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Medical physics graduate education in Mexico and its relation to the advances in radiation oncology☆

María-Ester Brandan[a,*], Alejandro Rodríguez-Laguna[b]

[a] Instituto de Física, Universidad Nacional Autónoma de México, Ciudad Universitaria UNAM, Coyoacán, 04511, Cd Mx, Mexico
[b] Departamento de Radioterapia, Hospital Médica Sur, Toriello Guerra, Tlalpan, 14050, Cd Mx, Mexico

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ABSTRACT

Aim: To evaluate the state of graduate education in medical physics and progress in radiation oncology (RO) equipment in Mexico since 2000, when conferring degrees from two master's-degree programs in Medical Physics began.
Background: Medical physics is a Health Profession and there are international recommendations for education, training, and certification. Both programs follow these education guidelines. The most common clinical occupation of graduates is in RO services. Techniques in Mexican RO include traditional and high-precision procedures.
Methods: Academic and occupational information about the programs and their graduates were obtained from official websites. Graduates were invited to respond to a survey that requested information about their present job. We obtained data on RO equipment and human resources from public databases and estimated staffing requirements of medical physicists (MPs).
Results: Medical physics programs have graduated a total of 225 MPs. Half of them work in a clinical environment and, of these, about 90 work in RO services. MPs with M.Sc. degrees constitute 36% of the current MP workforce in RO, estimated to be 250 individuals. Survey responses pointed out the main merits and limitations of the programs. The number of MPs in RO has increased fivefold and the number of linacs sixfold in 15 years. The present number of MPs is insufficient, according to published guidelines.
Conclusion: All MPs in RO services with advanced modalities must be trained following international recommendations for graduate education and post-graduation clinical training. Education and health institutions must find incentives to create more graduate programs and clinical residencies.
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1. Introduction

Medical physics is the sub-field of physics that applies the principles, techniques, and tools of physics to the prevention, diagnosis, and treatment of human diseases.[1,2] Also, medical physics is a professional specialization. Clinical medical physicists (MPs), who work in health services as part of the multidisciplinary team, perform many important tasks. MPs are responsible for the quality assurance, safety testing and correct maintenance and operation of treatment machines, ionizing and non-ionizing imaging equipment, procedures that make use of radiopharmaceuticals for diagnosis or treatment, radiation treatment planning systems, and the correct delivery of prescribed radiation doses to patients in radiation therapy. Also, they formulate radiation protection guidelines and procedures specific to the hospital environment and other professional groups and organizations, and they conduct specialized measurements and produce protocols to minimize radiation exposure of patients, staff, and general public.[2]

According to the ISCO-08 classification of occupations by the International Labor Organization (ILO), MPs – together with all other physicists – are professionals who belong to *Unit Group 2111: Physicists and Astronomers*, but MPs are also considered to be an integral part of the health workforce together with *Group 22: Health Professionals*.[3] Medical physics is, thus, a Health Profession and this requires that MPs who will practice their profession in a clinical environment receive a specific academic education and practical training. International health organizations and regional professional groups, such as the International Atomic Energy Agency

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* Corresponding author. Permanent address: Instituto de Física UNAM, Circuito de la Investigación Científica s/n, Col Ciudad Universitaria UNAM, Coyoacán, 04511, Ciudad de México, Mexico.
E-mail addresses: brandan@fisica.unam.mx (M.-E. Brandan), alejandro.rodriguez.laguna@gmail.com (A. Rodríguez-Laguna).

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(IAEA), the World Health Organization (WHO), the European Federation of Organizations of Medical Physics (EFOMP) and the American Association of Physicists in Medicine (AAPM) have analyzed and produced recommendations concerning the formation (education and training) of clinical MPs.[4]

In Mexico, MPs have been part of RO services since the 1950s. The first cobalt-60 irradiator was installed in 1956 at the National Cancer Institute (INCan) and the first MPs were associated with the radiation oncologists who used the first cobalt-60 units in the country and the Latin American and Caribbean region.[5] These physicists and others who followed during the next 50 years generally had a bachelor's degree in physics or engineering and the knowledge of the specialty came from training courses sponsored by the IAEA, the Pan American Health Organization (PAHO) and others, and directly from the radiation oncologist with whom they worked. Most of them obtained their education and clinical qualifications at the hospital.

According to estimates, in the 1990s there were about 20 clinical MPs working in Mexican health services, most of them in RO services. Those who had a master's degree in medical physics had obtained it in a foreign university. Before the turn of the century, two graduate programs in medical physics were created in the central region of the country, one at Universidad Autónoma del Estado de México (UAEMex, a state university) in the city of Toluca,[6] the other at Universidad Nacional Autónoma de México (UNAM, the national university) in Mexico City.[7] They have been active and consistently graduating MPs for almost 20 years; no other graduate programs in medical physics have been created. Most of the medical physics graduates from UAEMex and UNAM have clinical positions as MPs in Mexico and the region, and most of these work in an RO service.

The practice of RO in Mexico initiated in 1920 using orthovoltage equipment and has advanced progressively to procedures using Co-60 units, linacs, brachytherapy, and conformal techniques.[5,8] The IAEA Directory of Radiotherapy Centers (DIRAC)[9] indicates that 63% of the present radiotherapy pieces of equipment are 15 years old, or less. According to Gallegos et al.,[8] in 2018, 21 of the radiation machines were high-precision systems, including Novalis™, TrueBeam™, Tomotherapy™, Cyberknife™, and Gamma Knife™ units. These trends illustrate the important recent advancement in RO equipment.

This paper analyzes the state of graduate education in medical physics in Mexico and the presence of the medical physics graduates in RO services since the year 2000 when the conferring of degrees from the master's programs began. This information is discussed within the context of the advancement of RO equipment and techniques in the country.

2. Methods

Information for the analysis was obtained from online sources and earlier publications.[10,11] Academic and professional information on the graduates came from the programs' web pages.[6,7] These databases include general information about the number of individuals who have obtained the M.Sc. degree and personal information of each graduate, including the e-mail address and present job. The area of sub-specialization (RO, nuclear medicine, or diagnostic imaging) was deduced from the service they worked in. The assumed MP workforce in RO corresponded to those working in RO services. Current statistical information on equipment and other resources in Mexican RO centers was mostly obtained from the DIRAC database[9] and the National Center for Technological Excellence in Health (CENETEC) website.[12] A 2004 publication[11] on RO equipment in the country was consulted. One of the authors (MEB) estimated the number of MPs working in RO centers in 1997, 2007, and 2019, based on internal (unpublished) university reports and a publication.[10] An estimate of the required staffing for the country's equipment, techniques, and patient load, was done using the evaluation tool designed by the American Society for Radiation Oncology (ASTRO).[13]

An online survey was sent to the 225 graduates from the medical physics programs about their current positions in RO services and their perception of the coincidence between the formal education received during their education and the professional needs they faced working in the clinical environment. An invitation to respond to the survey was sent to the 225 individuals requesting that only those who were, or had been, holding a medical physicist position in RO services should respond. Mean values and standard deviations were calculated from the survey responses, and free-format responses to specific questions were classified by similarity.

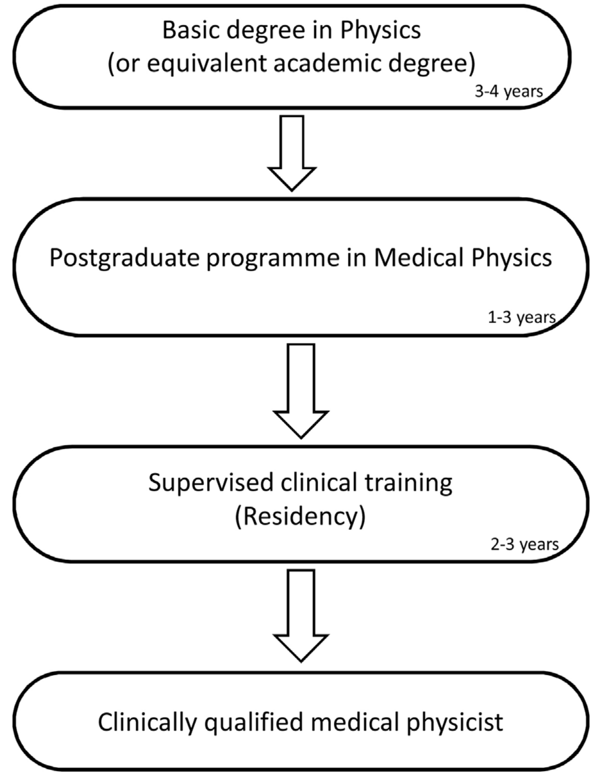

Fig. 1. The IAEA model for the education and clinical training of a clinically qualified medical physicist. Adapted from Ref. 4.

3. Results

3.1. The state of medical physics education and professional status of medical physicists in RO services

The Mexican graduate programs in medical physics have followed the IAEA model (Fig. 1) and have developed curricula at the master's level that adhere to international recommendations.[4] Both master's programs are 4-semester long, include several theoretical and practical courses and a one-semester clinical residency, and need a successful oral defense of a thesis to graduate. Physics of Radiation Therapy is part of the basic mandatory courses and clinical training in the physics of RO is part of the one-semester clinical internship; this activity shares its allocated time with practical training in the other subspecialties of medical physics, medical imaging, nuclear medicine, and radiation protection.

Admission calls for a bachelorś degree in physics or engineering and the passing of an entrance exam on the advanced physics courses of such a degree. Over the last decade, between 7–10 students enter the UAEMex program, and 9–12 enter the UNAM program every year. Graduation typically occurs at the end of the fifth semester, 5 graduates per year from UAEMex and 11 from UNAM, on average, during the last 10 years. Academic activities require fulltime dedication and students at both programs can apply for 2-year scholarships from funding institutions.

The UAEMex program is considered by the National Council of Science and Technology (CONACyT) roster of "quality graduate programs" (PNPC) as a program "In Development" stage. This means, a program with a positive academic perspective, sustained on its plan for improvement, and viable goals to reach in the medium time range. The classification of the UNAM program is "International Competence". This is the top classification level in the roster, meaning that the program has received national recognition for its impact forming highly qualified human resources, high academic productivity, and collaboration with other sectors of the society, supplemented by international collaborations that enable the mobility of students and professors, as well as the establishment of joint research projects. Thanks to these accreditations, students in both programs have access to scholarships during their studies.

After two decades, the number of graduates is 77 for the UAEMex program and 148 for UNAM's. There is no national certification program for MPs and no official list of MPs, beyond the information that each program keeps of its graduates. According to the studied programs' web pages,[6,7] about one half of the graduates work in medical services, mostly in Mexico but also in the Latin American and Caribbean region and the USA. The most frequent clinical positions are in the physics of RO, followed by physics of nuclear medicine and physics of diagnostic radiology. The published information indicates that about 90 master's graduates hold positions in RO. Independent estimates hint that about 250 MPs, with various degrees of education and training, work in Mexican RO services. Thus, about 36% of the present-day workforce has the education level recommended internationally for MPs.

Concerning the survey, a total of 43 anonymous responses were received from 15 individuals with the degree from UAEMex and 28 from UNAM. Pooled, the responses represented about 50% of the estimated 90 individuals in RO services. Seventy-two percent of the respondents worked in public services and 28% in the private sector. They had been hired as "medical physicists" (60%), "hospital physicists" (30%), "radiation safety officers" (5%), or "other" (5%). Nine of those employed as medical or hospital physicists (38%) were also radiation safety officers in their service. Respondents had worked in the service during a mean of 6.8 years (SD = 4.5 years, range 1–20 years). The average number of MPs in their service was 3.7 (SD = 2.6, range 1–11) individuals.

The survey asked all participants which were the main benefits they had received from their graduate education. The most frequent responses were:

- Solid understanding of radiation physics, dosimetry and radiation protection (28%)
- Ability to solve problems and challenges through the use of knowledge and the scientific method (28%)
- Theoretical and practical knowledge in medical physics (13%)
- Admiration and respect for the specialty (8%)

The survey asked the clinical MPs to mention those tasks in their work for which the master's program had prepared them poorly. The most frequent responses were:

- Insufficient clinical training (44%)

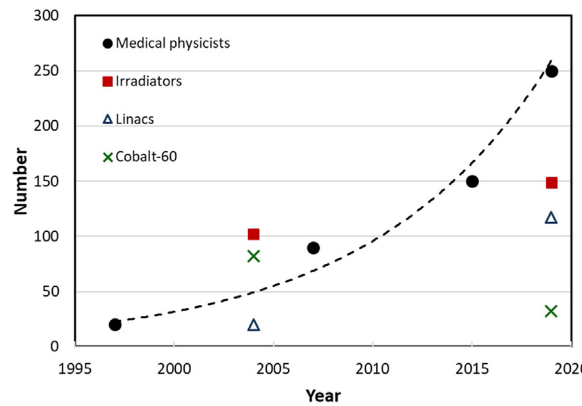

Fig. 2. The numbers of MPs in RO services, total irradiation machines for RO, Co-60 units, and linacs in Mexico since 1997. The number of MPs is approximate and has an (estimated) relative uncertainty of 20%. The dashed curve shows the trend for the number of MPs. Numbers of RO units are those published in 2004,[11] and those available at the time of writing this analysis.[9]

- Insufficient knowledge of the most advanced techniques in RO (21%)
- Difficulties in personal relations with other professionals in the medical team (13%)
- Insufficient knowledge of the administrative paperwork in a hospital (8%)

The survey asked the opinion of the MPs on the necessity of a graduate degree to perform as clinical professionals. This question is important because, as we showed above, only 36% of the current clinical MPs do have a graduate degree in medical physics and their clinical activities probably need collaboration with colleagues whose education does not include a degree at the graduate level. Among the respondents to the survey, 81% considered that a graduate degree was "essential" and 12% considered it "important" to do the tasks at the service.

3.2. The recent development of radiation oncology in Mexico

In general terms, there is a broad variety of equipment in the RO centers. Techniques in clinical use include 2-dimensional (2D) planning, 3-dimensional (3D) and intensity-modulated planning, 4D CT imaging, and 4D radiation therapy technology (the terms 4D medical imaging and 4D radiation therapy refer to techniques that study, characterize, and take into account patient motion during the processes of imaging and radiotherapy). In terms of irradiators, there are cobalt-60 units as well as high-precision novel systems, such as Tomotherapy^{TM}, robotic radiosurgery Cyberknife^{TM}, and linacs equipped with Image-Guided Radiotherapy (IGRT), Intensity-Modulated Radiotherapy (IMRT), Volumetric-Modulated Arc Therapy (VMAT) and Flattening-Filter-Free (FFF) systems.

According to the DIRAC database[9] (continuous update), in Mexico (124 million population, 2018 estimate) there are 89 RO centers with 149 machines (117 linacs and 32 cobalt-60 units). In 2004, there were 75 RO centers with 102 machines (20 linacs and 82 cobalt-60 units).[11] The comparison indicates for the last 15 years a moderate (19%) increase in the number of centers, a strong (46%) increase in the number of irradiators, a strong decrease in cobalt-60 units (only 39% of the machines that existed 15 years ago are running today) and a very large, almost sixfold, increase in the number of linacs. This indicates the expected transition from cobalt irradiators to accelerators. Fig. 2 displays data for equipment and MPs in RO services, since 1997.

These resources are mostly concentrated in the largest cities, Mexico City, Monterrey, and Guadalajara, and not necessarily distributed according to the population in the countryś 33 states.[8] There are 17 RO centers in Mexico City (population 8.9 million) while the state of Tlaxcala (population 1.3 million) has no RO centers.[12] There are two centers (in Mexico City and Guadalajara) equipped with Gamma Knife™ systems, 3 centers (two in Monterrey and one in Mexico City) with robotic radiosurgery Cyberknife™ systems, and 7 centers with helical Tomotherapy™ systems.[12] There are 18 conventional simulators and 50 CT simulators, the latter located in 22 states. RO centers in 5 states don't have simulators.[9] There are no centers for ion-beam therapy. According to current databases,[9,12] there are about 40 low- and high-dose-rate (LDR and HDR, respectively) brachytherapy systems installed.

Concerning the number of RO specialists, since its establishment, the Mexican Radiation Oncology Certification Board has certified 368 RO. There are now 346 certified radiation oncologists in active service.[14] Assuming a uniform distribution of human resources in the RO centers, these figures show about 2.5 radiation oncologists and 1.7 M P per radiotherapy machine.

We have estimated the recommended number of MPs using ASTRO's published tool.[13] The input number of new cancer cases per year was 190,667,[15] and 48% of these received radiotherapy.[16] The (simplifying) assumptions – among others – were that all irradiators formed one national center, one half of the linacs were multi-energy (the other half was single energy), and 12 of the systems offered novel modalities requiring high specialization of the MP staff (Tomotherapy™, CyberKnife™, GammaKnife™). 30% of the patients were treated with conventional external beam radiotherapy (EBRT), 40% were treated with EBRT 3-D, 20% of the patients were treated with an advanced technique (IMRT, IGRT, stereotactic radiosurgery (SRS), total-body irradiation (TBI), stereotactic body radiotherapy (SBRT)), and 10% were treated with brachytherapy (LDR or HDR). Other input data on available equipment were estimated from national databases.[12] Results were that a total of 345 MPs (2.3 M P per machine) are needed for the right MP staffing level in the country's RO services. This value was highly sensitive to the assumed patient load for advanced techniques. If only 15% or 10% of the patients were treated with IMRT, IGRT, SRS, TBI, SBRT, the required number of MPs would be 310 (2.1 M P per machine) or 274 (1.9 M P per machine), respectively. At present, the estimated number of MPs in the country is 250 individuals, which is below the model estimates. This indicates that the services are probably understaffed and that the future access of more patients to high-precision techniques will need larger numbers of MPs, and they should have the highest education and training.

3.3. *The collaboration of radiation oncology services and the medical physics programs*

The two universities granting the master's degrees do not have a university hospital, thus close collaboration between the graduate programs and external RO services has existed since the launching of the programs. The UNAM program, in the southern part of Mexico City, has as main clinical partners in teaching, training, and collaboration for thesis projects INCan and the National Institute of Neurology and Neurosurgery (INNN). INCan is a regional reference in the field of RO, as the institution that received the first Co-60 irradiator in Mexico. At present, INCan has 7 machines for EBRT and 3 for brachytherapy.[9] INNN was the first center to offer IMRT treatments in 2003, and it hired some of the first medical physics graduates from the UNAM program. Later, other collaborations have been established with Hospital de Oncología (public), Hospital 20 de Noviembre (public), and ABC Medical Center (private). The UAEMex program, located in the city of Toluca (70 km from Mexico City), initially established an agreement with the State of Mexico and Municipalities Social Security Institute (ISSEMYM) public health center in Toluca, and later has been also associated with centers in Mexico City, including those we have referred to. The RO service in Hospital Médica Sur, a Mexico City private hospital, collaborates generously with both medical physics programs for classes, laboratory sessions, short training, and thesis work.

An important field for collaboration between the medical physics programs and the RO community has been the direction of the medical physics M.Sc. thesis. The RO specialists have played an active role in the thesis work definition, research, and possible local applications of the results. A total of 29 M.Sc. theses on RO subjects have been successfully defended by students in the UAEMex program, and 31 in the UNAM program which, combined, represent 27% of all theses. The research topics most often found in the publications that have followed some of the thesis are skin dosimetry for electron beam treatments and characterization of radiochromic films for small field dosimetry in the UAEMex program, and use of thermoluminescent dosimetry in clinical studies, small-field dosimetry using ionization chambers and other appropriate detectors, in vivo dosimetry, use of Monte Carlo algorithms in treatment planning, and physics of SRS, in the UNAM program. The programs impart all graduates the education and professional competency of a master's degree, independent from the subject of the thesis.

4. Discussion

The results of the survey indicated that the programs' goal of providing concepts, knowledge, and tools necessary for the clinical practice of medical physics is recognized positively by the graduates. The most common limitation expressed in the survey referred to insufficient practical training in RO during the master's studies. This result comes not as a surprise since, according to the IAEA model in Fig. 1, the training should be provided by a post-graduation residency program that takes place in an accredited medical center. International recommendations[4] are for this activity to be a structured program, supervised by a qualified medical physicist, and not less than 2-year long. Given the current situation in Mexico, a "qualified" MPs able to supervise residents would be individuals with a level of professional experience and expertise equivalent to that of a certified MP. The International Medical Physics Certification Board (IMPCB) has established this as the minimum qualification for candidates applying to certification in countries where the complete formative and certification structures are still developing.[17] Unfortunately, it has not been possible to organize post-graduation residency programs in Mexican hospitals, despite efforts at different levels. Six-month long practices exist at three public Mexico City hospitals at a high cost for the "resident"; these centers accept a reduced number of residents each semester and the waiting time to be admitted could be up to two years. All this is overly insufficient to satisfy the current needs.

The creation of structured residencies, sufficient in number to satisfy the needs of MPs obtaining degrees from the programs, will require a concerted effort of medical services, universities and MP professional societies, under the leadership of health authorities. It is possible to identify about ten public and private hospitals in the country having the infrastructure (equipment and qualified human resources) required to carry a 2-year medical physics training in RO. There are also, but fewer, services equipped for training residencies in nuclear medicine and diagnostic imaging. A functioning and well-organized structure for the operation of medical residencies already exists, under the regulation of the Secretary of Health. A similar scheme, which included the accreditation of the service, rules for the selection of residents, supervision of the evaluation procedures, and the granting of an official certificate, could be possible. Probably, other paths to the solution exist, and all require the recognition of the problem, the will to solve it, and the funding.

Concerning the advancement of RO in the last 15 years, a strong increase in the number of RO oncology resources has taken place in Mexico. A simple estimate based on the 2004 survey[11] and present 2019 data,[9] indicates a 19% increase in the number of RO centers. A similar trend is observed in the number and technical complexity of the equipment. There are 46% more radiotherapy machines, the number of cobalt-60 units decreased by 61%, and the number of linacs has increased almost sixfold in the period. However, inequalities in the geographical distribution of the resources remain a problem.

The number of MPs in RO centers has increased rapidly since the end of the past century. Simple estimates based on the number of MPs in the late 90 s, 2007, 2015,[10] and 2019, shown in Fig. 2, give an increase by a factor of five in the number of MPs during the last 15 years. The number for MPs seems to correlate with the increase in the number of linacs, and one could interpret, erroneously, that the situation is acceptable. One must be aware that advanced techniques such as IMRT, Cyberknife™, Tomotherapy™, and others, do require "clinically qualified" MPs, that is, specialists with professional competence acquired in a complete academic education followed by structured training that enables them to practice independently. The trend seen until now in Mexico, where only one-third of the MPs have the recommended education, will not be sustainable as the most technologically advanced equipment dominates at our RO services. This situation is already taking place in many services.

Additionally, advanced techniques need more human resources than simple techniques (as an example, a linac requires more, and better prepared, associated MPs than a cobalt-irradiator), and thus, the number of clinically qualified MPs should increase more rapidly than just the number of machines. This was shown by the staffing evaluations described in the Results section.[13] Medical physicists will always encounter the accelerated, evolving nature of radiation therapy. For instance, MPs should be prepared to face developments of the security culture of the RO staff and the challenges related to new IT trends (big data, security issues, Artificial Intelligence). In the multidisciplinary environment, special social skills will always be needed, such as communication, negotiation, and leadership, to mention a few. These demanding abilities do require appropriate education and training.

5. Conclusion

Our analysis has shown some of the problems encountered today in the process of forming MP in Mexico. The educational stage works according to the international recommendations thanks to the 20-years-old master's programs. However, their graduates represent only 36% of the MP workforce in RO, and many more well-educated individuals are required to satisfy, not only the increasing needs of modern RO, but also those of other radiation techniques, such as molecular imaging and PET, mammography, and magnetic resonance imaging. The training stage should get organized to offer the level of training required to form clinically qualified MPs.

Radiation oncology technology has advanced significantly to support new capacities and to create new paradigms in planning and treatment delivery characterized by high precision and accuracy, high dose-rate delivery, hypofractionated therapy, 3D imaging for treatment verification, management of respiratory motion during radiotherapy, and integration of functional imaging in treatment planning, among others. Medical physicists working in RO services must be trained accordingly, following international recommendations of graduate education and postgraduation clinical training. Education and health institutions in Mexico must find incentives to create more medical physics graduate education programs at universities and to establish residencies at appropriately accredited health centers.

Conflict of interest

None declared.

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