR areas. It must not be seen as a project realized for a unique occasion or promoter. In fact, it is conceived to be applied in any specialized center, at the Catalan region or around the world.

1.1. Project objectives

Revealed at the previous introduction, the foremost objective of this final degree project is to design a complete IR service. To do that, the author has focused its attention on the current situation of the close territory, but also on the leading initiatives that are being carried out worldwide. In that context, the presented final design must fulfil two characteristics:

- **Ideality**: I must indicate how the physical spaces inside an IR must be distributed and related to achieve the best performance concerning patient security, efficiency and health professional comfort.
- **Exemplarity**: It must enable organizations not only to reproduce it, but also to extrapolate and adapt the concepts proposed on their own facilities.

This ideal and exemplar design must be materialized in two clear results. A first layout plan drawn using a technical Computer Aided Design (CAD) software. And a second written document summarizing the key points or concepts that must be considered when designing an IR zone. These two outcomes of the study must mainly indicate how IR services must be distributed inside an IR area, which design aspects beneficiate the patients or how the clinician's workflows can be optimized through an efficient architectural support.

Continuing with the desire of promoting the applicability of this project, a practical exercise concerning the current IR facilities of Hospital Clínic de Barcelona and Vall d'Hebron will be performed. Analyzing both situations, the aspects in which the hospitals could improve will be highlighted. The objective is to suggest solutions that could be implemented with a moderate investment and few structural modifications.

1.2. Project scope

The present project is conceived in Spain, more specifically inside the Catalan health public system. This situation has been chosen for proximity and the previous knowledge that the author has of it. In addition, the focalization on a specific territory and institutional framework enables a deeper insight in certain aspects such as regulatory concerns. Nonetheless, the study has never intended to leave any different organization apart. Although the attention is centred in Catalan public centres, the vast majority of ideas and proposals apply to any private or foreign entity.

Regarding IR, although it could include many different medical procedures performed through several imaging modalities, when referring to IR, this project only takes into account those procedures that use X-ray fluoroscopy techniques. More specifically, this final degree project is centred in those facilities in which fixed fluoroscopy systems (Figure 1) are implemented.

Figure 1. Main medical imaging equips used in IR. From left to right: Magnetic Resonance Imaging (MRI), Ultrasound (US) machine, Computed Tomography (CT) Scan and Fixed Fluoroscopy System or DIVAS.

Concerning electromedical equipment, in this occasion, it has been left in the background. On the one hand, the used equipment, its characteristics and requirements have been contemplated for the conception of IR areas. In that respect, no space can be designed without considering the elements that are going to fill it. On the other hand, a detailed selection of the machinery needed to equip the designed area, between the market possibilities, has not been included.

Another important matter that must be understood before proceeding is that the claim of this study is to propose a design, but not to implement it. The economic and technical resources that supposes the implementation of such project are out of range for the author. Moreover, the pursued objective is not an analysis about executing, guiding, or leading the implementation of a design. The pursued objective is to conceive it.

1.3. Limitations

The first barrier that limits the execution of the following project is the temporal period established by the final degree project framework. A project having these dimensions, would normally be realized by a group of experts working full time. In this occasion, there is a unique author with a limited number of hours per week and an execution time settled between the second week of February 2022 and the third week of June 2022, where this work must be presented. This drawback inhibits a further development of the task. Nevertheless, to enrich the project and face time limitations, a previous internship in Hospital Clínic de Barcelona has been realized. In there, specifically with the Infrastructures and Biomedical Engineering Direction, the author had the unique opportunity to personally discover the peculiarities of IR areas. In that respect, in September 2021, when the internship started, bibliographic research and immersive experiences initiated the conception of the presented project.

One of the main limitations of the project is the lack of shared information concerning hospitals architecture and distribution. Even though there is a traditional habit in publishing research findings and medical outcomes, healthcare organizations tend to keep confidential all the information regarding buildings distribution and internal functioning. This situation supposes an obstacle when looking for state of the art designs or future promising concepts. For this reason, to overcome the drawback, theoretical and published information has been complemented with personal experience and presential visits on hospitals from the territory. This enables a closer approach to the national state, but still does not allow to perform a deep insight on the international leading panorama.

Being mentioned before, the construction of an IR area implies a level of resources that is out of range for a unique individual. In that respect, that supposes a major limitation which prevents the author of this project to take further the proposed initiative. Besides, performing the design, implementation and evaluation of a whole IR area, what would be the ideal situation, would take a time incompatible with the nature of a final degree project. For these reasons, the project is limited to a design which wants to stablish the basis and be seen as a reference. Also aiming to leave the implementation to those who have the economical, technical and temporal resources to develop such activity.

At this section, it must also be highlighted that neither economical nor spatial limitations have been considered a major concern for design. The design or remodelling of new hospital areas is always limited by building's architecture or budget. However, in this case, these have not been given a crucial importance. As said before, the objective of this project is to present an ideal area. For this purpose, limitations such as the ones mentioned would just restrain the proposal of certain concepts that, even not being applicable in certain occasions, are effective and fit in other circumstances. Keeping this in mind, it must be pointed out that some solutions to face budget or space limitations without affecting performance are included.

2. Background

2.1. Interventional Radiology and Digital Subtraction Angiography

The present project is conceived around the medical subspeciality know as Interventional Radiology (IR). This discipline is based on the realization of minimally invasive procedures (MIP) through the guidance of medical images. Among the different image modalities used, X-ray fluoroscopy, Computed Tomography (CT), Magnetic Resonance Imaging (MRI), or ultrasound can be distinguished [1]. However, as previously explained, the current work is only focused on the ionizing modalities, specifically in X-ray fluoroscopy.

X-ray fluoroscopy, as its name reveals, uses X-rays to obtain real-time moving images. Its origins can be settled in 1895 when Wilhelm Röntgen discovered X-rays. Nevertheless, the evolution of technology, including electronic and processing advancements, led to the development and commercialization around the 1980s of Digital Subtraction Angiography (DSA) [2], which is the principal fluoroscopy technique used nowadays in IR. Thanks to the aid of a radiopaque contrast agent based on iodine, DSA enables to obtain images of dense soft tissue areas even if they are covered or surrounded by bone. In that respect, DSA is mainly used to perform MIP in the brain, heart, or general vascular system. Is for this reason that in many hospitals, the neuro, cardiac and vascular interventional radiologist are differentiated.

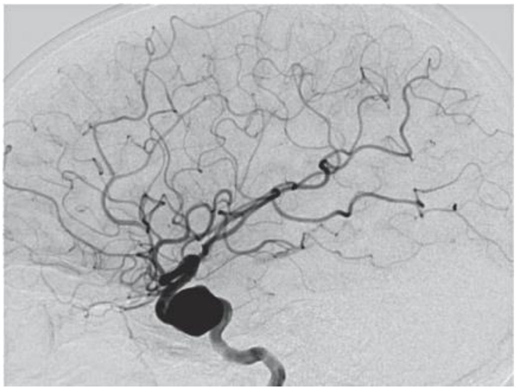


Figure 2. Cerebral arteriography of the right internal carotid artery showing a large fusiform aneurism.

Concerning the procedures performed in IR, DSA is used for diagnosis and therapeutics techniques. As mentioned before, it enables MIP which encompass different surgical techniques that are characterized by the reduced size of its incisions. This fact is later translated into a decreased wound healing time, less associated pain and diminished risk of infection. MIP realized within IR include, for instance, angioplasty (for arterial stenosis), embolization (to stop internal haemorrhages or for tumoral therapies), thrombolysis (to dissolve blood clots), ablations (for heart arrhythmias), nephrostomy (to treat kidney stones) or vertebroplasty (for spine fractures) [3]. Leaving apart therapeutic techniques, DSA is also used for diagnosis. In that respect, cerebral arteriographies are an example of it (Figure 2).

2.1.1. IR areas and equipment

DSA is performed with sophisticated imaging equips known as Digital Intravenous Angiography Systems (DIVAS). However, several names are used on literature. In that respect, they can also be referred as C-arms or rotational fluoroscopy/angiography systems. These systems are mainly fixed to the floor or to the ceiling (Figure 3). Nevertheless, mobile equips have recently reached the market. Additionally, two main types of DIVAS can be distinguished, the monoplane (Figure 3) and the biplane systems (Figure 1). Both are based on mechanical arcs equipped with x-ray tubes and flat panel detectors on its extremes. Monoplane systems are equipped with a single x-ray tube and its flat panel detector, both mounted on an arc shape structure, whereas biplane systems have two arcs, each one with its corresponding x-ray tube and its flat panel detector.

For its technical properties, the rooms where DIVAS are placed (IR, angiography or DIVAS suites) require specific radiological protection, special electrical supply and a specific digital infrastructure. In addition, since the MIP performed at these suites are considered surgeries, a proper lighting and a high level of asepsis are indispensable conditions. This last characteristic is achieved thanks to HVAC (Heating Ventilation and Air Condition) systems that contribute to maintain an acceptable count of the particles present on the ambient, but also help to counteract the thermal dissipation coming from the equipment and professionals.

Figure 3. IR suite equipped with Aurizon 7 (Philips), a monoplane ceiling mounted DIVAS.

Due to the special requirements of DIVAS, the type of patients and the pathologies treated, angiography suites for IR cannot work independently. As other hospital services, DIVAS suites must be accompanied by a series of spaces that are crucial for its proper functioning (Figure 4). First of all, a control room placed next to DIVAS suites is essential. This space is directly connected to the intervention zones through gate access and a radiation protective glass enables visual control of the suite from it. Interventionists use these spaces to protect themselves from ionizing radiation while they analyse angiography images and take in situ decisions in delicate moments of certain procedures. Additionally, it is used by other health professionals to complete patient's medical records and additional paperwork.

A second group of indispensable spaces are the technical rooms. Inside these rooms, all the technological machinery that accompanies DIVAS is placed including central processors, graphic cards, or switches for digital integration. Furthermore, the electrical infrastructure needed for the power supply is also centralized here. Leaving technical aspects, as in operating rooms, preoperative and postoperative zones are also necessity. Not only to be used as patient waiting areas, but also to be used as patient preparation spaces where nurses and anaesthesiologist play an important role.

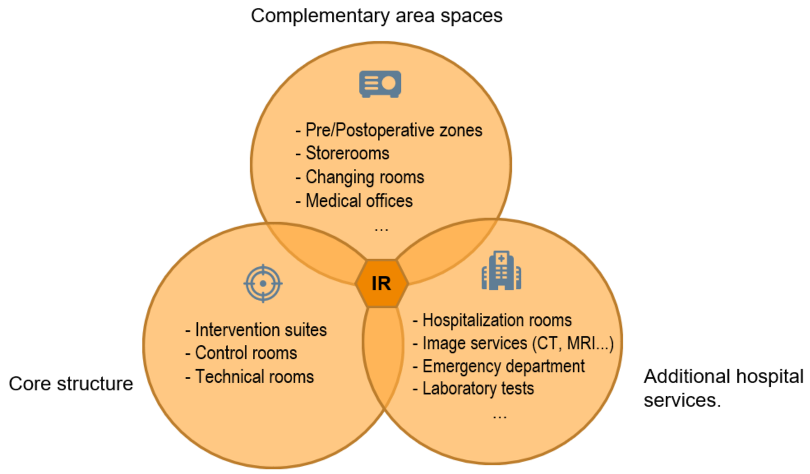


Figure 4. Representation of the main spaces and services involved in IR areas.

Apart from the core structures or units, IR areas include additional spaces which may not be as vital as the ones already explained but that are still required. Between these, medical offices, storerooms for consumables or equipment, changing rooms or rest areas for the employees can be found. Moreover, it must be taken into consideration that IR areas are not understood outside a hospital environment. Its access to other imaging modalities like computed tomography (CT) or magnetic resonance, its connection to the emergency department, or the availability of hospitalization rooms is fundamental.

2.2. Hospital and IR Areas Design

2.2.1. Main actors and necessities

IR areas are mainly placed on third levels hospitals, the type of hospitals that have a superior level of complexity in terms of facilities and services. This is due to the subspecialisation of its professionals, but also for the costs and requirements of the equipment that is found on it. In that respect, IR areas can be placed on general, university or monographic hospitals. In Catalunya, Hospital Clínic, Vall d'Hebron or Sant Joan de Déu could be highlighted as they are considered public reference centres. Nevertheless, private hospitals, are not an exception. For instance, also in the territory, Hospital de Barcelona has its own IR service.

In these large hospitals, independently of their private or public nature, the design of health areas is realized through the collaboration of the same institution and external enterprises. On the one hand, inside the hospital management hierarchy, divisions such as engineering, planning, or infrastructure departments can lead the design, restructuration, or construction of new areas. On the other hand, architecture, construction or engineering firms are also involved in these projects.

Concerning the necessity of new designs for IR areas, at first place it could be said that, although most third levels hospitals include in these times IR suites, the equipment evolution and the increase of MIP imply a constant change and adaptation of the current spaces. Moreover, IR facilities in many cases are designed as independent rooms. Still, due to present demands, they must be understood as a central piece of a complete area and not as an individual element. In addition, even though construction field corporations are required for this type of project, the participation of multidisciplinary equips incorporating health professionals is crucial to increase patients' security, improve process efficiency or ensure the performance of the radiology equipment.

2.2.2. State of the Art

One of the main trends that concerns the design of nowadays IR areas is the incorporation of Hybrid Operation Rooms (HORs). HORs can be defined as invasive treatment spaces designed for both open and closed surgical procedures, equipped with integrated image guidance equipment. This image equipment includes technologies such as DIVAS, CT, MRI, ultrasound, or combinations of each [4]. The implementation of these rooms on IR areas provides a direct access to different imaging modalities that complement the information obtained from DIVAS, already used in IR. This allows to perform complex procedures at once without breaks for the lack of imaging modalities inside the room. In addition, it offers the possibility to convert MIP into open surgeries if the situation requires it.

Related in part with HORs for its multiple uses, a characteristic that is pursued at present in different hospital departments is the implementation of flexible spaces. Adaptable spaces that could be used for more than a unique purpose and that cover today's necessities, but also admit the changes of tomorrow. This transversality could come in conflict with the separation of clean and dirty spaces. In critical hospitals departments like IR ones, in which aseptic environments are essential to avoid infections, potential sources of contamination must be separated from the sterile or disinfected points. This is achieved physically separating clean and dirty spaces, but also restricting human circulation or even establishing the circuits that the different personnel or patients must use [5,6].

Figure 5. Khoo Teck Puat Hospital, Singapore.

A different trend that surrounds hospital design too and, in one way or another affects IR, is biophilic design. Biophilic design encompasses all those initiatives that try to connect people, in this case patients, with the natural environment. In that respect, hospital gardens, which were an important part of the therapeutic regimen in the 19th century, are nowadays making a comeback [7]. The access to light, fresh air, or green spaces, is claimed to beneficial by both patients and clinicians [8]. Horatio's Gardens is one of many current initiatives that take this direction in the United Kingdom. Nonetheless, Singapore healthcare system seems to be taking the leadership in biophilic design with hospitals such as the Khoo Teck Puat Hospital (Figure 5).

Also concerning hospitals concepts, holistic design is gaining relevance. The terms holistic refers to the fact of dealing with the whole of something and not just a part of it. In the case of IR areas, that is translated into including in the design the patient, its family, the environment, the professionals working on it and even the equipment used. Inside this holistic concept, "home like designs", the incorporation of private family areas, the inclusion of multidisciplinary design equips, or the proposal of sustainable solutions seems to focus the perspective of design a little bit further that just the physical space and architecture.

A different aspect in which hospitals are working on is the evolution to what are called "Intelligent Hospitals". Here, sensor networks combined with internet of things (IoT) technology can be applied to monitor air purity, water quality or crowd inflow inside hospital buildings [9]. The idea of "digital twins", theoretically coming from Industry 4.0, has also its own place inside this concept of intelligent healthcare. Digital twins are virtual representations of a physical objects, individuals, spaces or processes that provide real-time monitoring and evaluation without the need of close proximity [10]. They can be used to support decision making, enhance process efficiency or for control purposes.

Continuing with the idea of process efficiency and optimization of workflows, real-time location systems (RTLS) have been implemented in various hospitals to identify and locate tagged equipment, personnel, or patients as they move through hospital facilities. These systems, even though they are claimed to be completely useful, can finally became unused or inefficient [11]. This sustains that the implementation of RTLS in hospital designs, as well as any technology or concept such as the holistic initiatives mentioned before, needs to be based on evidence and not on commercial or popular opinions, especially if the implementation involves huge public investments.

3. Market analysis

3.1. The need of new IR spaces

The number of procedures performed through IR and its importance has significantly grown the last decades [12, 13, 14, 15]. This has occurred thanks to the development of minimally invasive vascular devices such as catheters or guidewires, but also thanks to the development of medical imaging technology. In parallel, new technological solutions, each time more sophisticated, are appearing. In that respect, robotic arms to assist interventional angiographic procedures are an example [16].

This whole panorama, involving new technology and new IR procedures, leads to the need of new IR facilities designed to face the current and future challenges that the discipline could encounter. To materialize these new required designs, on the one hand, it is vital to study the situation of nowadays leading institutions in IR. On the other hand, it is important to know the organizations involved in hospital design since its collaboration and capabilities are crucial.

3.2. Interventional radiology referents and new projects

Starting with the leading institutions in IR, to discover the most novel transformations that are implementing the Catalan hospitals in terms of IR area design, the author of this work has studied the cases of Hospital Clínic de Barcelona and Vall d'Hebron. This has been realized through an extended internship at the first hospital and punctual visits at the second institution. Hospital Clínic de Barcelona as well as Vall d'Hebron are considered referents in the Catalan and even in the Spanish territory. Moreover, at this moment, both are involved in new projects concerning IR areas. In that respect, their situation and initiatives reflect not only the current situation of IR areas in the country, but also the future trends that will follow the surrounding hospitals of the region.

Besides, to tackle the initiatives developed worldwide, proposals of foreign hospitals have been reviewed. The focus has been settled to Heidelberg University Hospital (Heidelberg, Germany) and Memorial SK (New York, USA). Nevertheless, there exist other referents in IR such as the Karolinska University Hospital (Stockholm, Sweden) or the Rothschild Hospital (Paris, France).

3.2.1. Referents at the Catalan region: Vall d'Hebron

To begging with, concerning Vall d'Hebron, it must be considered that it is a third level hospital. Among its multiple IR suites, specifically located inside IR areas, the suites pertaining to interventional neuroradiology, interventional vascular radiology, cardiac catheterism or to the arrythmias' department can be found. Aside, the endoscopy department has its own IR suite, the neurosurgery department includes two HORs equipped with DIVAS and the trauma department has also its HOR. In numerical terms, the hospital owns a total of eleven DIVAS which include one biplane system. Among these eleven, four are placed inside HORs.

Referring to its ongoing projects, apart from a new IR suite currently under construction, the hospital recently received a European Regional Development Fund (ERDF) for the project named "One-Step Ictus". Through this fund and the association with the private entities Siemens Heatlhineers and Medtronic, a new IR emergency area designed for the treatment of moderate and severe stroke will be implemented. The area will include an entrance for emergency patients and it will be equipped with three DIVAS. One of these systems, with access to a sliding CT scan. The fund that makes this project possible will also be invested in a digitalization process in which all the data surrounding the IR area and their patients will be integrated in a unique platform. In addition, artificial intelligence is planned to be used in order to accelerate the pathways and the bedridden patients' displacements that are currently monitored by radiofrequency technology. In fact, the main objective of the project is to make processes agile and to reduce the number of displacements to which stroke patients are submitted inside the hospitals between emergency departments, CT facilities or intensive care units (ICUs).

3.2.2. Referents at the Catalan region: Hospital Clínic de Barcelona

Concerning Hospital Clínic de Barcelona, also a third level hospital, it could be mentioned that it also owns several IR suites equipped with fixed angiography systems. These are placed in tree main areas which are the interventional radiology area, the arrythmias' department and the area of hemodynamics and interventional cardiology. Inside this last area, there are included three of the seven suites that the hospital owns. Since it has been recently renovated (2021-22), it reflects the current trends. In that respect, it is interesting to analyze the solutions that have been adopted.

In a first place, it could be mentioned the hospital has a limited space. For this reason, the solutions adopted try to maximize the use of this space. In this direction, one of the newest IR suites includes its own storeroom attached. The storeroom is connected to the control room and it allows the professionals to get the material through the control room. Although the ideal solution would be to have all the materials inside the IR suite, to have an attached storeroom allows a close storage when space is missing. Another interesting solution to deal with space limitations is the implementation of a common control room. In that respect, the two remaining IR suites of the area share the same control room. This reduces the space for professionals to work comfortably but ensures the commandment of both rooms.

Another aspect that must be specially commented is that one of the suites pertaining to this area of hemodynamics and interventional cardiology has been designed as an HOR. It allows the minimally invasive procedures of IR, but it also allows open surgeries due to the aseptic conditions that it grantees. Moreover, it is equipped with the innovative DIVAS of GE Healthcare called Discovery IGS 7 (Figure 6). A system that offers the characteristics of fixed angiography systems and, additionally, can be moved inside the IR suite. This movement allows to park the equip, for example, on the corners of the suite, leaving the surroundings of the surgical table free for professionals to work.

Figure 6. Discovery IGS 7 from GE Healthcare.

Apart from the recent inauguration of this last area, Hospital Clínic has already initiated the transformation of the current interventional radiology area. In this new project, a biplane and a monoplane DIVAS from Siemems Healthineers (Artis icono biplane and Artis icono floor, respectively) are going to be redistributed to incorporate a new equip. These equips from Siemens are currently working on the hospital. Nevertheless, this new project will reorganize the area to add and additional IR suite also with a shared control room.

3.2.3. Referents out of the Catalan region

Leaving the local sphere and expanding the perspective to Spain, in Guadalajara's hospital, a new IR suite has recently been inaugurated (2021). Compared to other IR suites, it stands out for its large dimensions. Going into deeper detail, it has supposed and investment of 450.000€ and it planned to be used for 1.500 procedures each year [17]. Concerning the design of the space, an adjacent room has been equipped with a cutting-edge echograph intended to be used to perform guided biopsies. The echograph enables to combine US with CT and MRI images.

Concerning Europe, the Heidelberg University Hospital from Germany is one of the cases that has implemented robotic technology. Specifically, the department of cardiology, Angiology and Pneumology has acquired the Sensei System from Hansen Medical. With its robotic arm, the physicians can guide interventional catheters through a console. That is used to treat certain arrhythmias increasing the precision and reducing patient's exposure to radiation [18]. Accompanying the Sensei system, other robotic solutions have been proposed. A newer example that has recently received the CE approval is the CorPath GRX from Corindus (Figure 7). In that respect, robotic systems, seem to start gaining significance inside IR suites.

Figure 7. Robotic intravascular systems. On the left, the Sensei System from Hansen Medical. On the right, the CorPath GRX from Corindus.

In Memorial SK, New York, patient comfort and privacy seems to be a priority. Their departments have small private rooms where patients are prepared and monitored before interventional procedures. Although these spaces are used as preoperative zones, they share some common characteristics with hospitalization rooms including televisions and allowing access to relatives. Similar spaces are used as postoperative zones [19].

3.3. Private organizations involved in hospital design

Having reviewed some of the main referents in IR, it is important to get brief idea of the organizations involved in IR design. As it has been explained (Section 2), the design of hospital facilities results from the collaboration of health institutions and external enterprises. Although firms exclusively dedicated to the design of IR spaces do not exist, there exist several architectural and engineering organizations specialized on general health care infrastructures design.

In Spain, Casa Solo or PMMT are companies specialized in healthcare projects. Among other projects, the first firm realized the director plan to define the future growth and development of Hospital Germans Trias i Pujol. In parallel, the second firm is building a fourth level hospital in Bolivia and it participated on the emergency area transformation of Hospital Clinic de Barcelona. Out of the country, an internationally known firm is HKS Architects, with a special division for health environments. The firm has collaborated in projects such as the design of the Parkland Health and Hospital System in Texas or the renovation of the emergency department of Northwestern Memorial in Illinois.

4. Concept engineering

4.1. Discussion

In order to find the optimal distribution of spaces for an IR area, each of the elements involved in the daily activity of the service must be considered individually. In that respect, the following discussion starts studying the different individuals that participate in IR processes and follows with an analysis of all the required infrastructure. The final aim of this section in to analyse several options to organize, distribute and connect the main spaces that must include an IR area. Table 1, attached at the end of this section, summarizes the main addresses matters.

4.1.1. Individuals involved

The first element that must be analysed to set the basis of the design is the people that interact with the service. In that respect, the main individuals involved in IR areas are summarized on Figure 8. To begin with, patients must be placed on a central place. Each patient is a unique clinical situation. Nevertheless, they can be classified in three groups depending on their origin. Ambulatory cases, also called outpatients, could be considered a first group. These patients access the IR area from outside the hospital, are submitted to their corresponding medical procedure and leave the hospital when the intervention is finished. A second group could be the hospitalized patients. The main difference here is that these patients access the area from inside the hospital. After the intervention, they come back to the hospitalization room where they were accommodated previously. In a third place, there are emergency patients. These usually come from outside of the hospital facilities, pass for the emergency area and arrive to the IR service. Two important characteristics are that their procedures are not programmed and that their critical clinical situation gives them priority in front of other minor cases.

Leaving patients apart, hospital personnel must be considered. Here, on one side, there are included those individuals performing clinical activities such as interventionists, nurses, nurse assistants, anesthesiologists or radiographers. Apart from the service permanent staff, hospital professionals from other services must also be taken into account. On another side, there is the technical personnel. Here there is included the maintenance personnel, but also engineers or technicians. Finally, the cleaning staff must be mentioned. The procedures in which they are involved are crucial for the whole functioning of the area and they must also be considered.

Moving back to patients, family members or other relatives must be considered. Their access to IR areas is sometimes forbidden but, to improve patients' experience, they must be included in the design. Also, in the background, the remaining individuals that interact with IR areas are hospital providers. Into this group pertain consumables or equipment providers, but also, for example, post mail organizations.

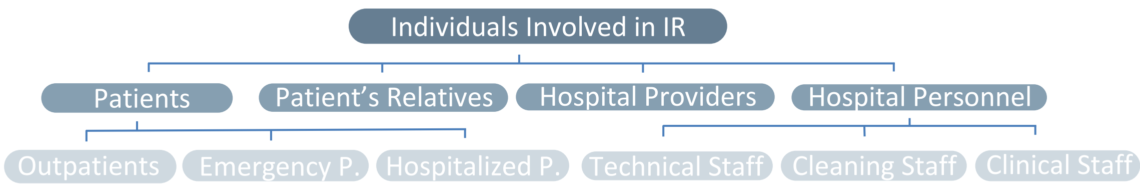


Figure 8. Main individuals involved in IR areas.

4.1.2. Main accesses and differentiation of general spaces

The presented situation implies the design of differentiated accesses and the separation of spaces inside the IR area. Concerning the accesses, at least, it must be contemplated that IR areas must be accessible from the inside of the hospital, where only accredited personnel can circulate, but also from the exterior corridors, where citizens move freely. In that respect, a first option would be to create an access for each group of individuals. Nonetheless, differentiating the access depending on individual's hygienic conditions is a second option. Following this last alternative, the IR area would ideally have five main access points. The two first ones, communicating with the exterior corridors, would be used, on the one side, by outpatients as well as relatives, and, on the other side, by hospital personnel coming from outside. The third access, ideally communicating with the exterior of the building, would be used by hospital providers. The fourth one, either opened to the internal or external hospital, would be used by the technical and cleaning staff for those activities without a clinical implication. Finally, connecting with the internal hospital, another access for the remaining patients and health professionals. This five-access solution differentiates those flows coming from the inside from those coming from the outside of the hospital. Apart from improving hygienic conditions, it stablishes a certain separation between ambulatory patients and the severe ones, who can cause an impacting effect in certain individuals.

In addition to the accesses, the distinction of restrictive zones inside the IR area helps in the promotion of asepsis. In that matter, 2 o 3 differentiated zones can be implemented. The first one, from now on called the transient zone, would actuate as a barrier between the exterior hospital halls and the heart of the IR area. Here, patients, relatives and health professionals would be allowed to circulate. The spaces found here must be the ones that require the interaction of the three last mentioned individuals. The second zone would only be accessible to health professionals. It would encompass IR suites and all the necessary satellite spaces. An alternative at this point is the division of this second zone into two additional ones, from now on called the clean and the aseptic zones. The aseptic zone would be the core of the area containing the IR suites. Here only personnel directly involved in the interventional procedure would be able to circulate through it. It could be compared to an ORs' zone. Finally, the clean zone would contain the complementary spaces of the IR area. Spaces that are crucial for the area functioning but are still potential sources of contamination. As before, only health professionals would access it.

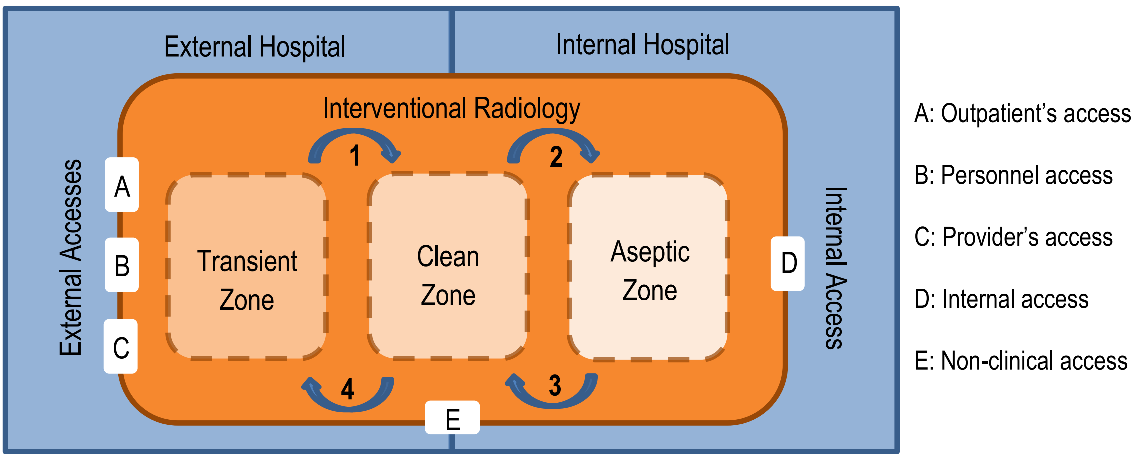


Figure 9. Conceptualization of an IR area. Principal zones, accesses and relation with hospital distribution.

At this point, it must be appreciated that hospital providers have not been mentioned. This is since the elements that they provide must have an access point. Nevertheless, they must not be able to enter the IR facilities.

4.1.3. Interventional radiology core units

The core units inside IR areas are formed by each IR suite and the rooms that must be attached to them. As mentioned on section two ("2. Background"), this core structure is formed by the IR suite together with the control and the technical rooms. These three, at least, need to be digitally and electrically connected. Besides, the circulation between them must be ensured. Additionally, a perioperative space can be found in certain occasions as part of this main unit. Like others, this aspect, will be discussed on the following paragraphs.

Starting with IR suites, they cannot be designed without a previous knowledge of the procedures performed inside, and most importantly, a knowledge of its crucial equipment. For this reason, Annex 1, which exemplifies the main technical equipment and electromedical equips found on IR suites, has been attached. These equips and procedures determine the illumination conditions, the necessity of a special HVAC system and the electrical, digital or gas connections. Nevertheless, for the scope of this project, the focus must be centred in DIVASs, the essential operational equip used inside IR suites. At this point, among other characteristics, what must be considered is that DIVASs dimensions require large rooms and, depending on how they are positioned, room accesses or medical procedures could be affected. Concerning this last aspect, IR suites can have unique access. Nevertheless, this situation implies that technicians, health personal and patients share the same path. To achieve the separation of unrelated procedures and improve its efficiency, differentiated accesses can be implement but, it must be considered that this situation adds potential sources of contamination. Apart, it must always be kept in mind that radiation emission is always present implying the coverage of walls, doors and windows with lead (Pb) for safety reasons.

Going into further detail, when designing these central nuclei, scrub sinks must be implemented. As in surgery areas, interventional radiologists must scrub their hands and forearms rigorously to avoid potential infections that could affect patients' health. In that respect, scrub sinks are paved near IR suites, in control rooms or even inside the same IR suites. Another important detail, sometimes forgotten, is the space required to keep lead aprons after interventions. Since in IR suites X-ray radiation is emitted continuously, it is essential for the professionals to wear radiological protection mostly based on lead. Although these could be matters concerning detail engineering, they must be kept in mind for the conceptual design since they require a proper space inside this IR core unit.

Attached to IR suites, a control room is indispensable. From there, the medical procedures performed inside IR suite are controlled. For this reason, apart from a communication system, it must have direct visual contact with the IR suite. This can be achieved through an opening or window. However, this opening must present a physical barrier for radiological protection and the maintenance of aseptic conditions. Since it is used as a refuge during those DIVAS acquisitions that emit high doses of radiation, it must also have at least one gate access communicating the control and the IR space.

Concerning the last-mentioned room, it must fulfill at least three conditions. The first one is that it must be close to the IR suite and control room due to the limited length of the DIVAS cabling. In that respect, although it seems a minor matter, the characteristics of the powering cabling are determined by the manufacturer and cannot be modified. The second requisite of technical rooms is that they need an independent ventilation system that enables its refrigeration and solves heat dissipation requirements. The third one is that they must include fire prevention measures.

Known the necessities of each space from the core structure, the possible connections and distributions can be settled. To begin with, an internal window and a gate access between the IR and the control rooms cannot miss. From this point, an option is to set a unique access. In this situation, patients and clinicians would enter IR suite through the control room. With this circuit, the differentiation between patient and professional circuits is lost. This interrupts the workflows and could transmit certain insecurity to the patient. The alternative is to open a second access on the IR suite promoting patients access to the IR suite without passing through the control. This would solve the previous problems. More accesses could be implemented for the cleaning and technical staff. Nevertheless, it must be considered that the aperture of additional accesses into lead covered rooms, like IR suites, require technical and economic resources which are not conventional.

Concerning technical rooms, to connect them with IR suites through a direct access is useful for the installation and maintenance of DIVAS systems. However, to avoid potential contaminations, the use of these accesses must be forbidden while medical procedures are being realized. Aside, an option to optimize physical space is their merging. If two IR suites are placed side by side, a unique technical room can be placed between them. In that way, a slightly larger room can contain the technical machinery of both suites. The same applies to control rooms, a slightly larger control, placed between to rooms, can cover the necessities of two spaces.

Lastly, there are the perioperative zones which include the preoperative and postoperative services. They can either be a unique space with a centralized service or several spaces attached individually to its IR suite and being part of the core unit. The first option optimizes nursing resources, but it demands a higher level of coordination between the IR suites and the perioperative zones to achieve an efficient flow of patients. The second option offers the opposite situation. On one side, it requires a nursing station in every zone. What means additional resources. On the other side, the proximity of the space facilitates coordination. Nonetheless, in any of the cases, like all the spaces of the core unit, they must be included inside the aseptic zone since they must have a close access to IR suites.

4.1.4. Patient spaces

One downside of many current IR areas is the lack of private spaces for patients, especially for outpatients. In that matter, sometimes the unique places were patients have a certain privacy are the changing rooms. Tiny spaces where there is only place to change the daily clothing for hospital coats. To confront this situation, this project proposes the addition of private rooms or spaces (PS) inside IR areas. Since they are mainly thought for outpatients, these spaces must not be seen as conventional hospitalization rooms. The idea is that the rooms could be shared with relatives before and after interventions, could promote proximity with clinicians and be used as changing rooms where personal belongings could be leaved. For its essence, the rooms would have to be placed inside the transient zone, where patients, relatives and health professionals are allowed.

Another space that is directly related with patient's personal attention is the reception. The area's reception must have a direct connection with hospital exterior corridors. Its function is basically to control the access to the IR area, to register patient's arrivals or to guide patients when accessing the facilities. This space can be part of the area, offering a better control and individualized attention, or it can be fused with another general reception of the hospital.

4.1.5. Health professional spaces

The procedures performed inside IR suites, are possible thanks to a previous preparation and organization of the needed resources. These necessary activities that surround medical interventions also require physical spaces. Between these, changing rooms, cleaning chambers or storerooms can be found.

To begin with, storerooms are crucial. IR suites already have the common material arranged in incorporated shelves or cupboards. However, space inside IR suites is limited, radiosensitive materials cannot be stored on it and a certain stock is essential. In addition, the vast variety of consumable products like catheters or guide wires makes impossible to gather all the material inside the space of intervention. Storerooms could be placed in either in the transient, clean or aseptic zones. The first option would facilitate the proximity with hospital providers since the zone is closer to hospital exterior. The second option would avoid a frequent crossing of merchandise or providers with patients. The third one supposes an advantage in terms of accessibility during interventions. Notwithstanding, the three of them, require hygienic measures to ensure that the material coming from the outside does not contaminate the interior atmosphere.

Even though consumable materials are frequent, reusable ones are also present. Scalpels, surgical scissors, but also electromedical equips such as videolaryngoscopes must be either sterilized or disinfected. This can be done on a proper cleaning area or in a general sterilization service of the hospital. In any case, a proper space to process dirty elements is always necessary, at least to keep common cleaning materials or to realize a first washing of certain objects. For a proper functioning, it must be close to intervention suites and separated from patient's concurred spaces. In that respect, the clean zone would be a good place ensuring a separation of dirty elements from the aseptic conditions of IR suites and avoiding interactions with patients. Nonetheless, the separation of the cleaning spaces from the IR suites slows down the workflow of the cleaning team.

Continuing, offices or dispatches for hospital personnel must be included. There, administrative tasks, preparation of daily cases or the study of medical images are performed. Those spaces can also be placed at the clean zone, neither at patient's closeness nor at interventional nearness. Additionally, leisure or rest spaces must exist. Employees must have space for work pauses and punctual meals. Here basic services such as toilets can be included. For their uses and level of cleanness, placing them on the clean zone allows to avoid external individuals access without interfering in the aseptic zone.

Last but not least, there are the personnel changing rooms. Since health professionals working on IR cannot work with common clothes for hygienic conditions, these spaces are a necessity. The two possible options here are the transient or the clean zones. To choose its place, personnel flows must be considered. In the case professionals were accessing the zone from the internal hospital, the proper option would be the clean zone. Nevertheless, employees just change their outfit at the beginning of their workday, moment in which they access the IR area from the external corridors of the hospital building. In that respect, the transient zone, closer to the exterior corridors, would be a good option. Going one step further, considering that personnel come from the exterior, if the changing room is placed between the two last discussed zones, it can serve as a filter. With a first access at the transient zone and a second one at the clean, employees would access the clean area, but also the interior hospital, already with the adequate clothing.

Summary of the main proposed alternatives			
Matter of interest	Necessities/Considerations	Alternative 1	Alternative 2
Differentiation of internal zones	-Promotion of asepsis. -Separation of processes. -Restriction of circulation.	Two zones: transient and clean zones.	Three zones: transient, clean and aseptic zones.
Area accesses	-Existence of internal and external hospital flows. -Differentiation between complete and partial access. -Restriction of circulation.	Differentiated accesses for each group of individuals involved.	Differentiation of access considering hygienic conditions.
Composition of the core unit	-Three spaces: IR suites, control and technical rooms. -Attached rooms within an aseptic environment.	Addition of the perioperative spaces as individual attached units.	Exclusion of the perioperative space. Proposal of a unique centralized service.
Core unit characteristics	-Communication between control and IR suite. -Proximity of the technical room and the IR suite. -Dimensions of IR suites. -Space for scrub sinks.	Unique IR suite access. Scrub space outside the core unit. Individual controls and technical rooms.	Multiple accesses. Scrub space integrated inside the control room. Shared controls and technical rooms.
Patient's spaces	-Patient privacy, intimacy and comfort. -Closeness with clinicians.	Implementation of changing rooms.	Implementation of patient private spaces.
Storerooms	-Accessible for providers and clinical staff. -Aseptic conditions.	Placed inside the transient zone to ease the access of providers.	Placed inside the aseptic or the clean zones for a fast clinical personnel access.
Cleaning area	-First material washing. -Storage of material. -Communication with central sterilization services.	Close to the IR suites for direct management of dirty material.	Relatively separated from IR suites to ensure aseptic conditions.
Personnel changing rooms	-Filter functions. -Dependence on personnel's first access.	Between external or internal corridors and the transient zone.	Between external or internal corridors and the clean zone.

Table 1. Summary of the main proposed alternatives.

4.2. Proposals

After the previous study of necessities, its consequent discussion and the suggestion of several alternatives, in this section, three main conceptual designs for IR areas are presented. To ensure that the explained concepts are appliable in any scenario, different architectural shapes are suggested to satisfy distinct building requirements and to compare its efficiency. Moreover, the designs show multiple alternatives concerning the distribution of key spaces. The pursued objective behind the analysis of the presented designs is the further selection of a final conception proposal.

Before boarding the particular cases, three clarifications must be done. Firstly, the following designs include exclusively a primary distribution of spaces and the communications between them. Future distribution or access changes are a possibility. Besides, final dimensions are specified in section 5 (Detail engineering). Secondly, the internal zones previously discussed have been implemented in the following designs. For its representation, the corridors of each hygienic zones (transient, clean and aseptic zones) are marked with a different colour. Moreover, the zones have been physically separated by a bifold door. Any space communicated through a standard door to one of these corridors is directly included inside the hygienic zone associated with the corridor. Thirdly, the communication of the area with other hospital facilities is represented through double hinged doors. Additionally, attention must be paid into the number of accesses and the spaces surrounding the area which differ in the three designs.

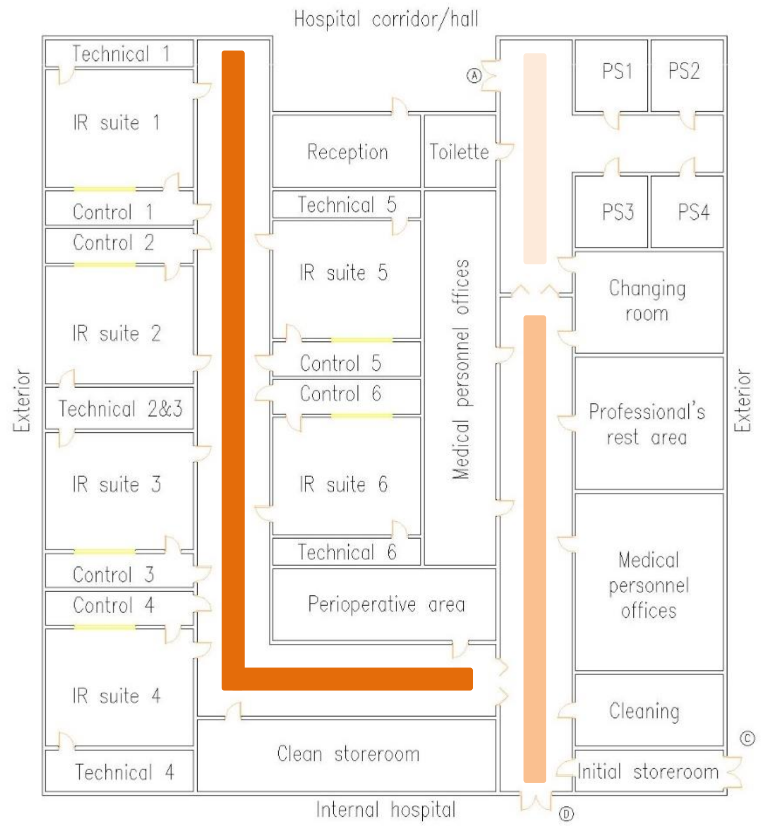
Given the indispensable clarifications, to begin with, the commons aspects found on the three designs can be explained. Starting with the hygienic zones, it must be remarked that, in all the cases, they have been distributed according to their aseptic conditions. The transient zone has been placed at the beginning of the areas, followed by the clean and finally the aseptic zone. This has been done looking for a progressive flow of patients to uncontaminated zones before interventions and a later progressive flow to outside the facilities after medical procedures.

Another common aspect that must be mentioned is the presence of two storerooms for each IR area. Due to the multiple advantages commented before, this solution has been considered the prevalent one. The first store zone, called initial storeroom, is communicated with the exterior of the area to receive providers. It has been designed to store temporarily the assets with its corresponding dirty envelopes. The second storeroom, the clean one, is closer to IR suites and contains those elements already unwrapped than can access the aseptic zone.

Concerning the core unit, two accesses have been created to each IR suite, one for patients and another for professionals. Moreover, these accesses have been separated as far as possible trying to differentiate workflows and avoid interferences. Asides, the visual connection between controls and IR suites has been represented with yellow widows. The idea of shared technical rooms is shown on all three designs. However, the same cannot be said for controls, which present two alternatives.

Finally, on the one hand, it can be indicated that toilets and private spaces (SP), both for patients and relatives, have always been placed at the transient zone. On the other hand, professional's rest areas, which are considered to include staff toilets, and medical personnel offices have been placed at the clean zone.

Tackling the first design (Figure 10), it presents three main area accesses. Although initially five accesses have been proposed, on the flowing designs several options have been considered trying to analyse area's performance with a reduced number of accesses. With the following layout, outpatients and professionals, at the bigging of their workday, would share the same access (A). Providers would have their own access from outside of the building shared with non-clinical personnel (C) and the internal access (D) would be used by staff being already inside the hospital and other patients, the emergency and hospitalized ones. Another characteristic to highlight is the perioperative space, in this occasion, the preoperative and postoperative zones have been unified into a unique large space that covers the necessities of all IR suites. Moreover, the presence of individual controls can be commented. Although some controls could be merged, for some professional, separated spaces are considered better. To end up with, the changing room, as in the second design (Figure 11), has been placed between the trainset and the clean zone. This gives it the filter performance previously explained.

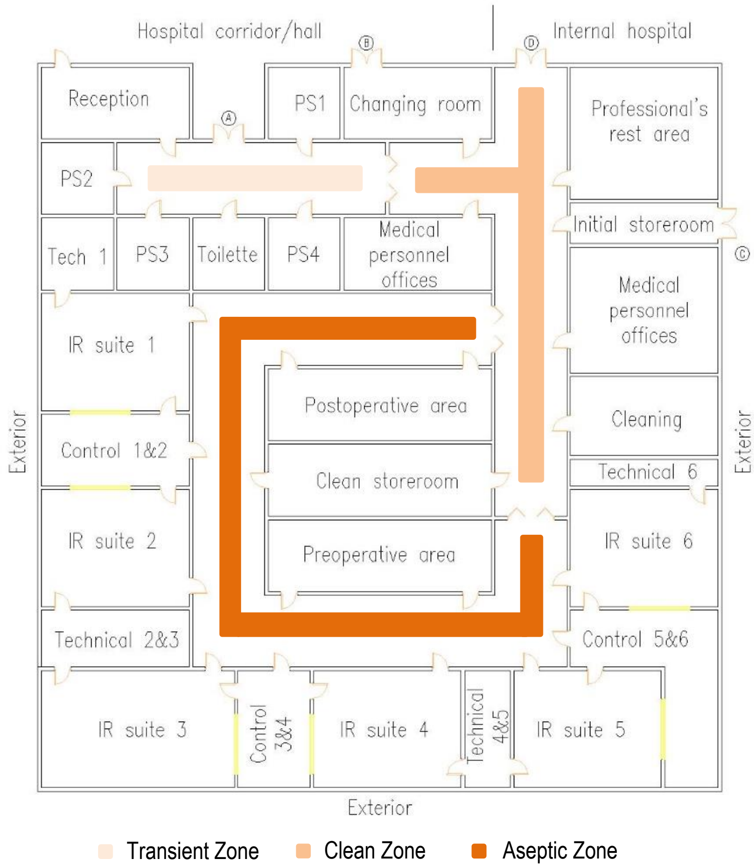


Transient Zone Clean Zone Aseptic Zone

A: Outpatient's/Personnel access, C: Provider's/Non-clinical access, D: Internal access

Figure 10. First proposal for the conceptual design of new IR areas. Scale: 1/500. Abbreviations: Private Space (PS), Technical room (Technical).

Concerning the second design (Figure 11), possibly, its main characteristic is the presented circular flow. On the last and following proposal (Figures 10 and 12), patients follow a straight trajectory that forces them to go back and forth inside the aseptic zone. Nonetheless, this second designs avoids this situation. An entrance, next to IR suite 6, and an exit, in front of the medical personnel offices, ensure that patients do not cross twice the same corridor. Referring to the perioperative space, here, it has been divided into a preoperative and a postoperative area. A situation that facilitates the boarding of different patient necessities. Another peculiarity of the design is the double access of the clean storeroom. It has been implemented to avoid the traffic of assets form the initial to the clean storeroom through the main corridor of the aseptic zone. Additionally, the communication of the area through four accesses must be commented. The difference here, respect to the last design (Figure 10), is that professionals have their own access. This avoids the circulation inside the transient zone without the adequate hygienic clothing.

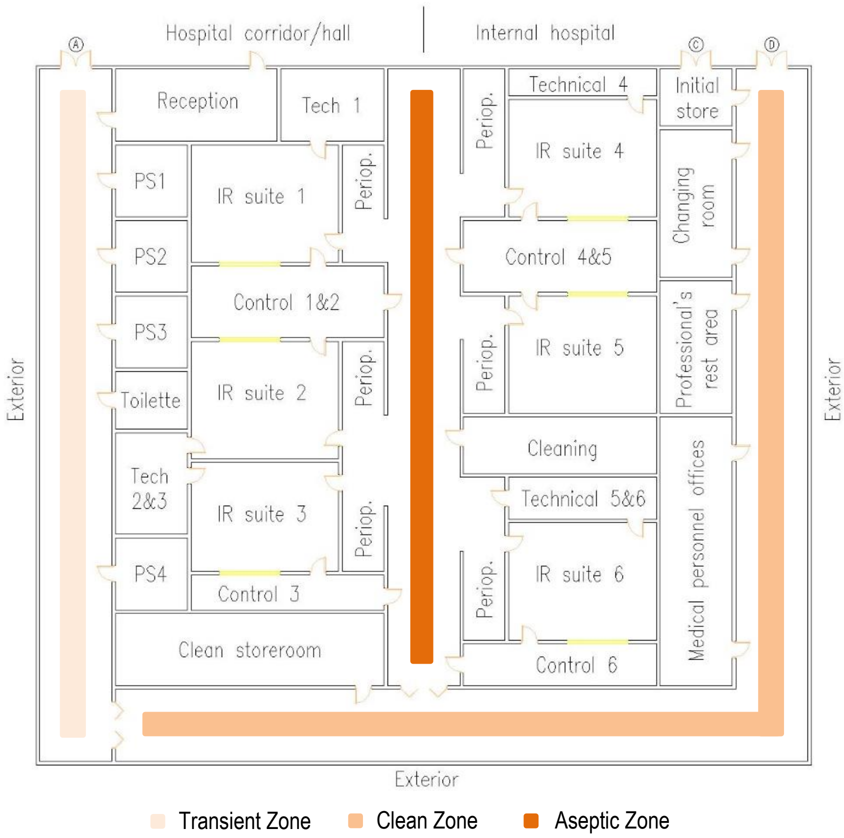


A: Outpatient's Access, B: Personnel access, C: Provider's/Non-clinical access, D: Internal access

Figure 11. Second proposal for the conceptual design of new IR areas. Scale: 1/500. Abbreviations: Private Space (PS), Technical room (Tech/Technical).

Coming back to the concept of linear workflows, the last proposal is presented on Figure 12. It has been designed with an external main corridor that concentrates all the services grouped at the centre. Possibly, the most important difference concerns the perioperative space. In this occasion, it has been individualized for each IR suite. A fact that enhances the proximity with the interventional human equip. Additionally, the cleaning room has been placed inside the aseptic zone leaving the clean storeroom at the clean zone. This situation facilitates the processing of clean and dirty instruments but, it could be a potential source of contamination.

Moreover, the initial store space has been communicated with the internal hospital. This layout has been proposed thinking on those hospitals where providers come from the interior of the building. In a similar direction, the changing room has not been implemented as before. It has been specially conceived for those situations in which health personnel access the area from the internal hospital at the beginning of their workday. Here, it must be pointed out that the last two scenarios would not be the ideal ones but, they must also be considered. Finally, the characteristics of the technical room 5&6 must be analysed. In the forgoing technical rooms (Figures 10 and 11), an access to its corresponding IR suite has been implemented to facilitate DIVAS installation. However, this is just a minor and punctual advantage. The technical room of an IR suite can equally play the same role. The unique requirement is that it must be close enough to the IR suite.



A: Outpatient's access, C: Provider's/Non-clinical access, D: Internal//Personnel access

Figure 12. Third proposal for the conceptual design of new IR areas. Scale: 1/500. Abbreviations: Private Space (PS), Technical room (Tech/Technical), Perioperative space (Priop.).

4.3. Final proposal

From the comparison of the previous presented designs and the aspects discussed during this whole document, a final conceptual design has been created (Figure 13). This embraces the ideal distribution of general spaces and the relation that they share with the rest of the area.

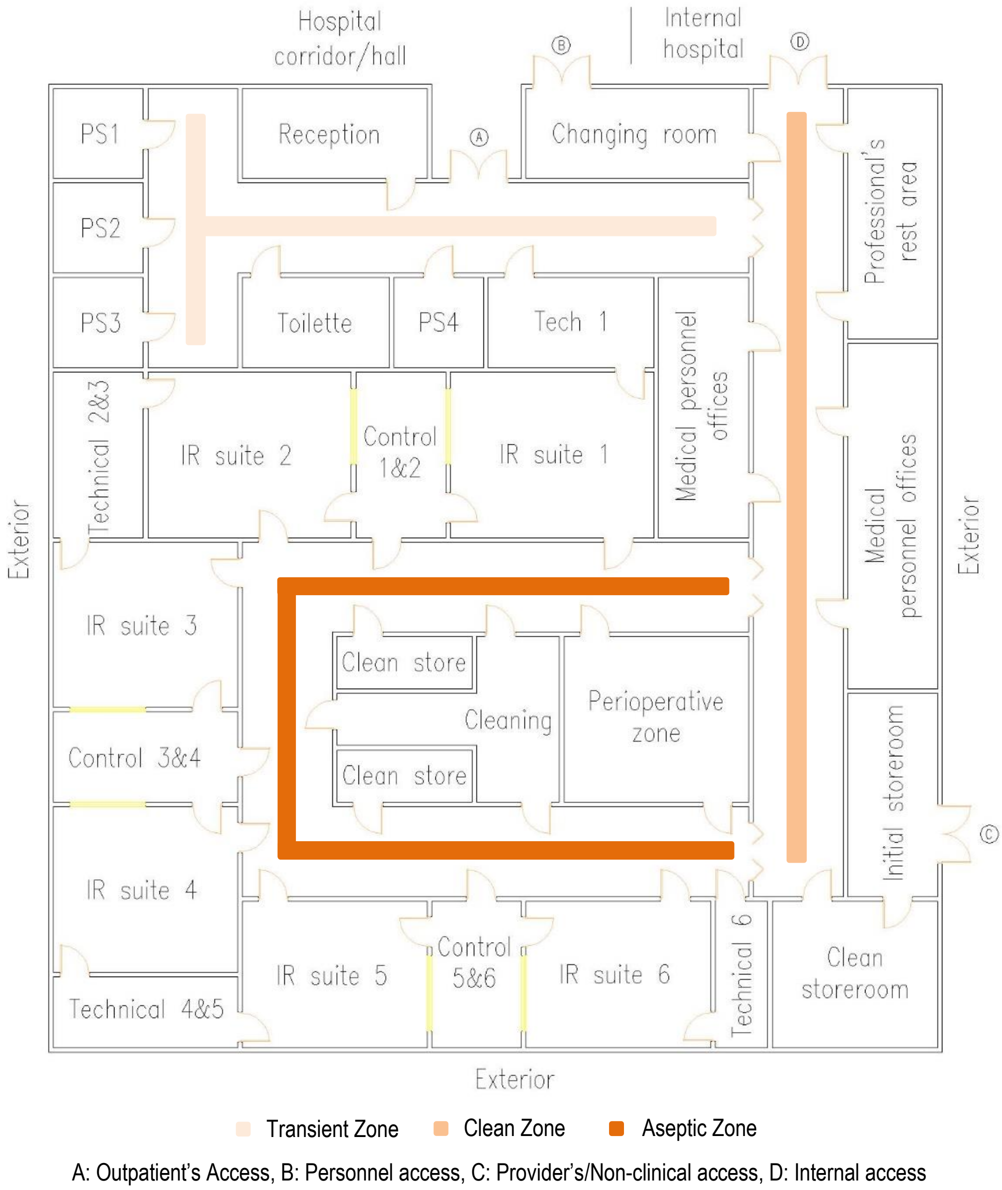


Figure 13. Final conceptual proposal for the design of IR areas. Scale: 1/400. Abbreviations: Private Space (PS), Technical room (Tech/Technical).

To begin with, referring to the structural shape of the design, the alternative proposed on Figure 11 has been the one adopted. The circular disposal of the internal corridors has been chosen looking for a continuous circulation and avoiding patient's back and forth movements. A central nucleus has been implemented containing preoperative, storage and cleaning spaces. The main idea is to make these spaces as accessible as possible for each of the IR suites placed around. Since these three spaces are crucial in many internal procedures surrounding medical interventions. Its proximity and accessibility accelerate the workflows mainly involving the nursing and cleaning staff.

Considering that some clinicians could prefer individual preoperative spaces rather that a centralized service. In Annex 2, a similar conceptual layout has been attached including these individual preoperative spaces. However, at this point, and knowing that it is far from an ideal concept, the design included on Annex 2 must just be analyzed for the distribution of its preoperative spaces.

Coming back to Figure 13 and concerning its core structure, the prevalent option has been the proposal of common control rooms. This configuration optimizes human and material resources, promotes collaboration between professionals and reduces the required space, if it is convenient. Moreover, these spaces are easily separable with a plasterboard if desired. Related to technical rooms, where it has been possible, an access from outside the IR suite has been proposed. This has been suggested to allow the access of maintenance personnel to the rooms without interfering in the IR suite activity.

Moving to the clean zone, spaces for storage have also been settled. These are thought to be used before accessing the central nucleus storerooms. As in Figures 10, an initial storeroom includes a connection with the exterior to receive hospital providers and, as in Figure 12, a clean storeroom has been implemented to store the material free from its external packages. Nevertheless, in this occasion, the storerooms have been placed one next to the other ensuring a direct transfer of the arriving material from one space to the other.

Medical personnel offices and professional's rest area have been placed on the clean zone as in the previous proposed designs. For the staff changing room, the solution proposed on Figure 11 has been adopted. It includes an exterior access for hospital personnel and a connection with the clean zone to promote the access of professionals with the adequate clothing. Finally, patient spaces have been placed on the top left corner of the area. This alternative is chosen to bring these spaces close to the exterior. A situation that not only offers the possibility of natural light, but also could even be used to communicate these rooms with green spaces pursuing a biophilic design.

5. Detail engineering

5.1. Main Proposal

5.1.1. Subdivision of general spaces

The final and detailed proposal for the design of an ideal IR area is presented on Figure 14 (go to Annex 4 to see the amplified plan). The area has been conceived from the last approach commented in concept engineering (Figure 13) and has been designed to enable a direct implementation of the configuration shown. Besides, it has been created to inspire future designs that could benefit from the concepts and ideas developed.

Figure 14. Detailed design proposal for an ideal IR area. Scale: 1/400. Units: Meters. Abbreviations: Private Space (PS), Changing Room (CR), Computed Tomography (CT). Accesses' users: Outpatients (A & G), Area personnel (B), Providers (C), Hospital personnel (D), Non-clinical personnel (E & F). Additional notes: Conventional doors are represented in orange, evacuation fireproof doors in red. Lead protective widows are marked in yellow. Floor standing DIVAS components appear in purple, whereas those ceiled mounted appear in blue.

Before tackling the details, respect to the conceptual proposal (Figure 13), one of the biggest changes that can be observed is the addition of a hybrid suite connected to a CT scan. Nonetheless, a whole section has been specially included in this document to comment this aspect and, as well as it happens with patients' private spaces, the matter is addressed latter.

Starting with the core structure, it maintains the essence of the conceptual design, but here, several important details must be commented. As previously explained, IR suites require scrub sinks and space to keep lead aprons. In this occasion, these spaces have been placed at the entrance of control rooms. This configuration separates these installations from the patient's circuit and allows to access the IR suites with an acceptable level of disinfection. Moreover, since scrub sinks are humid spaces, the design proposes to separate them with physical barriers.

Concerning technical suites, they have been provided with an additional functional access. Whereas the conception design included a unique access from the IR suites, the detailed design includes another access from outside the aseptic zone. This has been achieved adding an external corridor called "Dirty Corridor". The main idea is to provide technicians with an additional circuit avoiding the cleanest spaces ("Aseptic Zones") and allowing an access that does not interfere in the ongoing medical interventions. Besides, this "Dirty Corridor" enables a path for IR suites' waste evacuation. However, its accesses to IR suites must remain closed during medical interventions. (see Annex 5 for a further study of this and other workflows derived from the proposed design)

Moving to the perioperative area, it has been further developed in this detailed design. As it can be appreciated, it has been divided into a preoperative and a postoperative zone which contain space for four beds in each case. This separation avoids the undesired interaction between patients with completely different health conditions. But, since all perioperative beds are still in a common room designed with an opened concept, the nursing resources can be centralized in a unique point and patients benefit from a continuous surveillance.

The accesses to the aseptic zone have also been developed on this detailed design. As it can be appreciated, two vertical sliding doors separate the clean and the aseptic zones. These doors, covering an aperture elevated approximately one meter from the ground, represent two stretchers transfer systems. Mechanisms that enable to move patients from transport stretchers to the cleaner stretchers confined inside the aseptic zone. For personnel, two transfer rooms have been settled.

Another important change that has been implemented here is the incorporation of two general technical rooms. On previous sections, the need for HVAC systems, the electric supply and the digital or electronic support that require DIVAS have been addressed. However, the remaining spaces apart for IR suites, as in any other hospital floor or general building, demand a certain electrical and mechanical infrastructure. This includes differential and magnetothermal switchers, distribution panels or water and gas valves. To cover these necessities, a wet and a dry technical room have been incorporated. This separation avoids the undesired interaction between electrical and water systems. Nonetheless, it must be mentioned that, despite locating a general electrical control panel in this space, the installation of subpanels in the remaining technical suites is still necessary. Among others, these subpanels are used periodically to perform compulsory technical tests to check the state of the electric infrastructure. Moreover, concerning again the general technical rooms, a unique access from the internal hospital has been considered. It allows the access of maintenance personnel without interfering on IR procedures. Indeed, this access, together with the one found at the “Dirty Corridor”, enable all those non-clinical procedures previously mentioned.

Concerning the cleaning spaces, as in the final conceptual design (Figure 13), there is a large and central cleaning point implemented to clean the medical instruments used during IR procedures. In addition, it is also conceived to store those cleaning materials used specifically in IR suites. This cleaning space has been provided with an elevator for a direct communication with hospital’s sterilization center. Moreover, two additional small cleaning rooms allow the cleaning staff to store the remaining cleaning material that, for aseptic criteria, cannot be the same used in IR suites. It could also be commented here that the area has been provided with different toilets to cover the personal necessities of the staff.

A key aspect that has not been addressed before but has been included in the design are emergency requirements. On the detailed design (Figure 14), two main emergency corridors have been included. Furthermore, emergency doors have been represented in red. Double hinged doors represent those accesses closed during normal functioning. Bifold doors, those access closed only during emergency situations. All these measures have been implemented to facilitate evacuation and the sectorization of spaces to avoid fire propagation. However, concerning this matter, an additional study would be required to determine if additional or different measures are necessary.

Finally, the space thought for medical personnel offices has been divided in four main subspaces. Firstly, a common space with adjacent desktops is proposed for IR specialist to prepare their daily cases and write their reports. Secondly, there is a specific room to be used as a command center. The name reveals its functions, but the whole concept behind is further explained in Section 5.3. Finally, a room for meetings and some individual offices for coordinators have also been included.

5.1.2. Equipment

Although a complete equipment proposal is not included on this project, the specific DIVAS that should equip the proposed area (Figure 14) are indicated on this section. Since each DIVAS model has different requirements and functionalities, an IR area design must consider from the very initial phases the equips and final uses of each of its IR suites. In that respect, the proposed area is equipped with six IR suites. These suites have been designed for different speciates and the DIVAS placed on each suite has been selected with a sustained criterion.

IR suites 1 and 2 are mainly thought for general body IR procedures. Both suites are conceived to contain monoplane DIVAS but, IR suite 1 has been further designed to admit a movable system. As explained later, this first suite is, in fact, an HOR. For this reason, it could receive open surgical procedures which would benefit from a movable DIVAS that could be retired to gain additional space. Although currently these movable systems are produced by a unique manufacturer (GE Healthcare), they offer new possibilities that must be considered. IR suite 2 is designed to contain a ceiling mounted monoplane DIVAS. Since general body procedures require acquisitions on complex and distal body areas, ceiling mounted system with a larger scope and additional acquisition planes are preferred.

IR suites 3 and 4 are thought for neuro IR procedures. Since depth perception is critical in deep brain vessels, neuro interventional radiologist work with biplane systems. In that respect, suites 3 and 4 are equipped with biplane systems mounted between the ceiling and the floor.

IR suites 5 and 6 are designed for cardiology, a specialty widely extended in the field of IR. For the specific point in which the specialty is focused and the deep anatomical knowledge of the area aborded, floor mounted monoplane DIVAS are sufficient. In that respect, suites 5 and 6 are equipped with monoplane systems mounted at the floor.

Concerning DIVAS orientations, on Figure 14 it is proposed to place all the systems taking advantage of the larger side of each room, prioritizing patient's direct access and promoting the conservation of control room views. Another characteristic that must be mentioned here is the grouping of specialties. Since controls rooms are shared, IR suites thought for a same specialty have been placed together. This has been done looking for an extended collaboration between professionals sharing the same area of expertise.

An important detail that could be mentioned here is the implementation of a pressure gradient. As it will be explained later (Section 5.2), IR suites must present a supplementary pressure respect to adjacent rooms. To ensure a progressive air circulation, the author proposes a differential pressure of 25 Pa inside IR suites and a differential pressure of 15 Pa at the aseptic corridor and inside control rooms. Both differential pressures must take as reference the pressure level of the remaining adjacent rooms.

Finally, as repeatedly mentioned, IR suites need special HVAC systems. Their machinery can be placed inside IR suites' adjacent technical rooms. Nevertheless, the coexistence of DIVAS electronic components and water-based HVAC systems could result on undesired consequences. For this reason, the author proposes to install the HVAC systems on a superior floor, just above each IR suite. This would leave adjacent technical rooms only with the digital, electronic and electric infrastructures required for DIVAS or for the general facilities.

5.1.3. Area dimensions

An important aspect that must be analyzed and indicated quantitatively are the dimensions of the area. In that matter, possibly IR suites have the most exigent requirements. Due to the volume that DIVAS require, IR suites must have a minimum width and length. Additionally, for ceiling mounted DIVAS, the room height must be a specific one. In order to find the proper size for IR suites, the main space requirements of different DIVAS models can be compared on Table 2.

Referring to Table 2, it must be mentioned that apart from the systems included, the studied brands have a wider portfolio including additional DIVAS. Moreover, there are other companies with their own DIVAS such as Canon Medical Systems. Nevertheless, the cases included on Table 2 are enough to represent the specifications of the main current brands and their latest equips. It is also important to highlight that, since DIVAS are composed by multiple elements, their space requirements depend on these components forming the whole system. In that respect, the model of surgical table, the dimensions of the display monitor or the type of ceiling fixation determine the required space. Looking for those situations requiring the largest spaces, Table 2 exclusively includes the information of those DIVAS containing the largest configurations of each brand.

Analysing the dimensions of Table 2 it could be easily said that the current main commercial systems require an approximate area of 30m^2. Nevertheless, since some systems need until 35m^2 and that the minimum required space does not usually match manufacturers' recommendations, according to author's criteria, an area between 35m^2 and 40m^2 could be considered the recommendable one.

This recommendable area is just needed for the elements of DIVAS installed inside IR suites. In addition, the examination rooms must have space for voluminous medical equips such as aesthesia workstations, for storage furniture or for professionals to freely circulate around the suite. Moreover, the space required for future promising equips must be considered. For instance, new robotics systems for endovascular interventions occupy a noticeable volume considering their large command consoles. In that respect, for this project, a space of 70m^2 has been considered as the minimum to ensure the comfortable functioning of IR suites. As it can be appreciated on the final design (Figure 14), all the IR suites included have, at least, these dimensions.

<table>
<tr><th colspan="6">DIVAS space requirements</th></tr>
<tr><th>Model</th><th>Manufacturer</th><th>System</th><th>Required room width</th><th>Required room length</th><th>Required room height</th></tr>
<tr><td>Azurion 7 F20</td><td>Philips</td><td>Monoplane / Floor mounted</td><td>4000</td><td>6500</td><td>2300-2900</td></tr>
<tr><td>Azurion 7 C20</td><td>Philips</td><td>Monoplane / Ceiling mounted</td><td>4500</td><td>6500</td><td>2700-2900</td></tr>
<tr><td rowspan="2">ARTIS icono floor</td><td rowspan="2">Siemens Healthineers</td><td rowspan="2">Monoplane / Floor mounted</td><td>4580</td><td>6040</td><td rowspan="2">2400-3100</td></tr>
<tr><td colspan="2">Min. area = 28 m^2</td></tr>
<tr><td rowspan="2">ARTIS icono biplane</td><td rowspan="2">Siemens Healthineers</td><td rowspan="2">Biplane / Floor-ceiling mounted</td><td>Not found</td><td>Not found</td><td rowspan="2">2890-2920</td></tr>
<tr><td colspan="2">Min. area = 29 m^2</td></tr>
<tr><td>Innova IGS 5</td><td>GE Healthcare</td><td>Monoplane / Floor mounted</td><td>4400</td><td>6340</td><td>2710- 3050</td></tr>
<tr><td>Innova IGS 6</td><td>GE Healthcare</td><td>Biplane / Floor- ceiling mounted</td><td>4400</td><td>6900</td><td>2840-2850</td></tr>
<tr><td>Discovery IGS 7</td><td>GE Healthcare</td><td>Monoplane / Movable with wheels</td><td>5200</td><td>6600</td><td>2710-3050</td></tr>
</table>

Table 2. Minimum space requirements of different DIVAS. Units: Millimeters (if anything else is indicated). Data obtained from public brochures and datasheets. For an implementation project, specific dimensions must be confirmed with the manufacturer.

To determine the size of the principal spaces surrounding IR suites, two main characteristics have been analyzed. Firstly, the equips and material placed on each zone. Secondly, the number of individuals that must work or occupy each space simultaneously. On Table 3, these aspects are indicated as well as the area required by each space. Indeed, the area indicated in the table is the minimum required by each space to ensure its functioning, for a further comfortable working environment and to achieve efficient workflows, wider spaces can be implemented. In that respect, the values shown on Table 3 must be seen just as an indication of the minimal indispensable space.

Space	Equipment	Users	#	Min. area	Ratio
Core Unit					
Technical room	DIVAS electronic systems Infrastructure equipment (electric installations, digital integration…)	Technicians	2	4x4	4/9
Control room	Furniture (table, chairs, cupboards...) Scrub sink DIVAS control elements Electromedical equips Informatic material (computers, DICOM compatible screens…)	Technicians Clinicians Nursing personnel	5	4x4	1/3
Main Complementary Spaces					
Preoperative area	Small nursing workstation Patients' bed Electromedical equips (vital constants monitor, infusion pumps...)	Patients Nursing personnel	2	3x3	1/9
Postoperative area	Small nursing workstation Patients' beds Electromedical equips (vital constants monitor, infusion pumps...)	Patients Nursing personnel	2	3x3	1/9
Initial storeroom	Storage furniture (shelves…) Stored elements	IR area personnel Hospital providers	2	3x3	1/40
Clean storeroom	Storage furniture (shelves, cupboards…) Stored electromedical equips Stored consumables	IR area personnel	2	5x5	1/9
Cleaning zone	Furniture (cupboards, cleaning sinks…) Cleaning materials (mops, buckets…)	Cleaning personnel Nursing personnel	2	2x2	1/20
Private patients' room	Home like furniture (table, wardrove, armchair…) Appliances (television…)	Patients Patients' relatives Nurses/Clinicians	3	3x3	2/9
Personnel changing room	Furniture (Wardrove/lockers, benches…) Toilets	IR area personnel	4	3x3	1/20
Medical personnel offices	Office furniture (desk, cupboards…) Informatic material (computers)	IR area clinicians	4	3x3	2/9
Additional Complementary Spaces					
Professional's rest area	Furniture (table, chairs, cupboards, kitchen sink…) Toilets Appliances (fridge, microwave…)	IR area personnel	5	4x4	1/20
Reception	Office furniture (desk, cupboards…) Informatic material (computers, printers…)	Administrative staff	2	2x2	1/40

Table 3. Table indicating the minimum required dimensions of IR areas. "#" refers to the number of users that can simultaneously occupy a same space. "Min. area" indicates the minimum surface (m²) required by each space of an IR area containing a unique IR suite. "Ratio" indicates the proportion in which the spaces must increase their area each time that an IR suite is added. Its value must be multiplied by the area of each IR suite added. Then, the result must be added to the "Min. area" value.

5.1.4. Explanation of particular spaces

Patients' private spaces

As proposed on Concept engineering (Section 4), patients' Private Spaces (PS) have been included on the final design in order to tackle the lack of privacy and intimacy. These rooms could be compared to those already mentioned of Memorial SK (New York), which are used as perioperative zones but also intend to enhance patient comfort and provide familiar support [19]. Nonetheless, for this actual case, PS complement, and do not substitute, the perioperative zone. They have been mainly conceived for outpatients and their relatives, but without replacing perioperative facilities.

For a better understanding of the role that play these rooms, their functions must be explained. To begin with, their main function is to receive patients and their relatives after a first contact with reception. The site is conceived to be use as a changing room for patients, allowing them to leave there their personal belongings. In addition, the space must be accessible by interventionists and nurses to embrace the first doctor-patient personal contact, the filling of medical or administrative documents and the simplest nursing initial preoperatory procedures. Concerning this last matter, a little nursing point has been included near PS to facilitate these procedures and morally support patients on their arrival to the IR area. The point is also intended to coordinate the movement of patients form the PS to the IR suites.

Going into deeper detail, two interesting concepts leading hospital design have been applied to implement these spaces, the biophilic and the home-like design. One the one hand, biophilic designs try to connect people with a natural environment. Although this is complicated in environments such as IR areas that must remain clean, the situation of PS in inside the called transient zone can give certain flexibility. In the pursuit of the biophilic essence, PS have been placed attached to the exterior walls of the IR area. This has been done to ensure access to natural light and to open the possibility to access exterior green spaces if necessary. On the other hand, PS have been conceived with an inherent home-like design. The pursued objective is to humanize the usual cold aspect of hospitals welcoming patients in a warmer environment designed to promote relax and reduce perioperative stress.

Finally, the equipment of these rooms must be conceived as a mixture between that one found on a living room and that one found on a hospitalization room (Figure 15). It must include comfortable furniture such as armchairs or canapes, but also, ensure certain hygienic conditions. A hospitalization bed would not be strictly necessary since outpatients, in most of the cases, are able to stand up and walk by their own without difficulties. However, on the proposed design, to increase its functionality, space for hospitalization beds has been included. As a final remark, to have an individual toilet for each room is the ideal situation, but if space is missing, a communitarian one could be implemented.

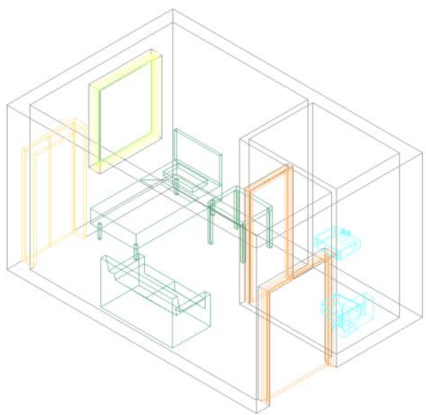


Figure 15. Equipment proposal for a patients' private space.

Multimodal Hybrid Suite

The complexity of some cases treated inside IR suites require the support of additional imaging modalities apart from DIVAS. Possibly the most know medical condition boarded in IR suites that faces this situation is stroke, also known as cerebrovascular accident (CVA) or brain attack. Stroke is the second leading cause of death globally. It affects roughly 13.7 million people and kills around 5.5 million annually [20]. Even though many stroke cases can be treated with medication to dissolve blood clots, to reduce blood pressure or to decrease cholesterol levels, endovascular treatment (EVT) performed in IR suites is also required, especially for acute ischemic stroke (AIS) with large-vessel occlusions. In that respect, candidates for AIS must undergo an initial brain imaging to determine if they can be selected for EVT or not. This is usually done through MRI or CT. Nevertheless, since earlier treatment leads to greater benefit, regardless of the imaging modalities and strategies used for this initial brain imaging, an efficient imaging workflow must be established to provide a faster treatment [21].

Following with the idea of combining DIVAS with additional medical resources to solve complex medical procedures, DIVAS are also used in conventional ORs. This gives place to the nowadays known as HORs. Even though IR suites already have a high level of asepsis, they do not reach the requirements of the most exigent ORs where major surgical procedures are performed. This changes in HORs, where the most exigent aseptic conditions that enable open surgery meet DIVAS technology. This has been reported to be useful, for instance, in trauma patients. In these cases, endovascular interventions along with open surgical management in HORs not only decrease surgical time, avoid exposure to anesthesia, hasten recovery, but most importantly breakdown the catastrophic sequelae of ongoing bleed by rapid hemorrhage control [22]. Moreover, they allow vascular control at difficult surgical terrains such as subclavian or iliac vessels with much compared ease and rapidity [22].

With all this context in mind, a multimodal hybrid suite (MHS) has been included in the final design of this project. This suite is conceived as a HOR equipped with a movable DIVAS and a CT scan. The purpose of this implementation is to cover those cases requiring both open surgery and EVT such as trauma cases, but also to cover those minimally invasive procedures that punctually could evolve to critical situations that require open or conventional surgeries. Furthermore, the implementation of a CT scan would benefit those patients requiring additional imaging technologies apart from DVAS. More specifically, it would contribute diminishing the treatment time and reducing the number of intrahospital displacements that these patients suffer. On the one hand, IR emergency patients, that are frequently directed to previous CT scans at emergency departments, would directly be scanned at IR facilities. On the other hand, IR procedures disrupted by the need of additional CT images, would be performed without interruptions.

The implementation of a CT scan, in front other possible imaging modalities, has been adopted thinking mainly with emergency cases. Concerning AIS, different procedures (nonenhanced CT, CT angiography or perfusion CT) make CT useful for treatment decision making in both the early (<6 hours) and the late (6-24 hours) windows in which AIS is boardable through EVT [21]. Furthermore, the agile image protocols of CT scans compared to those of MRI, make CT the preferred option. As mentioned before, in AIS, a fast intervention leads to greater benefits. Aside, the agility of CT scans also benefits polytrauma patients. Those patients who have been subjected to multiple traumatic injuries often associated with traffic accidents. In these situations, but also in other patients with internal haemorrhages, CT scans can highlight internal bleedings in imaging plans that cannot be reached through DIVAS due to its physical limitations.

On Figure 16 the design of the suite and its surrounding spaces can be appreciated. Even though the CT scan is considered as part of the suite, a radiative protected sliding door separates the space where interventions are performed from the CT space. This has been done to ensure the use of the CT scan, not only for those patients being treated inside the HOR, but also for ambulatory patients that need this radiographic service. It must be mentioned that, although a CT scan can complement certain IR procedures, the number of IR cases that require it is considerably low. In that respect, the implementation of a CT only to cover the necessities of a unique IR suite would be too expensive and inefficient.

To make accessible the CT system to additional hospital patients, the MHS, and especially its CT room, has been placed on a strategic point of the area. It is close to hospital internal corridors to attend hospitalized patients and close to the externals corridors to attend outpatients. Here, it must be clarified that CT procedures scheduled on this room must be short and cancellable. In that respect, any programmed scan must admit an adjournment if an emergency patient requires the service punctually.

Specially for outpatients, individual changing rooms have been implemented. These have a unique access but, in other layouts, changing rooms can be further developed (see Annex 3). Aside, a preparation space has also been placed next to the CT scan room. It has been designed as a waiting space for bedridden patients while themselves, or CT facilities, are being prepared. The waiting room situated next to reception (Figure 14) makes this last function too, but just for outpatients. In that respect, the waiting room, as the same way as the reception does, is designed to receive IR patients, but also those outpatients that come just for a simple CT scan.

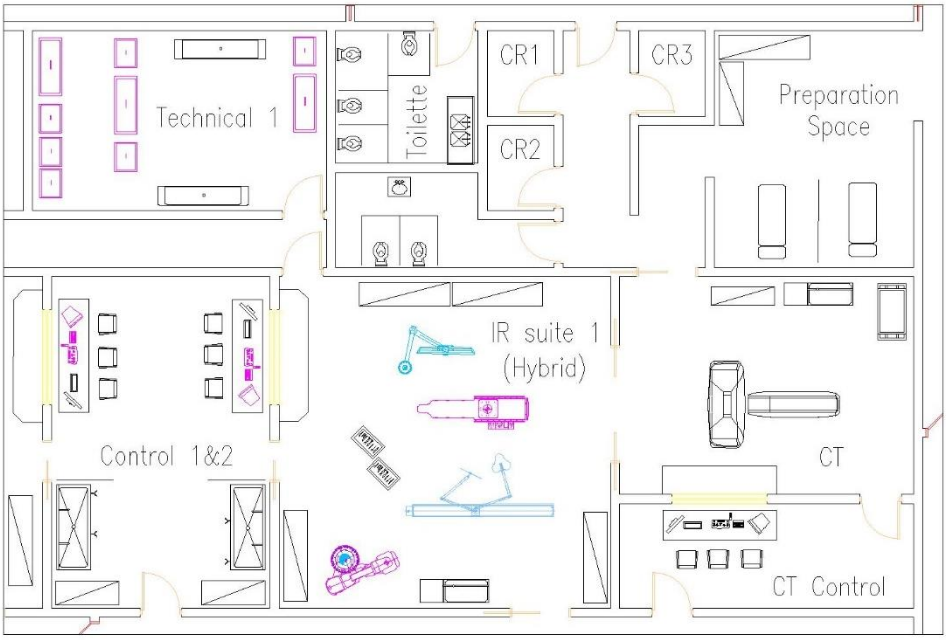


Figure 16. Design of the multimodal HOR facilities. Scale: 1/200. Abbreviations: Changing Room (CR), Computed Tomography (CT).

5.2. Technical requirements of IR infrastructure

In order to design an IR area, its specific technical requirements must be considered. IR suites must accomplish several strict conditions. Nevertheless, the remaining IR service, as part of a hospital and public building, is also limited by a series of regulations. All these matters must be reviewed for the proper understanding of the proposed design (Figure 14).

5.2.1. IR suites technical requirements

Electrical installation: Due to the intensities involved, the electrotechnical regulation for low tensions must be followed. In Spain, the regulation known as “Reglamento electrotècnico para baja tension” [23] must be considered. More specifically, ICT-BT-38 regulates the electrical installation of ORs and interventionism suites. Although the actual regulation must be consulted for further detail, its main specifications could be considered the following ones:

- The supply wiring must be triphasic containing a neutral and a protection conductor wire. It must be made of cooper and correctly insulated.
- Each IR suite must be equipped with a common and an equipotential busbar. The last one must be used to connect all those accessible metallic elements.
- Apart from a first complementary supply circuit, it is compulsory to have a second auxiliar supply called special supply circuit. This could be based on batteries such as Uninterruptible Power Supplies (UPSs). Nevertheless, it must ensure the supply in less than 0.5 seconds and for 2 hours at least.
- The floor must be antistatic and its insulation resistance must not exceed 1MΩ.
- The use of isolation transformers is mandatory. Those equips that are not connected through it require differential protective devices with high sensitivity (≤ 30mA).

Lightning conditions: To ensure the safety of medical procedures performed, a powerful lightning is needed. According to UNE 12464.1 [24], on the one hand, the maintained illuminance inside the OR must be at least 1,000 lx. On the other hand, 500 lx is the value fixed for the peripheral rooms of the service. For both spaces, the limit of Unified Glare Rating (UGR) must be 19 and the minimum Colour Rendering Index (CRI) 90. Additionally, Spanish recommendation guides [25] specify that the illuminance at the intervention zone inside ORs should be between 20,000 and 100,000 lx. Also, according to the previous guides, the light colour temperature should be between 4,000 and 5,000 K. Moreover, to avoid an excessive heating of patient’s tissues, light efficiency should not exceed 170 lm/W to ensure a maximum irradiance of 600 W/m^2 for an illuminance of 100,000 lx.

Climatization: For the aseptic conditions required, IR suites are considered type B ORs. Following UNE100713:2005, these must certify an ISO 7 [26]. This certification means that the air recirculation flow must be at least 20 movements/hour and must contain 1.200 m^3/h of exterior air [27]. Moreover, this recirculating interior air must be submitted to the same treatments as the exterior air. Besides, microbiological controls must be implemented. In that respect, three filtering levels must be ensured. A first prefilter EU4 is recommended. A second EU9 filter can be used. And finally, a third H14/U15 or H13 filters are implanted for type A and type B ORs, respectively.

Additionally, it must be mentioned that hybrid suites, where major open surgical procedures are performed, could be classified as type A ORs. For this reason, in Table 4, the parameters required for type A ORs have also been included.

Leaving ventilation, according to UNE100713:2005, IR suites should ensure a temperature between 22-26 ºC and a relative humidity equal to 50% ±10% [28]. Concerning room pressures, class A and B ORs must present a pressure higher than the one presented by the adjacent spaces. Moreover, for a better performance, a pressure gradient can be settled from the dirty to the cleanest areas.

OR Type (UNE 100713)	ISO (ISO 14644)	Flow type	Minimum exterior air flow (m^3/h)	Minimum propelled air flow in movement (m^3/h))	Minimum air recirculation per hour	Air velocity at the end of the diffuser (m/s)
Class A	5	Laminar	1,200	2,400	30	0.2
Class A	6	Turbulent	1,200	2,400	30	0.2-0.3
Class B	7	Turbulent	1,200	2,400	20	0.2-0.3

Table 4. Climatization requirements of type A and B ORs.

Gas installations: For the procedures performed, oxygen, medical air and carbon dioxide are needed. Additionally, an Anesthetic Gas Scavenging System (AGSS) is necessary. In that respect, these four gas installations must be submitted to tightness and cross-connection tests. The technical requirements for its installation are specified in UNE60670-6:2014 [29].

Radiological protection: Needed due to the emission of x-ray radiation inside IR suites, radiological protection is usually achieved through lead protection layers with a thickness between 1-2mm. The exact value must be determined by a service of radiological protection depending on the concurrency of the adjacent rooms and the power of the emitting equip.

Structural Support: Due to the weight of DIVAS, IR suites must support considerable loads. For this reason. A study to determine the maxim loads supported by the floor or the ceiling may be needed. If the studies indicate it, reinforcements must be added.

5.2.2. IR areas technical requirements

Among the different architectural and safety requirements, fire prevention and evacuation routs are two key aspects that must be considered when designing an IR area. The official documents that must be followed to address these matters are the Basic Document of Security in front of Fire ("DB-SI", in Spanish) [30] and the Basic Document of Usage and Accessibility Safety (DB-SUA, in Spanish) [31], both included in the Building Technical Code ("CTE", in Spanish). Nevertheless, the crucial aspects that address these documents are explained on the following paragraphs.

Fire prevention: Apart from the general fire prevention standards, due to the electrical installations and the nature of IR equips, special measures are needed. In general terms, fireproof doors must be implemented each 25m dividing the area in differentiated sectors and a fire control center must be stablished. Additionally, fire detectors, extinguishers and equipped fireplugs must be distributed according to the current regulation. More specifically, technical rooms' walls must be made of fire-resistant materials such as brick or special drywalls.

Evacuation routes: In front of the possible need to evacuate bedridden patients, the evacuation routes of hospital areas, according to the technical code, must have a minimum width of 2.20m. Moreover, emergency doors must open following the direction of the evacuation routes.

5.3. Value proposals for the reinvention of traditional spaces

Probably the most innovative proposal presented on this project is the implementation of patients' private spaces. Nevertheless, a detailed explanation of their nature and functions has already been provided. Is for that reason, that the following lines are focused on the remaining traditional spaces of IR areas. Indeed, here are presented a series of value proposals for the reinvention of storerooms, conventional medical offices, cleaning spaces or resting areas. Some of these proposals are inspired by the latest solutions implemented in leader hospitals.

From conventional store spaces to intelligent storerooms

To begin with, storerooms could behave as intelligent inventories. On the one hand, with a distribution comparable to the one presented in this project (Figure 14), an initial storeroom could be used to informatically record the arriving consumables. On the other hand, a second storeroom could be used to count the spend of those products by the time there were used. Going one step further, a digital inventory actualized automatically could be programmed to order the missing products. Apart from automatizing the management of consumables, this system would contribute to control their consume.

From medical personnel offices to control centres

Other spaces that could be reinvented are the medical personnel offices. Nowadays, these are mainly used by interventional radiologists for the planification and study of daily cases. Nevertheless, with the digitalization on new IR areas, these spaces could be also used as control centres. In that respect, a concept comparable to the "Còrtex" proposed by Sant Joan de Déu [32], reduced and adapted to the necessities of an IR area, could be implemented.

This control centre concept would have three main functions. The first one would be the commandment of the area through a follow up system able to report the state of the facilities. The idea would be to accelerate the workflows, knowing from an office the availability of the area. Additionally, the system could control the state of crucial equips such as DIVAS or HVAC circuits to detect anomalies. This could be implemented through the concept known as "Digital Twins" [10], interactive virtual models that enable a real time follow up of the facilities.

The second function of the proposed control centre would be patients related. The idea would be to centralize the monitored clinical data to the medical offices. The data could come from the IR suites, from the perioperative zones or form the patients' private spaces. In any case, the awareness of patients' situation would be direct and immediate to face adverse situations.

Finally, the third function of the centre would be the communication with all the members involved in any process of the area. Since the concept of the control centre enables to manage both patients and facilities, it should also enable to contact clinicians, nurses, technicians or even patients' relatives to coordinate all processes in which they are involved.

From resting areas to polyvalent spaces

Professionals' rest areas have always been separated from clinical activity. They are usually conceptualized as places for leisure pauses incompatible with health procedures. Nevertheless, many professionals, although the presence of these spaces, use other environments to rest or have their punctual snacks while they keep working on a more relaxed way. From this situation comes the idea of merging rest spaces with other spaces involved in not highly demanding clinical activity. In that respect, spaces such as nursing points or medical offices, could be designed incorporating concepts implemented on rest spaces. Nurses and clinicians could evaluate certain reports or control patients' situation while simultaneously having small snacks or brief amusing chats with their workmates.

From individual cleaning points to sterilization networks

In many hospitals, cleaning points are few more than a basic sink and complementary storage furniture. They are mainly used for the first washing of reusable materials. A procedure realized before the exhaustive disinfection and sterilization processes done in general hospital services. Nevertheless, larger and centralized cleaning spaces admit more possibilities. The option proposed here would be the connection of a centralized sterilization service with the different cleaning points distributed along the hospital. This connection, realized through elevators or rail mechanisms, would allow a fast transference of the dirty and clean material between the sterilization station and the different cleaning points. Moreover, it would avoid crossing spaces concurred by individuals. A situation that would reduce potential infection scenarios and would allow to control the entrance and exit of surgical material from the area. Indeed, the cleaning space included in the proposed design (Figure 14) encompasses this philosophy.

From basic rooms to intelligent suites with smart accesses

Due to the existent technology, domotics could enable to control certain area spaces. If IR areas where properly equipped, domotics could be used to automatically restrict the access to particular spaces, to control doors' aperture when X-ray radiation is emitted or to monitor the usage of the facilities from control centers as previously proposed.

5.4. Statements for the design of IR areas

Although the present work includes several designs realized to inspire the conception of new IR areas. Each scenario has its own limitations and the implementation of already existing designs may result complicated. For these situations, but also for the conception of any new IR area, the following section recaps the main points/concepts that must be considered for the design of new IR areas. These key points result from an interdisciplinary collaboration with clinicians, but also technicians and other specialists.

- **Necessary spaces.** The spaces that must undoubtedly include any IR area are IR suites, control rooms, particular technical rooms, cleaning zones, storerooms and perioperative spaces. Apart from those, medical personnel offices, general technical rooms, a rest are for professionals, changing rooms, waiting rooms or a reception are needed but they can be placed on adjacent facilities.
- **Complementary spaces.** Spaces that can improve the quality and efficiency of the area are differentiated clean spaces (explained later), differentiated storerooms (explained later) and patient's private spaces. Concerning this and the first pint, ideally, all the mentioned necessary and complementary spaces must be included in a unique IR area.
- **Proximity of related spaces.** For the procedures performed and its technical necessities, IR suites must be attached to control rooms and rigorously close to technical rooms. Clean storerooms, perioperative spaces and cleaning points must surround the first core structure. The distribution of the remaining facilities must be done following hygienic criteria and grouping those spaces involved in common procedures.
- **Shared and centralized spaces.** Merging and creating shared rooms facilitates the collaboration between professionals, reduces the total required personnel and solve space problems. In IR areas, perioperative zones, control spaces and technical rooms can be designed to cover the necessities of more than a unique IR suite. For a further development of this strategy, professionals must be grouped according to their area of expertise. Nonetheless, if the implementation of this whole concept results is an extreme reduction of workspace, it becomes counterproductive.
- **Technical spaces.** Technical rooms are needed due to the electric, electronic and digital requirements of IR suites, but also to cover general hospital technical necessities (electricity, water supply, etc.). Since there are multiple scenarios, their dimensions must be discussed with hospital technicians and commercial houses implementing DIVAS. Nevertheless, a separation between wet and dry components is crucial. Moreover, a differentiation of IR suites' technical spaces from general technical rooms is recommended. Going one step further, it is advisable to install HVAC systems of IR suites on adjacent superior floors.
- **Separation of workflows and individuals involved.** The following individuals must be considered and provided with different accesses for the optimization of workflows, avoidance of visually shocking situations and maintenance of hygienic conditions:

- **Medical team and cleaning staff:** They must have access to every patient related space. A changing room, ideally paced at the entrance of the area, must promote that professionals wear the adequate work clothing.
  - **Logistics and maintenance personnel:** Their circulation must not interfere with patients' pathways and their access must be limited to store and technical rooms. The ideal situation is to provide these last spaces with an external access point or circuit.
  - **Outpatients:** They must be separated from acute patients and form all that hospital staff not directly involved in medical procedures. They must have an individual access from the external hospital and their presence in professional spaces (control rooms, medical offices or cleaning zones) must be restricted.
  - **Hospitalized and emergency patients:** They must have a fast individual access from the internal hospital to avoid outpatients and ensure agile medical processes. Their presence in professionals' spaces must be restricted.

- **Promotion of aseptic conditions.** A considerable level of asepsis is required in IR procedures. To achieve it, this work stablishes the following four solutions:
  - **Hygienic zones:** If the area is physically divided in subzones, the restricted access to these subzones reduces its contamination and separates conflictive procedures. To implement this strategy, each space of the area must be included in a concrete subzone depending on its contamination potential or its aseptic requirements.
  - **Straight forward workflows:** If the architecture promotes an unidirectional circulation, undesired back and forth movements are avoided.
  - **Filtration of exterior supplies:** If an initial storeroom is used to eliminate the exterior dirty envelopes of the arriving material, the crossed contamination that could be associated with these consumables or new equips is reduced.
  - **Waste evacuation pathways:** If a differentiated circuit to evacuate IR suites waste is used, contamination scenarios are avoided.

- **Flexibility, adaptability and oversizing of spaces.** These characteristics ensure that personnel could work comfortably. Besides, they are required due to the voluminous mobile elements involved such as the stretchers, but also, due to the essence of equips such as DIVAS. The future changes, the new procedures and the new technology associated to them also demand these characteristics. In that respect, additional space is needed. Nevertheless, it must be designed with a polyvalent nature.

- **Multidisciplinary methodology.** As well as hospital technicians were involved before, interventionist, nurses, cleaning staff and even patients may contribute to the success of an IR area design. These individuals are the final users of the facilities. To cover their necessities must be a priority and their preferences must be included as far as possible.

- **Revalorization of spaces.** Conventional spaces such as waiting rooms, medical personnel offices or even key spaces like control rooms can adopt new proposals. To limit their possibilities to conventional roles may ensure their functioning but prevents the discovery of new potential uses and functions.

5.5. Practical case: study of Vall d'Hebron facilities

As it has been explained previously (Section 3, Market analysis), Vall d'Hebron is going to implement a new IR emergency area soon. This new area will substitute the current interventional neuroradiology service which will disappear leaving space for the coming project. The novel emergency facilities will be focussed on the treatment of moderate and severe stroke patients. Indeed, the conceived proposal intends to directly receive bedridden patients arriving through emergency pathways, perform immediately a fast diagnosis followed by a first approach (TAC, intravenous thrombolysis or even drain placements), observe patients' evolution in a semicritical area and finally, if necessary, derivate them to an IR suite or ICU. The whole proposal is intended to reduce the number of displacements between departments that suffer stroke patients inside the hospital. A situation related to several risk factors [33, 34, 35], but most importantly, related to imbalances in blood pressure [36, 37] which difficult neuroprotection and are associated with bad prognostics [38]. On Figure 17, the last floor plan approved by the organizations involved in the project is presented. It includes a CT scan and three DIVAS, two of them biplane systems.

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Figure 17. Floor plan of the new IR emergency area of Vall d'Hebron. Conceived inside the One-Step Ictus project.

5.5.1. Critical analysis

Comparing Vall d'Hebron's future area and the one proposed in this project, the most noticeable common aspect is the implementation of a multimodal suite. Both proposals include a sliding CT scan that can be moved and used inside an attached IR suite. Nevertheless, in Vall d'Hebron's proposal, the CT scan is combined with a biplane system. This situation is ideal for the management of stroke patients in which biplane systems play an important role. However, double arc DIVAS may result excessive and even inefficient to address other pathologies.

Also concerning the multimodal suite, the absence of patient changing rooms for the CT facilities diminishes accessibility in terms of outpatient's usage. This would be explained by the fact that the area is designed specifically for emergencies. Moreover, the CT could still be used by hospitalized patients what would increase the profit that the hospital takes from its implementation.

Leaving the multimodal suite, a valuable aspect that includes the new proposal of Vall d'Hebron is the separation of internal and external hospital corridors. On figure 17, two differentiated corridors are clearly marked, one for the general hospital public and another for the area's personnel and bedridden patients. In addition, the internal corridor gives access to elevators A1 and A2 that connects the area with ICUs and the surgical areas. Nonetheless, to access hospitalization rooms or additional hospital services patients would still have to use the general external passages.

Another mentionable aspect is that two of the IR sites have their own storerooms attached. The designed connection gives an excellent scenario in terms of material accessibility and complements the lack of space that suffer many IR suites, especially those with biplane systems. Also concerning the storerooms, it is interesting to see how these are provided with exterior accesses. This allows a fast and practical refiling of the consumable materials. It also offers a place to external providers to leave their material without accessing the area. Nonetheless, these spaces must be used properly to avoid compromising the aseptic conditions of adjacent IR suites.

Aside, a particular matter that gathers the attention is the isolation of the waiting room. Unfortunately, the proposed layout complicates the communication between waiting patients or relatives and professionals. Finally, it can be pointed out that the personnel's changing room is close to the entrance, but still does acts as a barrier to avoid external contamination.

5.5.2. Proposed alternatives

Taking the last point, the first alternative that proposes the author of this project is the displacement of the changing room to the bottom right corner of the area, where office 3 ("Despacho 3" on Figure 17) is found. This would place the room next to the right entrance of the area and would promote that professional were wearing the adequate clothing from the very first moment.

A second alternative would be to move the waiting room to the right side of the angiography suite equipped with the monoplane. Removing the changing rooms from the top right corner of the area together with the adjacent spaces would leave place for this initiative. With this configuration, patients and relatives would have their zone in front of the area's entrance. A situation that would accelerate the workflows and would give a feeling of closeness.

Additionally, opening a corridor through the personnel's resting zone ("Office" on Figure 17) and the supervisor's chamber would create a direct access to internal elevators (A6 and A7 on figure 17). By doing this, the external corridors would be avoided when transferring patients to higher floors where the hospitalization rooms or the additional hospital services are found. However, it must be said that these internal elevators are not currently used for patients. In that respected, possibly important modifications would be required to implement this proposal.

Going one step further, the biplane DIVAS placed on the multimodal suite could be rotated 90º to the left. This would move the C-arms of the system far from the control window ensuring the visual perspective of the suite. Moreover, the professionals, which mainly perform their procedures placed at the right side of the patients, would be faced to the window facilitating the communication with the control. The CT, in this configuration, would be placed perpendicularly to the surgical table but, due to the rotations that surgical tables allow nowadays, that would not suppose a drawback. The unique downside that presents this option is the possible insufficient wideness of the room.

5.6. Practical case: study of Hospital Clínic de Barcelona facilities

As previously mentioned, Hospital Clínic de Barcelona has recently inaugurated a new IR area of hemodynamics and interventional cardiology. Since its main characteristics have been discussed previously on this report (Section 3, Market analysis), this section is just intended to suggest a series of feasible changes that, according to authors criteria and the proposals of this project, could help improving the service. For its proper understanding, it is essential to analyse the current setup of the IR area attached on Annex 6. Notice that Figure 18 includes the proposed changes and excludes those zones that have not been modified.

5.6.1. Critical analysis

At a first sight, the current layout presents two main drawbacks. The first one is the existence of a unique central corridor. This situation inhibits the separation of workflows increasing potential sources of contamination. With the current disposition, all the staff, independently if their activities have a clinical implication or not, share the same pathway. Technicians, cleaning personnel or interventionist circulate through the same circuit with all the hygienic consequences that this implies.

The second drawback of the current floor design is the general exposure of the area to the public. Outpatients, relatives or even visitors, can freely circulate through the central corridor. There is not a barrier to control the access to the area and that adds complicates the maintenance of aseptic conditions. Also concerning the accesses, since the area is placed on a sixth floor, the possibility to have multiple entrances is limited. It can be appreciated that there is basically two main access points, one at each extreme of the central corridor. In that respect, there are not additional accesses that could be used to separate workflows.

Leaving the addressed considerations, the floor presents several optimal solutions. The first that can be mentioned is the distribution of HE16 and HE19 IR suites. Their configuration with a shared control room optimizes space and promotes collaboration. The proximity of the storeroom, the cleaning space and the scrub point, all of them placed next to the mentioned IR suites, is ideal to make procedures further efficient and comfortable. Besides, the presence of an external storeroom at the entrance of the area gives the possibility to stablish a system with cleaner and dirtier store spaces, as the initial and clean storerooms proposed on this work.

5.6.2. Proposed alternatives

The improvement proposal presented for the current layout of Hospital Clínic de Barcelona is mainly based the implementation of additional corridors. As it can be appreciated on Figure 18, a first new passage has been suggested on the right side of the floor. Although it seems a simple solution, it has many implications. To begin with, this configuration sets the reception at the entrance of the area offering a control of the access. Apart, it maintains an external access to the initial storeroom. An excellent situation for hospital providers. Nevertheless, what is most important is the added vales that gives to the changing rooms. With the configuration proposed on Figure 18, personnel do not access the facilities wearing street clothing. The changing rooms gain the filter functions repeatedly explained on this report.

The second major change suggested is the isolation of the main corridor. Although this may enter in conflict with the floor facilities found beyond the IR area, this has been proposed as a possibility to enhance aseptic conditions. The idea behind this objective is to restrict the principal entrance of the area through a stretchers' transfer systems or by the simple control of reception staff. It must be mentioned that this would imply the fusion of two currently separated technical rooms into a shared one.

Considering the hypothetical case in which regulations and architectural capabilities where not an obstacle, a floating external corridor on the top left corner of the area has been also proposed. This passage would add an extraordinary pathway specially conceived for technicians and the evacuation of IR suites waste. Despite not being represented for the lack of building's structure awareness, an internal elevator would be the ideal method to access it.

Finally, some changes have been proposed for the IR suite placed on the top right corner. The principal change has been the reorientation of the DIVAS. If there were not technical downsides, to install the arched infrastructure on the opposite side of the room would facilitate control tasks. Apart, the redistribution of the accesses proposed would ensure a further insolation of the suite and an easier access to the stored material.

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Figure 18. Improvement proposal for the current area of hemodynamics and interventional cardiology, Hospital Clínic de Barcelona.

6. Execution schedule

6.1. Work-breakdown structure

In order to tackle the initial objectives and complete the mandatory tasks of this final degree project, the realized work was initially divided in partial packages boardable individually. These are presented in the Work-Breakdown Structure (WBS, Figure 19).

As it can be appreciated on the WBS, the project is comprised of 4 main structural work packages. For a further understanding of its essence, a brief description of these packages is given at the following WBS dictionary (Table 5).

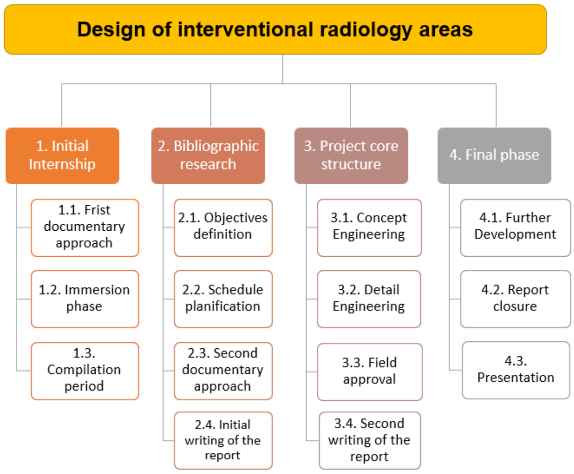

Figure 19. Work-breakdown structure.

Work package	Description
Initial Internship	Being the initial task, it comprises the first approach to the subject. Here IR and its key features must be investigated theoretically. Being done that, a practical in-situ immersion must be realized in a hospital. The author must personally experience the daily routine of IR facilities, understand its activity and determine its necessities. After the practical experience, a time must be considered to recap and process the collected data.
Bibliographic Research	Here is comprised the definition of the exact objectives that this project should tackle. With the previously acquired experience, the important points that must be covered become clear and it is possible to determine the time frame in which those must be accomplished. Research must be realized to cover the state of the art and analyze the marked. Simultaneously, it is planned to start the writing of this same report.
Project core structure	The concept and detail engineering are included here. A first conceptual design of an IR area mut be obtained. After the pertinent modifications raised from the final involved users of the facilities, a detailed design must be realized. Again, this one must be validated by those individuals involved in IR procedures. This last design must be accompanied by a summary of the main general statements for the design of IR areas and an example of its implementation. Simultaneously, this same report must be written.
Final Phase	Here the ultimate details of the project must be done. The ramming unwritten or uncompleted sections of this same report must be finished. The final conclusions must be obtained and the design of the document must be polished. Moreover, a time must be considered for any setback or possible further development. Finally, the preparation and presentation of the project is also included at this package.

Table 5. WBS dictionary.

6.2. Tasks development

To determine the time required to develop the current project, the time needed for each previously mentioned work package, called activities on Table 6, has been estimated. On the same table, the order in which the activities must be done is also specified. From it, a Program Evaluation Review Technique (PERT) chart has been created (Figure 20). The analysis of the earliest and latest times included on the chart give the critical path. This path contains those activities that cannot be delayed if the project is intended to be finished on time. In the concerned case, activities such as concept or detail engineering could be done simultaneously to the report writing. Nevertheless, these first two tasks must be finished on the specified time since they are part of the critical path.

Activities (With its associated letter)		Precedent Activities	Duration (Weeks)
1.1. Frist d. approach	A	-	2
1.2. Immersion phase	B	A	8
1.3. Compilation period	C	B	4
2.1. Objectives definition	D	C	2
2.2. Schedule planification	E	D	1
2.3. Second d. approach	F	E	2
2.4. Initial writing	G	E	2
3.1. Concept engineering	H	F	3
3.2. Detail engineering	I	H	4
3.3. Field approval	J	I	1
3.4. Second writing	K	G	2
4.1. Further Development	L	K, J	2
4.2. Report closure	M	L	1
4.3. Presentation	N	L	2

Table 6. Order and time needed to complete each WBS package/activity.

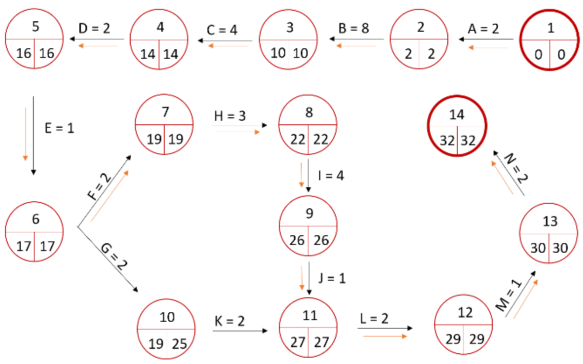

Figure 20. Program Evaluation Review Technique chart.

6.3. Final followed schedule

Although the duration of each activity is important, it is vital to stablish a calendar to execute the project. The timeline followed for the realization on this project is presented on Figure 21 through a GANTT diagram. Despite the fact that the project started in 2021 with the phase called Initial internship, in order to visualize the detail of the planification, this initial phase has not been included in the GANTT diagram. In that respect, the first documentary approach was realized during the two last weeks of September 2021, the immersion phase during the whole months of October and November 2021 and the compilation period during December 2021.

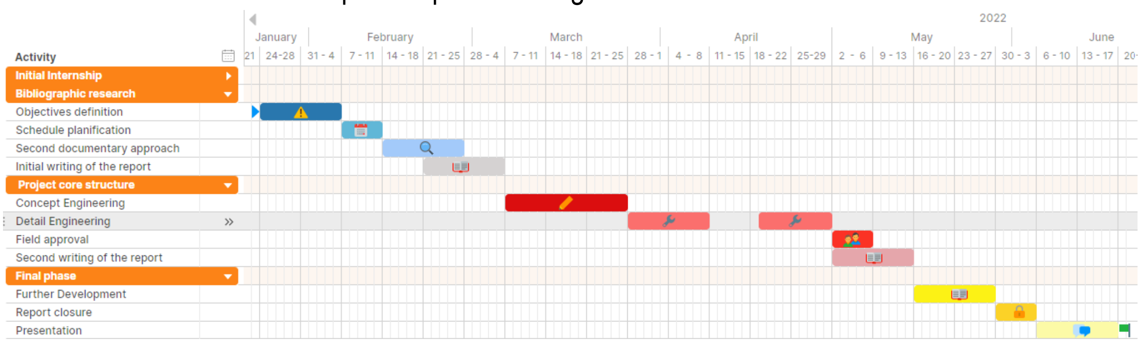

Figure 21. GANTT diagram containing the execution timeline of the project.

7. Technical and economic viability

7.1. Technical challenges involved in the design of IR areas

Design and conception of an IR area

From the feasibility point of view, the current project has needed not much more than a computer aided design software, a biomedical engineer and the collaboration of the involved organizations such as Hospital Clinic. Nevertheless, the design and conception of IR areas in current hospitals is realized together with external firms such as engineering or architectural studios. These have additional resources out from the scope of a hospital or the author of this project. Besides, they work with a larger number of professionals including technical or industrial engineers and architects. This multidisciplinary teams are needed to face matters such as buildings' structural requirements or the design of the electrical infrastructures. In that, respect, a design project for an IR area needs additional technical documents apart from a floor paper plan as the one presented in this occasion.

In the framework of a Catalan public hospital, the design and conception of IR areas starts with a competitive public tendering ("licitación pública" in Spanish). This initial tendering is published by the hospital, the public entity effected in this case, to find an architectural and an engineering studio. Among the documents that the hospital presents to support the tendering, there is the report known as functional plan. Inside this plan, a first design, comparable to the one presented in Figure 14, and the requirements of the new IR area are included. From it, the interested firms obtain the details that must include the new IR area and apply to the tendering if they consider it appealing. Then, the hospital selected firms will have to submit a project including the detailed technical plans for the construction of the area and the estimated budget. This project will be the one developed.

Implementation of the proposed design

For what concerns implementation, even it is not the main subject of this work, it is important, at least, to mention how it is performed. It begins once the architectural and engineering project is defined. At that moment, the hospital launches a second competitive public tendering. The construction and installation companies selected are the ones in charge of the building and the electrician and mechanical installations (gases, water, HVAC…). Once these finish, the only remaining task is the equipment. In that respect, the electromedical equips and the needed furniture are acquired through a third tendering.

7.2. SWOT analysis

Coming back to the project presented in this report, a SWOT analysis (Figure 22) has been realized to study its viability. The explanation of the points listed on it is given in the following paragraphs.

<u>Internal Analysis</u>

Starting with the strengths of the project, the first characteristic that must be highlighted is the presentation of a complete design. The hole work addresses not only IR suites, but it is equally focused on the surrounding spaces and their necessities, usually unconsidered. Referring to its applicability, a concrete and detailed design of a unique area has been provided. Nevertheless, it has been created to enable the extrapolation of the concepts included and it is complemented by a series of statements which are thought for different scenarios.

Following with the strength, in the pursue of a multidisciplinary design, the project has considered the opinion, advice or preferences of all those individuals involved in IR procedures. Furthermore, all the received inputs have been contrasted with personal experience and on-site verification. Finally, the whole work has been focused on the latest possibilities of the field and it has been realized considering that future changes must be admittable.

Concerning the weaknesses, even though the design is presented as an ideal solution created from contrasted information, its performance cannot be properly evaluated if it is not implemented. The construction of an IR area is far from the possibilities of a final degree project. The resources needed are enormous, especially considering that the ideal concepts presented have leaved the economic feasibility on a second plane. Moreover, the project has not completely addressed two crucial aspects that must fully include a guide for the design of IR areas. These are the equipment and technical requirements. Although some aspects have been discussed, these two matters require an extended study unrealizable within the presented work due to its dimensions.

External Analysis

Moving to the opportunities, this project has been realized in a time where the number of IR procedures performed is increasing progressively. The advantages on MIP linked with the development of new interventionist tools and implantable devices results in a larger number of programed procedures that demand space. In that respect, and particularly in Catalonia, many IR projects for the implementation of new IR suites are being performed. In all these projects, the presented work could be of valuable consideration. Indeed, it is substantially engrossing due to the lack of public accessible guiding references containing a complete and detailed design of IR areas. Referring to the last opportunity included in the SWOT analysis (Figure 22), private firms or hospital collaborators, could use the information provided in this report to get a deeper understanding of hospitals' internal functioning, especially of IR facilities. This would ease the design of new facilities or even the development of new IR related products.

Tackling the threats, it must be considered that medical technology is evolving unceasingly. For instance, DIVAS systems suffer continuous upgrades and new robotic systems could change completely the IR paradigm in the following years. This situation could generate a scenario with thoroughly new necessities not boarded on this project. Besides, the future of radiology is found on non-ionizing imaging devices. Even if this is a distant reality, the present work is conceived for fluoroscopy devices emitting X-ray radiation. Leaving context apart, guides with a recommendatory nature comparable to this project or design proposals are usually developed by more than a unique professional. Teams, that usually have the additional resources of a private firm, could deepen much more on the detail of certain technical subjects and be considered a better reference in certain aspects. Nonetheless, it must be mentioned, that the field experience included in this document would steel be a valuable characteristic difficult to find in comparable projects. Finally, it could be said that, as many university studies, this actual work risks to remain in the academic sphere and do achieve its transition to other private or public institutions.

Internal Analysis	
Strengths	**Weaknesses**
- Complete design - Applicable in multiple scenarios - Multidisciplinary opinion included - On-site current situation assessed - Latest and futurist perspective	- Lack of performance evaluation - Number of resources needed for the implementation - Lack of a detailed equipment plan - Need of additional technical requirements
External Analysis	
Opportunities	**Threats**
- Growth of IR - Ongoing new IR facilities projects - Lack of available public references - Unawareness of hospital/IR requirements and its internal procedures.	- Changing technological aspects - Future abandon of radiative technology - Comparable work from technical consultancy or design firms. - Poor repercussion of the project.

Figure 22. SWOT analysis.

7.3. Economic viability

To tackle the economic concerns, as it has been realized with the technical challenges, the economic viability related to the conception and the implementation of IR area designs have been discussed separately.

Design and conception of an IR area

Focussing on this particular project, those resources associated with an economic expense have been summarized on Table 7. As it can be appreciated, the resources are few. If additionally, it is considered that the AutoCAD licence has been provided by Universitat de Barcelona and that the personal computer can have a further use out of this project. The final cost of the project is reduced. It is also important to highlight that the nature of the project is exclusively informative and advisory. The idea behind this work is to share the included concepts and not to obtain a profit from it.

Resources Requiring Economic Investment	Unit Price	Amount
Human Resources		
Biomedical engineer	15 €/h	500 h
Project's supervisor	20 €/h	50 h
Technical Resources		
Personal computer	800 €	1 unit
AutoCAD (including Architecture Package) *	291 €/month	3 months
Total expenditure:	**10.170 €**	

Table 7. Used resources associated with an economic expense.

It must be mentioned at this point that the presented project has had the voluntary participation of organizations such as Hospital Clínic or Vall d'Hebron. This altruistic activity has enabled the development of the project and the incorporation of field professionals' opinion. Although it might be seen as a rudimentary activity, this same collaboration has an economic value, for instance, if it is realized with a private company.

Taking again the Catalan public context and a third level hospital as reference, the final design presented here (Figure 14) could be compared to the initial layout included inside a functional plan. In that respect, the cost associated would directly be the salary of the technical team working on it. A team that would be composed by industrial engineers and architects, among others, and that would be part of hospital's permanent employees.

Implementation of the proposed design

If the proposed design (Figure 14) was supposed to be implemented, to determine what would be its cost several factors would have to be considered. Due to the multiple variables that determine the final price of a project with such dimensions, an approximated price has been estimated taking as reference the experience of Hospital Clinic's organization. Following their advice, the surface of the designed area has been divided in three different modules. Then, each module has been given an estimated price for unit of area. On the one hand, those zones having the highest technical challenges and requiring extra architectural efforts have been considered to cost 4.000 €/m^2. On the other hand, those zones with the lowest structural and technical requirements have been valued with 2.500 €/m^2. The price of those spaces found in between has been fixed to 3.500 €/m^2. Assuming these conditions, the price associated to the implementation of the proposed design is 7,617,500 €. For further explanations, the classification of each space is represented on Table 8.

Material Execution Budged				
Level of requirements	**Spaces included**	**Price/unit area (€/m^2)**	**Total area (m^2)**	**Final price (€)**
High	IR sites, CT, control rooms and technical suites.	4,000	827.50	3,310,000
Medium	Perioperative zone, patients' private spaces, genera technical room, nursing and TC's preparation space.	3,500	266.25	931,875
Low	Corridors, personnel's offices and remaining spaces.	2,500	1,350.25	3,375,625
			2,444.00 m^2	**7,617,500 €**

Table 8. Estimation of the implementation costs associated with the proposal presented in this project.

Although it might be seen as a stratospheric amount, this last economical reference is not the definitive price. Indeed, this would correspond to what is known as the Material Execution Budged (Presupuesto de Ejecución Material or PEM, in Spanish). This budget includes the cost of materials and the workforce. Moreover, it must be included inside the project submitted by the firms selected at the initial public tendering. Going into deeper detail, it could be mentioned that it is estimated from huge databases which contain the reference prices for the vast majority of existent materials, metaBase form ITeC is an example of these databases. Nevertheless, it must be considered that additional expenses exist. For instance, PEM does not include statal taxes or the costs derived from the construction firm. In addition, a supplementary budget would be necessary to by all those medical equips vital in an IR area (DIVAS, anaesthesia workstations, ultrasound machines, infusion pumps…).

8. Regulation and legal aspects

8.1. Buildings construction and security

A first constriction than must be considered when designing a certain building or facility is that there are national regulations that establish a criterion to ensure basic safety and habitability requirements. In Spain, the document that englobes the main regulations in that concern is the Building Technical Code ("Código Técnico de la Edificación, CTE") [39]. It is divided in six basic sections that cover: structural safety, fire protection, usage and building accessibility, healthiness, noise management and energy saving affairs. This document must be applied in nearly all the phases of a project including its conception, construction or maintenance. Although the compulsory nature of the different sections mentioned before depends on the type of project, public buildings must meet the specifications of CTE even for simple or minor projects.

Apart from secondary national regulations that affect building (EHE-08 or NCSE), in Catalonia there are also regional constraints that must be taken into account. For instance, it is the case of the law about prevention and security against fire ("Llei de prevenció i seguretat en matèria d'incendis en establiments, activitats, infraestructures i edificis") [40]. Even though this subject is already boarded in CTE, this regional law settles concrete norms and, for instance, indicates the basis of the inspection protocols and sanctions.

8.2. Catalan public healthcare background

Following with the regional regulation and considering an IR area inside the Catalan public framework, it must fulfil the standards to enable hospital accreditation. Inside the Catalan health system, public hospitals, as well as primary care or mental health centres, must be accredited by the Department of Health of the Generalitat de Catalunya.

The accreditation is based on an evaluation process carried out by a multidisciplinary group of technical professionals. This external group of experts assesses the organization taking as reference a series of benchmarks previously established. Accreditation is voluntary for private centres, although it is a necessary condition to became a provider of the Catalan Health Service (CatSalut). In that respect, it is a compulsory condition for public hospitals, the hospitals that form the Integrated Health System of Public Use of Catalonia ("Sistema Sanitari Integral d'utilització pública de Catalunya", SISCAT) [41].

The basis of the current accreditation standards was defined on the governmental order from the 10th of July 1991. This order includes structural, functional and organization criteria. However, the actual standards that must be applied nowadays [42] have been actualized recently. Indeed, they are approved by the governmental resolution "Resolució SLT/474/2020".

8.3. Spanish legislation applicable to radiodiagnostic facilities

Nuclear and ionizing radiology emitting facilities in Catalonia are regulated by a series of Spanish laws and statements. In that respect, in order to address the regulatory issues, it is crucial to understand the legislative hierarchy of the territory. In Spain, laws approved by the parliament are the statements with a major rank. Under the influence of Spanish laws and following a descending hierarchy order, royal decrees dictated by the government and ministerial orders are found. These develop specific aspects of the mentioned laws. Then, having a recommendatory nature, there are safety guides, technical and security standards, and some specific recommendations from technical organizations with competence in the field of interest.

Presented the Spanish legal hierarchy, regulation of medical radiodiagnosis facilities and specially IR areas, can be addressed. In this domain, two basic laws must be considered due to the use of ionizing radiation [43]:
− "Ley 25/1964 de Energía Nuclear" [44]
− "Ley 15/1980 de Creación del CSN" [45]

The first one regulates the use of nuclear energy and ionizing radiations. It stablishes security and protection principles in front of the hazards associated with those energies. The law has been partially modified on several occasions. In that respect, the last modification published dates from 05/2011, actualized at 05/2021.

The second law stablishes the legal basis for the creation of the Nuclear Security Council ("Consejo de Seguridad Nuclear", CSN), an organization independent from the general administration of the state that is finally controlled by the Congress of Deputies and the Senate. The mission of CSN is to protect workers, general population and environment from damaging radiation to ensure the secure functioning of radiative facilities and to stablish preventive and corrective measures to face radiologic emergencies [46]. Some of CSN competences that have a direct impact in IR areas are:

- The inspection and control of nuclear, radioactive and X-ray facilities
- The authorization of radiological protection (RP) services or technical units, individual dosimetry services and service companies in the field of RP.
- Monitorization of radiation levels both inside and outside the facilities.
- Management of the licenses needed for the personnel of radioactive facilities and the accreditations to operate and direct radiodiagnosis facilities.

Complementing these two main laws, the law "Ley 14/1999 de tasas del CSN" and the law "Ley 54/1997 del Sector Eléctrico" must also be considered since they modify in a certain way the two firstly mentioned laws.

Going into deeper detail, there are several Royal Decrees that develop concrete aspects concerning the facilities in which ionizing radiation is emitted. Among these 1836/1999, 783/2001 and 1085/2009 can be highlighted. For this concrete project, the Royal Decree 1085/2009 is specifically important since it approves the regulation that must be applied for the installation and use of X-ray equipment for medical diagnosis purposes.

Among the existing technical standards, the safety guides published by CSN and the Spanish Association for Standardization and Certification (Asociación Española de Normalización y Certificación, AENOR) stand out [47]. In that respect, guides GS-5 and GS-7 contain aspects that can be directly applied to the radiodiagnosis facilities of healthcare centres. Indeed, concerning the use of X-rays for medical purposes, the guides GS-5.9 and GS-5.11 must be considered. Related to the scope of the present project, GS-5.11 [48] indicates the technical aspects of safety and radiological protection of diagnostic X-ray medical facilities.

8.3.1 European influence in ionizing radiation matters

Also affecting IR areas, the European Directive 2013/59/Euratom came into force in 2018. The directive establishes basic safety standards for protection against ionising radiation. On the one hand, it emphasises the need for justification of medical exposure and introduces requirements concerning patient information. On the other hand, reinforces certain aspects such as the record and report of doses from radiological procedures, the usage of diagnostic reference levels, the availability of dose-indicating devices and the improved role and support of the medical physics experts in imaging [49].

8.4. Technical regulations of operation theatres

Finally, due to the nature of the procedures performed inside, IR suites are considered Operation Rooms (ORs). In consequence, for safety reasons, there are a series of technical standards that they must fulfil. An example, concerning climatization, are the norms UNE 100713 and UNE 171340. These classify IR suites as type B operation theatres, what according to ISO, is equivalent to class 7 rooms [27]. This classification inside the group of high-risk areas implies, among many requirements, that they must have, at least, three progressively exigent levels of air filtering.

However, climatization is not the only regulated aspect in IR suites. Aside, IR suites must fulfil additional standards concerning electrical infrastructures and illumination or mechanical installations, including gases or water supply systems. In that respect, the main requirements that IR suites must fulfil have been already explained in Section 5.2, Technical requirements of IR infrastructure.

Also related to ORs nature of IR suites, the guides “Bloque quirúrgico, estándares y recomendaciones” [50] and “Unidad de Cirugía Mayor Ambulatoria, estándares y recomendaciones” [51] are particularly interesting. Since there is neither a general national Spanish nor Catalan guide regulating the design of IR areas, these two last mentioned documents, that do not have a compulsory character, contain useful recommendations about ORs’ facilities that can be applied to IR areas. Moreover, coming back to the last subject, they resume and indicate all the compulsory technical standards that ORs must fulfil for safety reasons.

9. Conclusion and future trends

The number of procedures that admit IR and its importance has significantly grown the last decades. The volume of cases that are boarded each year increases progressively and this is occurring thanks to the benefits found in MIP. In parallel, the development of new vascular devices such as catheters or guidewires and the evolution of medical imaging has boosted this growth. Besides, new technological solutions, such as robotic arms systems, are appearing to improve the current interventions. This whole panorama, involving new technology and a raising number of IR procedures, leads to the need of new IR facilities designed to face the current and future challenges that the discipline could encounter. Surrounded by this context, this project has tried to gather the necessities of IR services and propose a design able to cover all of them.

In the pursue of this design, the first relevant characteristic, that the author of this project has found to be vital, is the inclusion of large spaces. On the one hand, IR areas ideated for DIVAS must include large angiography suites compatible with the dynamic machinery of its interior. In that respect, it must be ensured that the size and mechanical movements of DVAS do not affect the clinical activity. On the other hand, due to its technical requirements, IR suites must be conceived with adjacent technical and control rooms. This situation, requiring both clinical and technical large surfaces, confronts the space limitations of many hospitals. For this reason, although ideal designs can propose extended IR areas, alternatives to optimize the surface requirements, such as unified perioperative spaces or shared control rooms, are crucial.

A second aspect that has been noticed to be essential when designing IR areas is the separation of conflictive activities. There are several complementary activities that must be done periodically for the proper functioning of the area. However, these can interfere in the normal clinical activity. Examples of these activities are the cleaning or the technical maintenance procedures. In front of these scenarios, hospital infrastructure must facilitate these procedures while separating them from the clinical ones, which are ideally performed in cleaner environments. Following this line, the infrastructure must also separate patient's pathways. A separation of internal hospital activities from patients' corridors is necessary, but a separation between different patients is also required. For instance, the encounter of outpatients with emergency patients must be avoided.

A third point found to be specifically required by IR areas is its connection with additional medical imaging services. Apart from an indispensable communication with general hospital facilities such as emergency areas or sterilization centres, MRI or CT technologies must be easily accessible. Going one step further, these complementary medical technologies can also be incorporated inside IR areas. This situation avoids displacements and provides the fast response that require certain clinical cases. In that respect, the proposed design has shown the possibility to incorporate complex imaging technologies ensuring its use on additional procedures to guarantee its amortization.

Another matter found to be significant enough is the need of interdisciplinary human equips. During the conception of this project, the author has always considered that the patients must be placed on a central place of the design. In that respect, any proposal must be done looking for its benefit. Nevertheless, there are many different professionals that daily work on IR areas and their priorities must also be regarded. Apart, the high technical requirements of such infrastructures demand qualified profiles for its design. This fact makes the design of IR areas unconceivable without the collaboration of interdisciplinary groups composed with individuals pertaining to different areas of expertise.

Concerning the future of IR areas, it could be said that it encompasses the improvement of patient experience. Biophilic and home like design are two reviewed proposals that go in this direction. These initiatives capture the essence of a general trend that seems to be pursuing the healthcare community, the humanization of hospital facilities. Nevertheless, these initiatives with an aesthetic nature must be accompanied by physical changes in the internal organization and infrastructure of hospitals. The patient's private spaces proposed in this project chases this objective. It promotes a closer accompaniment of patients while easing legal formalities and prioritizing privacy.

Aside from patient experience, future IR areas must facilitate professionals' activities. This includes the implementation of centralized services, such as the presented cleaning zone, that enable to increase the efficiency of current procedures reducing the required resources. Besides, the benefit of professional personnel also implies the reinvention of traditional spaces. Changes applicable to resting areas, medical offices or conventional storerooms have been proposed on this project. Nonetheless, there is still place for novel revolutionary concepts. Apart, regardless of any feasible change, the only way to facilitate professionals' activities is to include their needs in the implemented designs.

In any case, what must be ensured by the coming IR designs is the incorporation of wide flexible spaces. Spaces able to embrace future changes without implying dramatic structural changes. Continuously, new interventional procedures are proposed. These, together with the implementation of novel technology, require updated infrastructures. For this reason, the modern areas must be designed as adaptable and transversal spaces that could be used for more than the unique purpose.

To end up with, it could be said that the initial concept of isolated IR suites inside punctual hospital departments must be abandoned. New IR suites must be centralized in specialized areas clustering professional personnel and services. From the author's point of view, this is the only way to make hospital resources further accessible, to speed up healthcare procedures without increasing its associated risks, and finally, to enhance patients' experiences.

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10.1. List of figures

10.2. List of tables

Annexes

Annex 1: Equipment of an IR suite

The following annex has been attached to provide an example of the main equipment found inside an IR suite. On the one hand, Figure A1.1 is a schematic representation of the electromedical equips that could be found inside an interventional neuroradiology suite. On the other hand, Figure A1.2 has been included to exemplify the technical infrastructure that this last suite requires. Although both figures represent a particular neuroradiology case, its main characteristics can be extrapolated to other specialities.

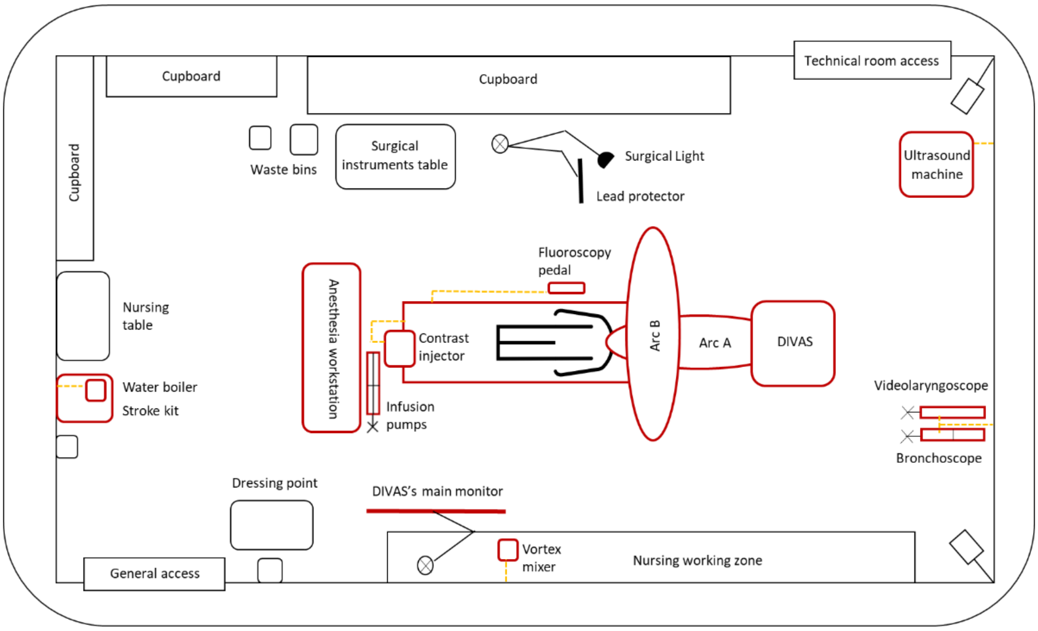


Figure A1.1. Representative layout of an interventional neuroradiology suite equipped with a biplane DIVAS. Electromedical equips are represented in red. Yellow dashed line represents their electrical connections. (Own Source)

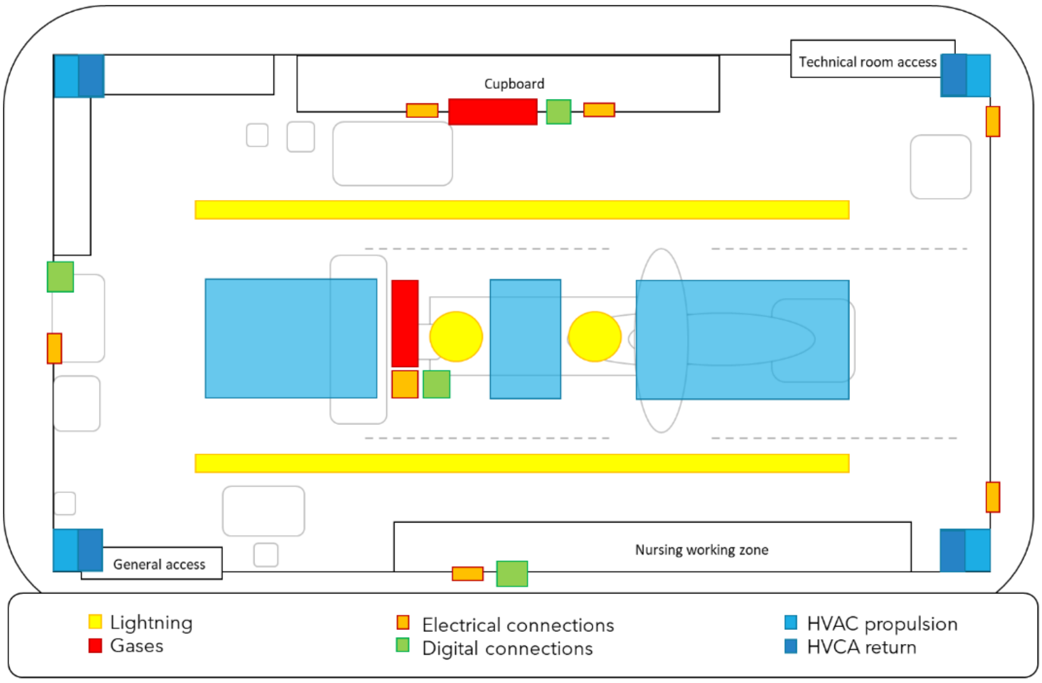
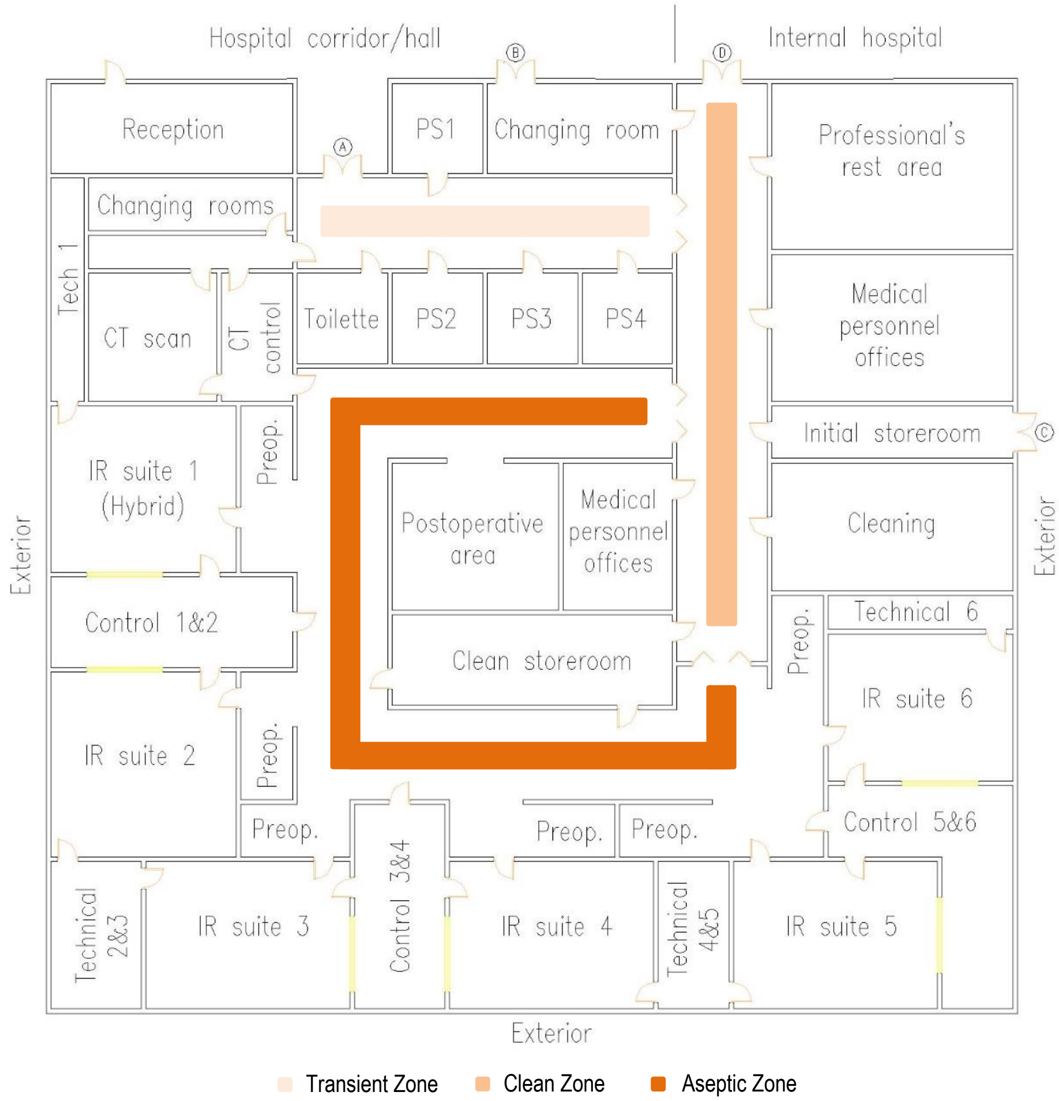


Figure A1.2. Example of the technical infrastructure required by an interventional neuroradiology suite. (Own Source)

Annex 2: Alternative conceptual proposal

This annex includes an alternative conceptual proposal for the design of IR areas (Figure A2.1). Compared to the final proposal presented in this project (Section 4, Figure 13), the proposal attached on this annex already includes a CT scan. This configuration, compared to the final design (Section 5, Figure 14), it offers a further separation between those patients accessing the facilities for simple CT acquisitions and those accessing the facilities for interventional processes. It also stands out for the combination of a circular layout with individual preoperative spaces. Nonetheless, this configuration has many drawbacks. A first one could be the separation of the CT scan from the internal access. A situation that reduces CT accessibility for emergency or hospitalized patients. As this last one, other downsides are the separation of the initial and the clean storerooms, the distance between the cleaning space and some IR suites or the lack of exterior connection that have patients' private spaces.



A: Outpatient's Access, B: Personnel access, C: Provider's/Non-clinical access, D: Internal access

Figure A2.1. Conceptual proposal for the design of an IR area. Scale: 1/400. Abbreviations: Private Space (PS), Computed Tomography (CT), Technical room (Tech/Technical), Preoperative space (Preop.). (Own Source)

Annex 3: Alternative detailed proposal of a multimodal HOR

This annex includes the design of a multimodal Hybrid Operation Room (HOR) (Figure A3.1). Compared to the main proposal of the project (Section 5, Figure 14) the unidirectional circuit that stablish the layout of the changing rooms can be mentioned. Moreover, the individual perioperative space could be highlighted. For its structure, this design could be implemented in an area as the one conceptualized on the previous annex (Annex 2).

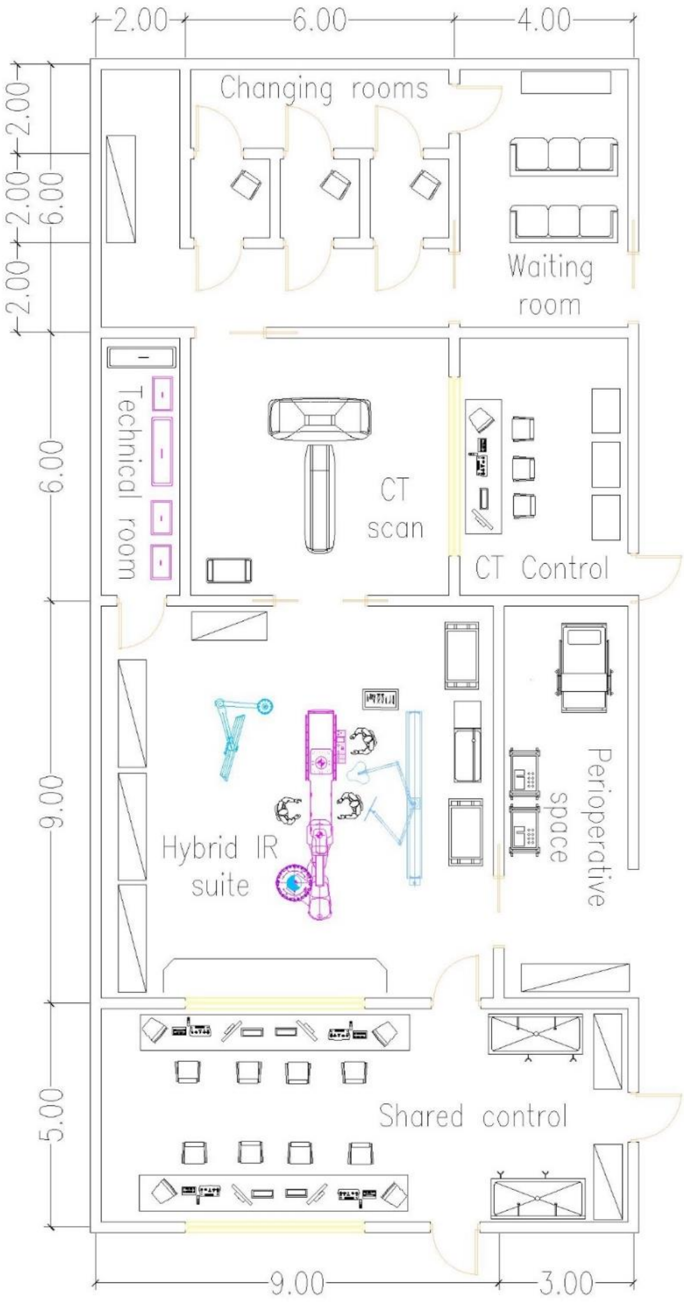


Figure A3.1. Design for a multimodal HOR facility. Units: Meters. Abbreviations: Computed Tomography (CT). Additional notes: Lead protective widows are marked in yellow. Floor standing DIVAS components appear in purple, whereas those ceiled mounted appear in blue. (Own Source)

Annex 4: Detailed design proposal for an ideal IR area

The following annex includes the final detailed proposal for the design of the ideal IR area presented in this project. For a better appreciation, it has been attached in a larger scale (1/300).

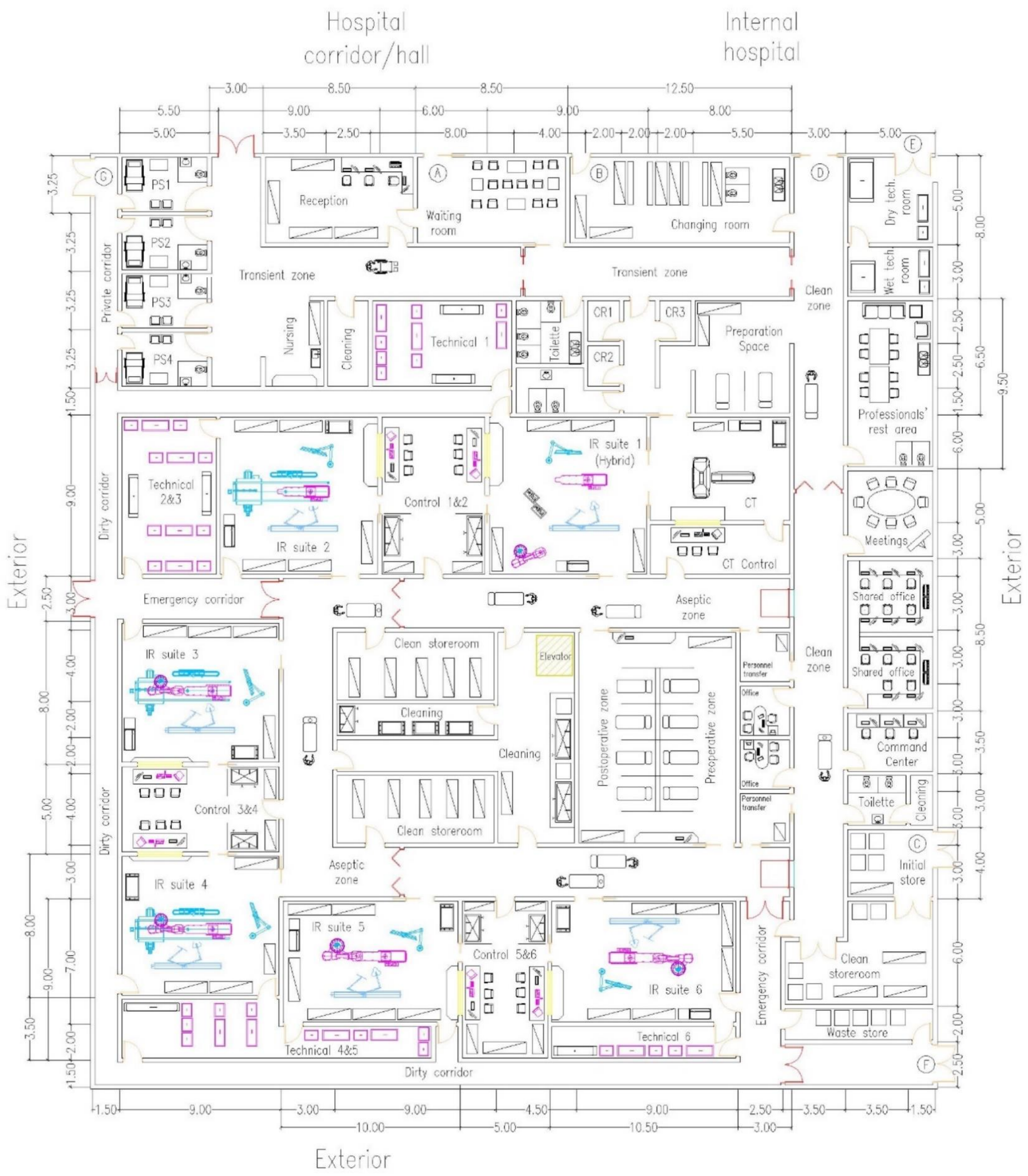


Figure A4.1. Detailed design proposal for an ideal IR area. Scale: 1/300. Units: Meters. Abbreviations: Private Space (PS), Changing Room (CR), Computed Tomography (CT). Accesses' users: Outpatients (A & G), Area personnel (B), Providers (C), Hospital personnel (D), Non-clinical personnel (E & F). Additional notes: Conventional doors are represented in orange, evacuation fireproof doors in red. Lead protective widows are marked in yellow. Floor standing DIVAS components appear in purple, whereas those ceiled mounted appear in blue. (Own Source)

Annex 5: Workflows of the detailed proposed design

The following annex includes the circuits and workflows that result from the implementation of the proposed design (Section 5, Figure 14). As it can be appreciated (Figure A5.1), there is a clear separation between clinical and non-clinical procedures. The waste evacuation circuit (green) and technical circulation (yellow) avoid area's centre where patients and professionals circulate. Furthermore, the access of clinicians to patients' private spaces could be mentioned. This situation has been pursued to promote the perioperative interaction between patients and medical professionals. A scenario, that according to authors criteria, could increase patient's satisfaction and reduce their stress. Another aspect to point out is the minimum interaction that show CT outpatient with the area. Those patients, that only need a CT acquisition, do not have to cross the hole area. This makes processes more agile and contributes on the maintenance of aseptic conditions.

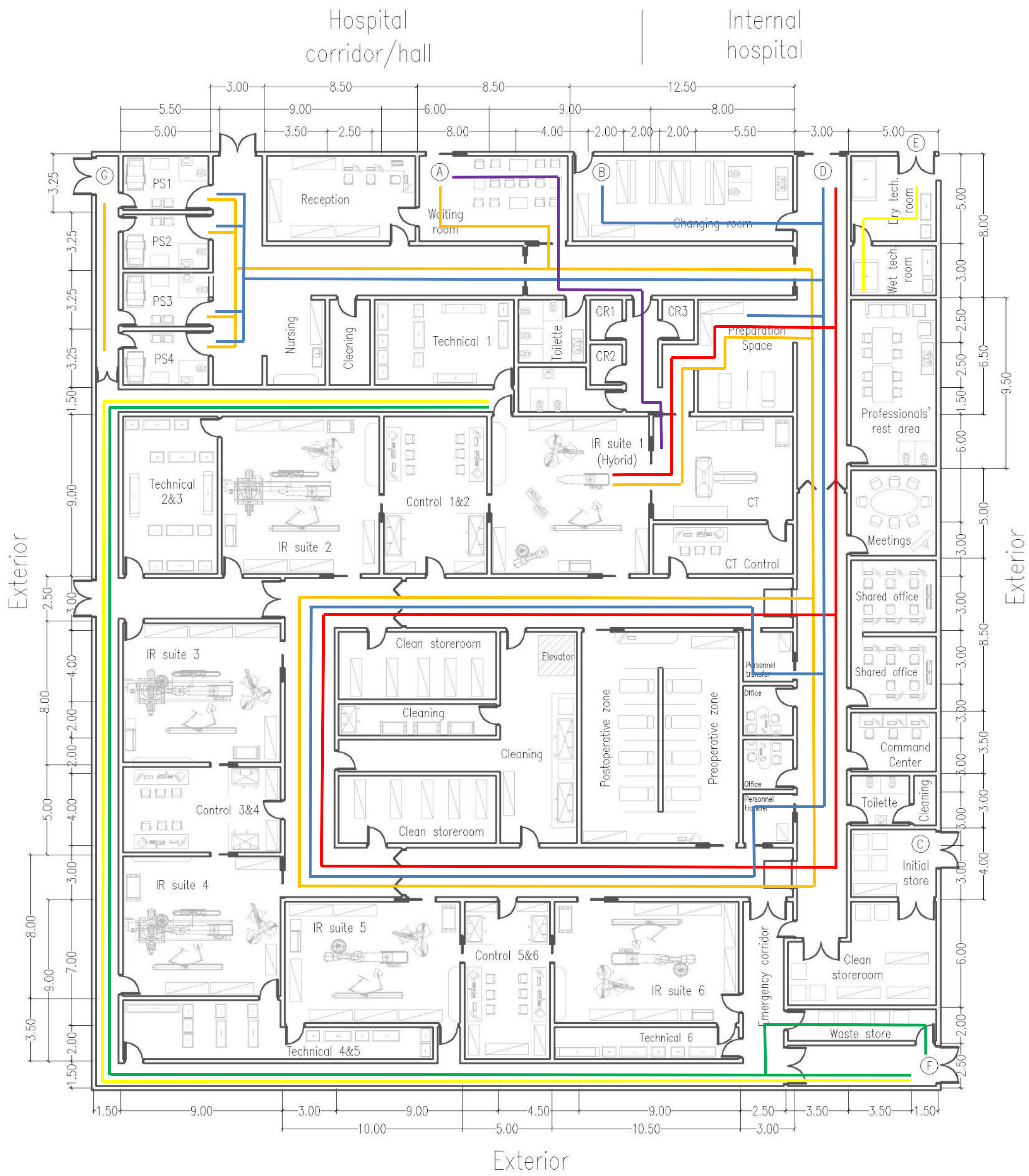


Figure A5.1. Circuits and workflows resulting from the detailed design proposed for an ideal IR area. Scale: 1/300. Units: Meters. Abbreviations: Private Space (PS), Changing Room (CR), Computed Tomography (CT). Accesses' users: Outpatients (A & G), Area personnel (B), Providers (C), Hospital personnel (D), Non-clinical personnel (E & F). Colour Code: Clinicians circulation (Blue), Emergency and hospitalized patients' routes (Red), IR outpatients' pathway (Orange), CT outpatients' circuit (Purple), Waste evacuation (Green), Technicians' circuit (Yellow), Cleaning staff circulation (Green & Blue). (Own Source)

Annex 6: Plan of the current hemodynamics and interventional cardiology area of Hospital Clínic de Barcelona

This annex contains the layout of the current hemodynamics and interventional cardiology area of Hospital Clínic de Barcelona. Notice that it differs from the layout proposed in Figure 18 (Section 5).

Aside, it must be mentioned that the technical room placed on the bottom left corner of the area (Figure A6.1) has not been included on Figure 18 (Section 5). This has been done to emphasize the changes proposed. Nevertheless, the suite is still necessary for the layout proposed (Figure 18, Section 5) and it must be considered part of the final proposal.

Figure A6.1. Current hemodynamics and interventional cardiology area of Hospital Clínic de Barcelona. Scale: 1/100. Provided by Hospital Clínic de Barcelona.

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