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SAFETY BRIEF

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MEDICAL SERIES

Understanding Adverse Drug Reactions*

by James T. O'Donnell, M.S., PharmD

As many as 1.5 million persons are hospitalized each year because of an adverse drug reaction. This brief outlines the types of reactions, the importance of recognizing them, the elements involved in such reactions and measures to be taken by caregivers to prevent them. Almost any drug can cause an adverse drug reaction in at least some patients. Approximately ninety percent of reactions are caused by such drugs as anticoagulants, antimicrobials, cardiac drugs, central nervous system drugs, bronchodilators, and hormones.

Reliability and Safety of Medical Devices: Part II

by James R. Wingfield, M.S.

The development of safe, reliable medical devices requires the implementation of a rigorous and disciplined approach throughout the product design phase. Program planning and design assurance activities have long served other industries which, like medical devices, have a measure of risk associated with their use. The payback in monetary terms is expected to exceed the incremental cost of development. A rigorous design approach also fulfills the responsibility of manufacturers to exercise diligence in the design of critical medical devices.

Electromagnetic Interference and Electrostatic Discharge Testing on Medical Products: An Introduction

by Richard M. Bilof, Ph.D.

Electromagnetic Interference (EMI) and Electrostatic Discharge (ESD) testing are essential elements to the design of almost any new electronic or electromagnetic product. EMI describes a wide range of environmental electrical disturbances which can adversely affect the performance of electrical equipment. Electrostatic Discharge (ESD) interference is a specialized type of ambient interference that results from the extrememly rapid equalization of charges between conductive surfaces. Humans experience ESD as a brief electric shock. Several examples are presented of hospital equipment subject to EMI and ESD and mechanisms developed to eliminate them.

UNDERSTANDING ADVERSE DRUG REACTIONS

by Dr. James T. O'Donnell

An adverse drug reaction is any unintended or undesired response to a standard drug dose. That could mean a lot of things, from the adverse effects of the drug to an overdose, from a hypersensitivity or bizarre reaction to a drug interaction. Whatever the cause, an adverse drug reaction has potentially serious consequences - it can lead to further illness, to delayed recovery, to death or to increased health care costs.

Nurses may be considered the first line of defense, because they are with patients more than any other health care worker. They are in the best position to prevent an adverse drug reaction or to recognize one and to intervene before it is too late. To do this, they need to know which drugs can be trouble, what kinds of reactions to expect, and how to recognize an adverse drug reaction as soon as possible. Drug reference books, package inserts, and hospital pharmacists can provide the specifics on drugs prescribed to patients.

TYPES OF REACTIONS

There are two broad categories of adverse drug reactions - type A and type B. A type A reaction results from an exaggerated but otherwise normal pharmacologic action of a drug in its usual therapeutic dose. One example of this type is an intravenous (I.V.) injection of atropine which causes the patient to experience dilated pupils and dry mouth. Other examples of this effect include orthostatic or exercise hypertension from guanethidine and drowsiness from phenobarbital. The incidence of injury from a type A reaction is high, but the number of deaths is generally low.

Predictability is the key to a type A reaction. If the drug's properties are known, the kind of reactions that the drug can cause are fairly certain. It is necessary to factor in dosage, because most type A reactions are dose-dependent.

In some cases, a phsician prescribes a drug because it causes a type A reaction. If the patient who received atropine is about to undergo surgery, chances are the physician ordered it specifically to diminish secretions. That would not be the case, however, if the atropine were being used to treat symptomatic bradycardia (slow action of the heart).

Another example of a type A reaction is the use of diphenhydramine, an antihistamine, which causes drowsiness that many patients find unacceptable. Instead of abandoning this drug, manufacturers saw another way to market it. They started using it as an ingredient in sleep aids. Moreover, they found that diphenhydramine is safer than benzodiazepine sedative hyponotics (such as flurazepam [Dalmane]) used for the same purpose.

Type B reactions are not as predictable as type A ones. They are unusual and unexpected and they occur even when a drug is given in its normal therapeutic dose to a patient who should be able to handle it. For example, it is not usually known which patients will develop malignant hyperthermia from general anesthetics. Many immunologic reactions (allergic and hypersensitivity reactions) fall into this category. Anaphylaxis is a classic type B hypersensitivity reaction. Because it is potentially life- threatening, anaphylaxis is one of the most serious adverse drug reactions. It commonly occurs after a drug has been injected, but it can develop with any route of administration.

WHICH DRUGS ARE THE MOST DANGEROUS?

Almost any drug can cause an adverse drug reaction in at least some patients, but certain drugs cause approximately ninety percent of reported adverse drug reactions. Here is a look at them:

Anticoagulants
- heparin
- warfarin

Antimicrobials
- penicillins
- cephalosporins
- sulfonamides

Bronchodilators
- theophylline
- sympathomimetics

Cardiac Drugs
- digoxin
- quinidine
- diuretics
- hypotensives

Central Nervous System Drugs
- analgesics
- anticonvulsants
- sedative-hypnotics
- neuroleptics

Diagnostic Agents
- X-ray contrast media

Hormones
- estrogens
- corticosteroids
- insulin

NEED TO RECOGNIZE AN ADVERSE DRUG REACTION

Recognizing an adverse drug reaction is important for three reasons:

1. ***Therapy should be changed as soon as possible.*** The drug should be discontinued or the dose altered to limit the signs and symptoms of the reaction. In some cases, an antidote may be given (e.g., naloxone to reverse the effects of morphine and other opioid analgesics). In other cases, symptomatic therapy (e.g., steroids and other treatment) or both an antidote and symptomatic therapy would constitute the treatment.

2. ***Assure that everyone knows about the patient 's reaction to avoid future problems.*** A patient who has had an adverse drug reaction should not receive that drug again. The reaction must be documented in his medical records so that all caregivers are notified of the problem. Also, the patient himself should be told which drug he reacted to and what the reaction was so he can alert future caregivers to the problem. He may carry a card or wear a bracelet warning others that he has had a reaction to a certain drug.

   The patient also should not receive a drug if he has previously developed a complication that is a common adverse effect of that drug. For example, halogenated anesthetic gases are associated with jaundice, particularly if these gases are administered repeatedly within a short period. Thus, a patient who has had jaundice before should not be anesthesized with this type of gas.

3. ***Avoid the risk of a lawsuit.*** Suppose the caregiver does not recognize a mild ad-

verse drug reactiion and because it progresses, the patient dies or suffers a serious injury. The caregiver could be liable for negligence if the patient (or his family) files a lawsuit.

Recently a Montana man who had previously had a serious allergic reaction to penicillin died after receiving cephalosporin. His nurse and physician did not realize that cross sensitivity is common with these two drug classes. They did know, however, that he was allergic to penicillin. The patient's family sued the hospital, the nurse, and the physician for negligence; the case was settled out of court.

MAJOR ELEMENTS OF A DRUG REACTION

Every adverse drug reaction has three major elements - a specific drug, a site that is affected, and a pathologic change in the body:

The prescribed drug: It is well known that thousands of prescription and nonprescription drugs are available. Some drugs, such as chemotherapeutics, are notorious for causing adverse drug reactions. In those cases, it is easy to predict and identify adverse reactions. In other cases, however, the reaction may be unprepared for or may be missed entirely. For example, it may not be expected that a patient taking metoclopramide (Reglan) will develop extrapyramidal symptoms, but some do.

Consider, too, the problem with the many new drugs marketed each year. Our bodies have never been exposed to some of the chemicals used in these drugs. Because we do not have prior experience with them, our bodies may treat them as foreign substances and this can make for some unusual reactions. For example, about fifteen percent of patients taking enalapril (Vasolec) develop a cough, a reaction which also occurs with other angiotensin converting enzyme (ACE) inhibitors.

The site affected: Every organ and tissue can be the site of an adverse drug reaction. Most reactions occur, though, in organs or tissues related to absorption, metabolism, storage or excretion of drugs, such as the gastrointestinal system, liver and kidneys.

CALCULATING THE HUMAN TOLL

- Up to 140,000 deaths each year can be blamed on adverse drug reactions.
- As many as 1.5 million persons are hospitalized because of an adverse drug reaction.
- Approximately 30% of hospitalized patients experience an adverse drug reaction.
- The chance of suffering such a reaction is ten times greater for medical patients than for surgical patients. (That is not surprising, considering that medical patients receive a considerably greater number and variety of drugs).
- About 70% of adverse drug reactions are minor, the remaining 30% are associated with serious injury and death.

The physiologic change: Some of the pathologic changes caused by adverse reactions are permanent and can be examined, biopsied, measured, tested, etc. (e.g., cirrhosis and necrosis). Others are temporary, such as inflammation and edema following a severe hypersensitivity reaction. Still others are functional and do not cause visible changes (e.g., vasodilation that is not great enough to produce pulse and blood pressure changes).

Sometimes, it is not easy to determine whether or not a reaction was caused by a drug or by something else, such as a disease or life-style change. This happens because clinical findings, including signs and symptoms and laboratory test results, could be identical in either case. For example, a patient with cancer of the gastrointestinal tract who is receiving chemotherapy may develop nausea and vomiting. It would be uncertain whether this was from the disease or from a reaction to the treatment.
So without distinct pathologic changes or a clear connection to a drug, an adverse drug reaction may be difficult to recognize and diagnose. If an adverse drug reaction has not even been considered, it might even be overlooked.

RAISING THE RED FLAG

There are warnings, or red flags, that should *lead* caregivers to suspect an adverse drug reaction. They include:

- clinical or laboratory findings that are not typical of the patient's disease;
- a pathologic change at a site that is not involved in the disease being treated; and
- a pathologic process that is not consistent with the patient's disease.

If a patient suddenly develops new signs and symptoms, his drug Kardex should be consulted to determine whether or not the problem could be related to a drug he is receiving. Was the drug administered *before* the reaction occurred? Or did the signs and symptoms develop first? In other words, the drug could not be responsible if these signs and symptoms developed *before* the administration of the drug. Then, it is necessary to look for another cause.

For example, suppose a patient receiving gentamicin has blood urea nitrogen and serum creatinine levels twice the normal levels. Review the patient's record and note whether these levels were high before the patient received the drug and whether the levels remained essentially the same after treatment. If so, the drug did not cause the problem. On the other hand, if another patient developed a rash after receiving ampicillin, the drug could reasonably be blamed for the rash.

Sometimes, the nurse, pharmacist and physician may suspect a certain drug has caused the adverse reaction, but neither is sure. The physician may decide to "challenge" the patient; that is, give the drug again and observe the patient for a reaction to establish the link. This would be done only if the consequences would not be life threatening, of course.

There are not many patients receiving only one drug - this is an age of polypharmacy. In rare cases, however, it will be easier to determine if the drug is causing a reaction. Consult a drug reference or pharmacist to learn whether the drug causes a unique reaction.

When giving I.V. vancomycin for a staphylococcal infection and the patient's blood pressure suddenly drops and his face becomes very flushed, you know that the patient is experiencing "red neck" syndrome, if vancomycin is the only drug he has been receiving. This occurs when the

drug is given too rapidly. Its hallmark is a sudden, sometimes severe, drop in blood pressure that may be accompanied by flushing or a maculopapular or erythematous rash on the face, neck, chest, and upper extremities. (The flushing or rash can occur without hypotension). The patient may also develop wheezing, dyspnea, angioedema, urticaria, and pruritus. This reaction calls for the immediate administration of antihistamines, corticosteroids or I.V. fluids.

TOXICITY AND NEW DRUGS

Some drugs have to be given in near-toxic or toxic doses to be effective (e.g., chemotherapeutics, anticoagulants, and some psychotherapeutics, such as lithium). Knowing this, caregivers should be prepared to observe the patient closely and to identify quickly a toxic reaction, then to intervene to prevent serious injury.

If the physician prescribes a newly marketed drug, caregivers have to be particularly vigilant. Talk with the pharmacist or double-check the product literature (if available) for information about the usual dosage range and adverse reactions which might be expected.

Be aware, however, that not everything is known about a new drug, including the toxic dosage and adverse reactions. The number of persons involved in clinical trials is generally small, so the safety profile is usually incomplete before marketing.

Also, early phases of clinical trials are typically performed on healthy, young, adult males, even if the drug will ultimately be prescribed primarily for the elderly. Adverse drug reactions that may be unique to seriously ill patients, the elderly, pregnant women (or any women) and children are not usually known because these groups, in most cases, are excluded from clinical trials (although new federal regulations require that the elderly be included).

For these reasons, many experienced physicians adopt a "wait and see" attitude - they will not use a new drug until it has been on the market for a year or more. During that period, several hundred thousand patients will take the drug and serious adverse reactions will be discovered and reported.

The most important thing to know is which reactions to anticipate with each drug prescribed. For example, if it is known that a drug can cause severe organ damage, the baseline laboratory results should be checked and subsequent results for toxicity should be reviewed.

REPORTING REACTIONS TO THE F.D.A.

Drug manufacturers monitor adverse drug reactions and report them to the FDA (Food and Drug Administration). The FDA also wants to hear from nurses whose patients have experienced serious reactions associated with drugs - especially drugs that have been on the market three years or less. Nurses and other professional caregivers are the ones most likely to see the reactions and can give the best clinical descriptions. Unlike manufacturers, however, they are not required to make such a report. What constitutes a serious reaction? According to the FDA, it is one that is:

1. life-threatening
2. causes death
3. leads to hospitalization or prolonged hospitalization
4. results in permanent or severe disbility

The FDA also wants to know about drugs that do not produce a therapeutic response. It does not need to hear about inappropriate use of a drug, prescriber errors, or admininstration errors. (The United States Pharmacopeia, though, *does* want to know about medication errors - particularly errors caused by sound-alike or look-alike drug names. The hospital pharmacist should be consulted for more information).

A report can be submitted to the FDA even if the sender is not sure whether the patient's reaction was serious or if it is suspected, but not known for certain, that a drug caused the reaction. To file a report, use form 1639, which should be available in the hospital pharmacy. The form should be filled out as completely as possible. It is not necessary to include the patient's name or initials, but they should be known if the FDA requests follow-up information.

Some 60,000 reports are collected annually; over 400,000 are currently in the FDA's database. That translates into improved patient safety because the more reports submitted, the more information the FDA will have. It can then alert health care professionals to these problems.

PREVENTING SOME REACTIONS

Not much can be done to control bizarre, type B reactions, except obviously to make sure that the patient does not receive the drug again. Type A reactions, however, can be prevented or quickly treated because they are predictable. Here are some preventive measures professional caregrivers can use for type A reactions:

Take a complete drug history. Flag the patient's chart and other records (his medication Kardex, for example) according to hospital policy if the patient has a drug allergy or a previous hypersensitivity reaction. Continue to monitor his therapy, watching for drugs that could cause a reaction. Check with the hospital pharmacists to make sure they also have this information about allergies and other reactions.

Suggest that duplicate or excessive drugs be eliminated from the patient's therapy - the fewer drugs, the less chance of an adverse drug reaction.

Understand the indication and goal of therapy for each drug prescribed, as well as possible adverse drug reactions (including interactions). Caregivers who do not understand the therapy should consult a drug reference book, talk with a pharmacist or ask the prescribing physician.

Anticipate adverse drug reactions when therapy is started or stopped (especially if the patient is on long-term therapy) or when the dosage is increased.

Suggest that the physician order blood levels to determine therapeutic or toxic effects when indicated.

Assess liver and kidney function. In many cases, these organs are the site of toxicity because they are necessary for metabolizing and excreting drugs. Toxicity would show up in altered laboratory values, such as blood urea nitrogen, serum creatinine, and liver enzyme levels.

Suspect an adverse drug reaction if the patient develops an unexpected complication. Caregivers should alert the physician

and inform him of the findings, including the severity and duration of signs and symptoms, how they related to the reaction when the drug was administered, and any aggravating factors (e.g., dizziness as a sign of orthostatic hypotension).

Teach the patient the early signs and symptions of potentially serious adverse drug reactions and ask him to report any such reactions to his caregivers. If he is being discharged, advise him to contact his physician and pharmacist about any problems.

Tell the patient to avoid over-the-counter medications unless he first checks with a nurse, physician or pharmacist.

Institute a regular chart review of medications by a team consisting of a nurse, physician, and pharmacist.

WHAT THE J.C.A.H.O. REQUIRES

To meet standards set by the Joint Commission on Accreditation of Healthcare Organizations (JCAHO), a hospital must have an adverse drug reaction reporting program in place. The hospital's pharmacy and therapeutics committee is required to review "all significant untoward drug reactions" to assure quality patient care.

What is a "significant" reaction? According to the JCAHO, it is one in which:

- the drug suspected of causing the reaction must be discontinued;
- the patient requires treatment with another drug, such as an antihistamine, a steroid, or epinephrine; and
- the patient's hospital stay is prolonged - for example, because surgery had to be delayed or because the patient needed more diagnostic tests.

Why is such a reporting program important? For one thing, the quality of care improves when it is known which patients are at higher risk for an adverse drug reaction and which drugs are most likely to cause adverse reactions. Caregivers will be more alert for the early signs and symptoms or problems and thus be prepared to intervene before things get out of hand. Second, the hospital will get more mileage out of its health care dollars because the lengthy stays and extra treatments associated with adverse drug reactions will be decreased.

Third, reducing drug-induced injuries will decrease the number of malpractice lawsuits brought against the hospital and staff. That saves money, time, and aggravation.

PATIENT SAFETY

With all the drugs available today, remembering the ones that could cause an adverse drug reaction - and recognizing those reactions - is a formidable task. Patient safety is at stake, so professional caregivers share a duty to be alert for problems and protect their patients from harm. They should have an up-to-date drug reference book at hand and know whom to contact and what to do if a patient is suspected of suffering an adverse drug reaction.

SELECTED REFERENCES

1. *Accreditation Manual for Hospitals*. Chicago, Joint Commission on Accreditation of Healthcare Organizations, 1991.

2. *Drug Information 90*. Bethesda, MD, American Hospital Formulary Service, 1990.

3. Fincham, J., "A Statewide Program to Stimulate Reporting of Adverse Drug Reactions," *Journal of Pharmacy Practice* v. 2 #4 (August 1989): 239-244.

4. Palmieri, D., "Clearing Up the Confusion: Adverse Clinical Effects of Medications in the Elderly," *Journal of Gerontological Nursing* v. 17 #10 (October 1991): 32-35.

5. Pearson, K, and D. Kennedy, "Adverse Drug Reactions and the Food and Drug Administration," *Journal of Pharmacy Practice* v. 2 #4 (August 1989): 209-213.

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RELIABILITY AND SAFETY OF MEDICAL DEVICES: PART II

by James R. Wingfield, M.S.

CONTENTS

I. INTRODUCTION

The manufacture and sale of medical products for use on humans follows essentially the same development sequence as any commercial product. Medical device development is unique, however, because of two important factors:

1. Medical devices play an important, frequently critical role in the practice of medicine, and
2. the medical device industry is regulated by an agency of the Federal Government: the Food and Drug Administration (FDA).

Historically, the FDA's attention has centered primarily on drug products. This changed, however, with the passage of the 1976 Medical Device Amendments to the Federal Food, Drug and Cosmetic Act which gave the FDA the responsibility and authority to assure that medical devices are safe and effective. The decade which followed the 1976 device amendments is characterized by the FDA concentrating its efforts in regulating the manufacturing side of medical devices. Under the regulation, medical products which are shown to be adulterated (i.e., that is, defective in quality, performance, or labeling) must be recalled and corrected by the manufacturer or distributor. An analysis of product recalls which occurred during this period indicates that only about half of the recalls were related to manufacturing methods. The rest were due to deficiencies of design, an area outside the influence of manufacturing regulations.

Moving to bring this into balance, the FDA has issued Pre-Production Quality Assurance guidelines for the design and development of medical devices. While these are not yet policed with the same force as the Good Manufacturing Practices (GMP) regulations governing manufacture, they form a basis for increasing regulatory control over this important area of device development.

The FDA classifies medical devices as Type I, II, or III depending on their criticality. Type III devices have the greatest potential patient risk associated with their use, while Type I devices produce little or no risk. Although a design defect in a Type I device may have little effect on the patient risk, there is some producer risk in attempting to scale back the rigor of the development process for a product of lesser criticality. Recalls and/or field repair often result regardless of device type.

II. THE MEDICAL DEVICE SYSTEM

When a medical device has more than a single component, it is more appropriately regarded as a medical device system. A typical system may consist of a hardware element, a disposable element and a pharmaceutical*.

Each element of the system has its own characteristics and each is brought to the final design configuration by a separate and independent development process. The final performance of the system may then depend on variables which are inherent in each of the elements of the system.

Examples of a medical device system are:

a. electronic pumps for controlled intravenous infusion
b. dialysis systems

Each has a hardware device, a disposable element and specially formulated solutions which are automatically administered to a patient according to a predetermined program. Each also has its own special therapeutic objective.

In the case of intravenous infusion, the volume of IV solution delivered over time is set and controlled by an automatic pumping device which comprises the hardware portion of the system. The pump (flow rate) accuracy may be affected by variations in the tubing through which the solution flows, and even by the solution itself. These variations are therefore important to the overall performance of the system. Solution viscosity and temperature and dimensional variations in tubing diameter and wall thickness are some of the more prominent variables which have been identified with flow rate accuracy, a performance attribute which the medical community prefers to hold at no more than ± 2% of the operating set rate. The dimensional variations in the tubing are produced by an extrusion pro-

*When a system is being analyzed for its inherent hazards of use, the operator and links to other product systems must also be included as components.

cess which is statistical in nature. The sum of these and other statistical variations results in the final performance of the medical device system being statistical also.

Hardware, in the most general sense, is medical equipment which can be reused, and has a life cycle of significant duration. Disposable elements are intended for single use only or limited use on a single patient. A pharmaceutical is that part of the system which, as a drug or solution, is administered into the body or blood stream.

Although each of these distinctly different elements of the system is designed, tested and manufactured in its own unique way, the ultimate qualification of the system must include the combined operation of all of the elements. The range of the hardware control error, the statistical variability of the disposable portion and the physical susceptibility of solutions to such environmental conditions as temperature all contribute to the accuracy and precision of the integrated system.

While disposable products are often thought of as such items as operating room gowns, surgical drapes, gloves, and similar single use items, some hardware has become so miniaturized and inexpensive that special disposable hardware components have appeared and are in common use. Among these are ingestible electronic telemetry tablets, glucose sensors and thermometer probes. In some instances, such as in the case of kidney stone snares, the strength of the snare can only be assured by using high grade stainless steel wire, a material not generally associated with throw-away items.

Consequently, the medical device development process is discussed here as a general model for medical device development. Each medical device or device system will, as a practical matter, incorporate only those steps which are applicable to the specific product.

III. QUALITY, RELIABILITY, SAFETY AND PERFORMANCE

All systems have four primary attributes by which they are measured:

- Quality
- Reliability
- Safety
- Performance

Although these terms are often used without specificity, they actually define separate engineering disciplines each with its own unique methods and objectives. The attributes defined by these terms are distinguished as follows:

Quality: the specification of standards for materials, processes, manufacturing, fabrication and workmanship and the measurement and control necessary to assure compliance to these standards.

Reliability: the specification of operating requirements and an assessment of the probability that a product or system will operate correctly within its performance specification under specified conditions for specified periods of time to meet the specified requirements.

Safety: the identification of hazards and safe design goals and the design assurance that a critical product or system will remain safe during operation or will safely degrade to predefined failsafe states in the presence of a failure.

Performance: the extent to which a product or system will accomplish its intended purpose or function within the limits of its technical specifications and under specified operating conditions.

These engineering disciplines overlap many times during a typical development program. One of the roles of the reliability engineer is to assure that this overlap occurs in a planned and well orchestrated manner. This assurance involves program planning, the development of specifications and protocols, testing requirements and procedures, design reviews and similar activities which introduce rigor into the program.

Each of these engineering disciplines is conceptually distinct. It is possible to meet performance criteria and yet be deficient in one or all of the remaining categories. Similarly, the product may be of high quality or safe and reliable without performing to expectations. The incorporation of quality, reliability and safety into the performance objectives of the development program is a goal which must receive the support of management at the highest levels of the company.

One of the axioms of reliability is that complexity drags down reliability. Similarly, one of the axioms of safety is that a safe design approach usually increases complexity particularly where safety is achieved through the use of automatic fault detection methods. When medical devices are non-critical in nature, the need for a fault tolerant design approach is lessened. Reliability can then be increased through design simplification and other techniques of reliability engineering. The first requirement for critical devices however, is safety. Reliability must then be optimized within the constraints of the safe design approach.

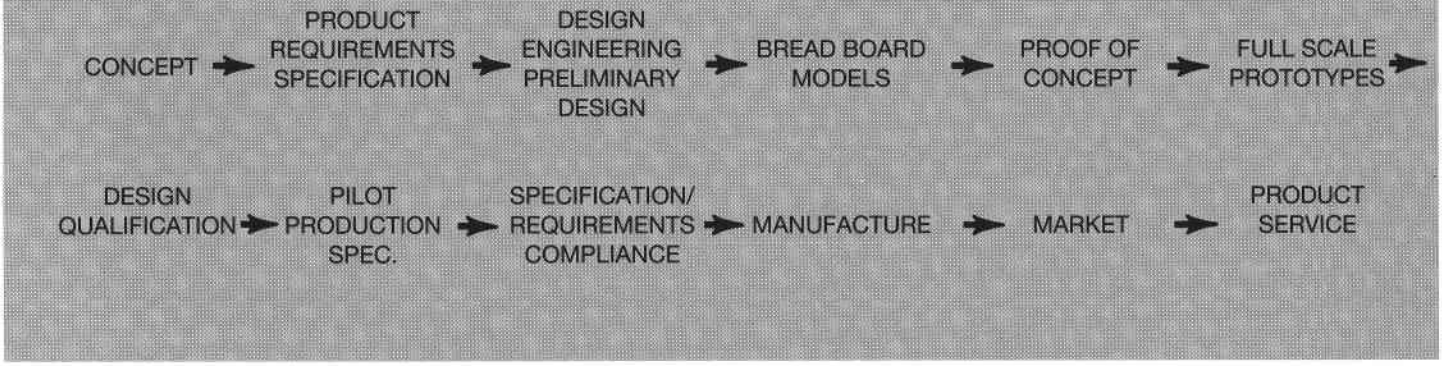
It is often a common assumption that high reliability is equivalent to safety. This is generally not, however, the best safety option for electronic devices. For many years, designers, users of medical equipment, and the FDA have accepted many potentially unsafe equipment failures as random or chance component failures. Whenever a failure of medical hardware is ascribed to the random failure of an electronic component, it is presumed to be a circumstance governed by the materials physics of the component and therefore beyond the control of the product design. This presumption is behind the insistence by the FDA that critical hardware devices must have a list of critical components. These are components which, if failed, could render the device unsafe. This then implies that the identification and quality control of the critical components qualifies as a safety strategy.

In the world of electronic components, most failures do occur virtually at an atomic level. Even the best materials and processes for manufacturing electronic components will give birth to components which exhibit inherent random failures. In recent years, however, more sophisticated electronic technology has evolved permitting design approaches which can detect and circumvent the consequences of random component failures. The interception of these critical component failures reduces the component to a non-critical status.

IV. PRINCIPAL PRODUCT DEVELOPMENT ACTIVITIES

The development of any product, commercial or medical, is forced to follow a general sequence of development steps. Since the development of medical devices must be comprehensive in terms of program rigor, a

FIGURE 1
PRODUCT DEVELOPMENT TIME LINE



disciplined approach must be imposed on the development sequence to assure product performance, reliability, and safety (i.e., in general, a high level of design assurance).

A typical hardware development sequence time line is shown in Figure 1. Each step shown in the figure represents a phase in the development process. Each of these phases is supported by a series of design assurance activities and program requirements which are superimposed on the time line as shown in Figure 2.

The design assurance steps shown in Figure 2 play an important role in the design process because they tend to force the process to challenge itself throughout the duration of development. Designers must address the consequences of unsafe product failures early in design; however, their normal orientation and the pressures they face in meeting management deadlines tends to focus their attention primarily on the functional, non-failed, performance of the product. The design assurance engineer, working with the design engineers and others, balances this by carrying the burden of Quality, Reliability, Safety* and the consequences of failure, throughout the development process. The Design Assurance function must report to a high level of management in order to avoid the intimidation of development time pressures.

The product development time line and the supporting Design Assurance activities are discussed in the following text in the numerical sequence shown in Figure 2. Ordering the events in this manner is not intended to imply that each has a distinct position in the development time line which is invariant. Each activity actually has its own time line which starts and stops at various points throughout the product development program.

V. DESIGN ASSURANCE ACTIVITIES

1. Product Specification

The product specification (sometimes called the Procurement Specification or Requirement Definition) is the single initial document which most completely describes the product to be developed.

It should not be restricted simply to the limits of output performance parameters such as flow rates, accuracy, filtration rates, temperature, tensile strength, etc. The product specification must also define the environment in which the product is to be used, stored, and shipped. Size, weight, power requirements, back-up battery requirements, reserve power, operator interface, human factors, materials and finish, alarms, Quality Reliability and Safety requirements, operational features and the interface with other equipment which may be part of the system are examples of what must also be considered in this document.

The product specification should be as detailed as knowledge and experience permit. It needs to be ambitious and as rich in detail as possible. Such a document should not be authored by design engineers alone. It must reflect the combined wisdom of all of the principal departments which will at some point be involved in the development program; marketing, sales, medical, legal, regulatory affairs, engineering, manufacturing, packaging and product service.

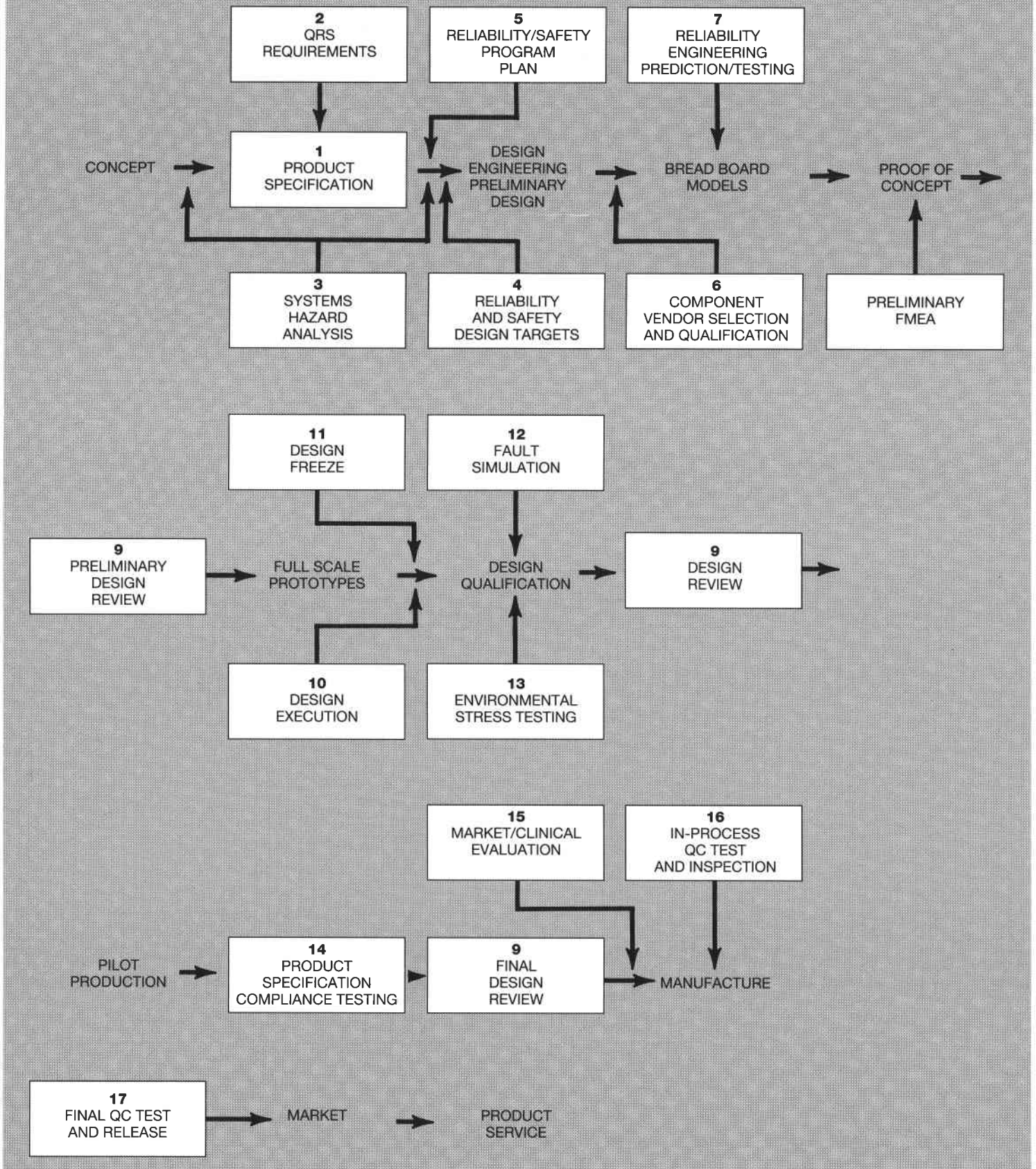
After it receives approval, the product specification should become a controlled document which is periodically updated and revised to reflect the evolving product. Initial requirements which cannot be met for technical reasons should only be changed by an examination of the issues during a scheduled and documented design review. All revisions must be circulated for review and at the completion of the project, the product specification should reflect the design configuration and operating philosophy to which the final product has evolved.

2. QRS Requirements

In addition to details of product design and performance, the product specification must contain a requirement for Quality, Reliability and Safety (QRS). Often these requirements are placed in the specification in a form that requires that specific QRS plans be developed and implemented during the course of the project.

*Companies often mistake these three disciplines as simply Quality Assurance. In fact they are quite different.

FIGURE 2
PRODUCT DESIGN ASSURANCE ACTIVITIES



Along with a clear statement of the expected quality, reliability and safety goals, the plans which "shall" be developed and implemented include:

Quality Acceptance Plan

- Classification of defects
- Accept/reject criteria

Reliability Program Plan

- Accelerated life testing
- Reliability prediction
- Reliability demonstration
- Reliability growth
- Failure analysis

Safeability Program Plan

- Hazards identification
- Task Analysis
- Functional Flow Analysis
- Systems Hazards Analysis
- Safe design approach
- Safety checking (FMEA)
- Fault simulation
- Sneak path circuit analysis

The plans, their implementation, and the results of their execution are among the items which are placed on the agenda of the Design Review Committee. (Section V.9)

3. Systems Hazards Analysis

A systems hazards analysis (SHA) is performed as early as possible in the program but not before the operating and functional design principles are as well known as possible. Ideally, the results of the SHA, should appear in the product specification as safe design requirements as early as possible. Product designers must be made aware of any safety concerns associated with the application and function of the product, and the product specification provides an opportunity to highlight these issues at the outset. When lack of experience and knowledge about a product prevents the identification of hazards with any degree of confidence, the product specification should at least call for a formal SHA study to reveal any inherent hazards which may attend its use. This analysis is usually performed by the reliability/safety engineer in conjunction with the design engineers and medical consultants. Often, in a mature industry, the hazards associated with the product use are known. Regardless, the objective of this analysis is to answer two fundamental questions:

1. Given a specific medical device and application, what extraordinary conditions of design performance can produce a potential risk to the patient?
2. What failures in the medical device/system including errors in its use, can combine to produce a potential risk to the patient?

This kind of analysis does not attempt to address the normal medical risks which may be an inherent consequence of the therapy or diagnostics. Those risks are presumed to be understood and accepted by the community of knowledgeable users. The output of this analysis sets safe design goals for the designers so that they can incorporate safety performance along with technical operating performance during the design process. With the benefit of the SHA results, designers can then employ various safe design strategies to control both the safe operation and the consequence of unsafe failures.

Ideally the hazards to be avoided are included in the requirements definition in order to initially specify the reliability and safe design goals with greater precision. Often, however, the hazards may not be entirely known and even if they are, there may not be a thorough understanding of the events which can precipitate the hazard. Undesirable events range from component failure to environmental effects (Electrostatic Discharge (ESD), Electromagnetic Interference (EMI), brownouts, etc.) to human error. The influence which the designer has over reducing the potential for human error can, in many instances, be significant. In any system, if it is determined that human error can lead to harm in some way, then this may require the specification of other procedural safety methods in addition to whatever other design options which may be available. Every critical product, process or system has associated with it an irreducible degree of procedural safety which can not be replaced or "designed out" by attempting to devise an automated design solution. The total safety of any product is inescapably a balance of both automatic and procedural safety. In simple systems, procedural safety may in fact be a more reliable approach where the operator can be expected to be a trained professional. Fault tree analysis, task analysis and functional flow analysis often prove helpful in identifying potential man/machine interface errors and systems errors which can lead to the production of a hazardous condition.

4. Reliability and Safety Design Targets

Assuring that Reliability and Safety are incorporated into a medical device requires attention throughout the design phase. The first step in achieving a safe design is to use the output from the Systems Hazards Analysis to define the design safety targets. An automatic intravenous infusion pump, for example, should always detect air in the IV tubing, stop the pump, and sound an alarm. The pump should never permit a free flow condition to occur and its accuracy with respect to volume delivered over time should always be within the limits specified for the device/system. The designer must convert these safety targets from an "on paper" requirement into the operating hardware of the pump. The design task is not always a simple one. In order to detect air in the tubing for instance, the designer can surround the tube with a sensor/detector which sends an ultrasonic signal across the tube and measures the signal attenuation. When the tube is empty, or when an air bubble has come into line with the sensor, the condition will be detected, the pump will stop and an alarm will sound.

This approach is simply "safe" design; if an electronic component in the sensor circuit randomly fails (a condition inherent to electronic components), it must be acknowledged then that the sensor itself can fail and remain disabled without detection until it shows up by bench test or mishap. An additional design requirement is, therefore, to monitor the condition of the sensor automatically during use and have the pump stop and alarm if the sensor fails even though there may not be any air in the tubing.

This approach transcends ordinary safe design and reaches for a higher plane commonly referred to as "failsafe" design. Failsafe, or more correctly, fault tolerant design is a complex undertaking which carries with it more stringent requirements for analyzing and testing the product to assure that all such disarming failures can be caught by self-checking circuits.

Similarly, reliability goals must be set and agreed upon. A simple numeric can be used to define reliability. In the case of repairable devices, this numeric is called Mean Time Between Failures (MTBF). This number is usually expressed as the number of failures per million hours of operation. When actual reliability is very high, this number is very small. All instruments with electronics and/or moving parts, however, have an inherent failure rate which is never zero. In some respects this is an elusive number. In fact, it may be several numbers arrived at by different means:

Mission Reliability
(a requirement)

An analysis of the mission requirements may dictate what the device reliability must be for the mission to be successful.

Inherent Reliability
(a property)

The highest achievable reliability with that design configuration, materials and components under ideal circumstances.

Predicted Reliability
(an estimate by analysis)

Reliability is estimated by applying accepted rules, such as part count method, published failure rate data for components, historical reliability of similar devices/components, and preliminary laboratory test results.

Achieved Reliability
(historical evidence)

Analysis of failure rate data for similar devices which are in actual use provides a more precise estimate of true reliability. Field tracking is important for many reasons, one of which is that it improves the accuracy of the reliability prediction methods.

All of these measures play an important role in the assessment and achievement of the programs reliability goals. These are even more effectively realized by a consciously applied program of reliability growth, which entails a program of accelerated life testing designed to force out potentially weak points during development, an aggressive analysis of all failures, a determination of root causes and implementation of corrective actions.

The specification and achievement of reliability and safety goals cannot be left to happen by accident. These goals must be reflected in the product specification along with the development of a program plan for achieving these objectives during design.

5. The Reliability/Safety Program Plan

Individual program plans must be developed which detail the specific approach necessary to achieve the reliability and safe design goals. The attainment of high reliability is a multi-faceted issue which involves far more than the use of simple reliability prediction schemes. Reliability can be affected by actions taken in design, manufacture, field use, and maintenance, which covers the entire product life cycle. Device reliability must be addressed during the design phase by considering not only the inherent reliability of the device in the laboratory but also the ease of producibility in manufacturing and ease of maintenance in the field. Field use factors include the influence of the environment in which the device will be used and the skill levels of those who will be expected to operate and service the product.

Reliability prediction schemes will often yield optimistic estimates of reliability. They may not account for the pitfalls inherent in the application of a new technology or even the application of a mature technology in a new or different design context. Since hidden problems are always uncovered in the field, this suggests that an appropriate test program can be of great value in forcing potential problems to appear while the product is still under control of the designer.

A key requirement in any test plan is the definition of a failure and the incorporation of methods to detect the associated degradation of performance. The reliability program planner must take this into account to insure the effectiveness of the reliability test program.

The safe design program plan requires similar attention. Utilizing the results of the systems hazards analysis, the design approach must be considered for the best methods for mitigating or preventing the hazard. Microprocessor based systems may make use of various kinds of fault detection methods, including self-initiated tests or built-in diagnostics to detect, alarm and send the control into a pre-defined failsafe state. At the low end, simpler forms of redundancy and operator-initiated tests may also be employed. If the device is classified by the FDA as a critical device then any component whose unsafe failure can not be easily detected must be specified as a critical component and a high degree of control over the part quality and the vendor who supplies that part is then required.

Design complexity tends to reduce reliability and the additional circuity and design effort required to create a fault tolerant system adds complexity. Consequently, the reliability of the system must be maximized within the constraints of the safe design approach. Safety always comes first.

The Safe Design program plan must also include steps to check the design as it evolves to assure that the design approach can be expected to achieve its objective with respect to safety. Normally this involves analytical methods such as Failure Modes and Effects Analysis (FMEA), in certain instances Sneak Path Circuit Analysis (SNEAKS), and when applicable, software validation, all to assure the effectiveness of the safe design approach.

6. Vendor Selection and Qualification

The vendor of a component or even an entire system plays an important role in the development process. Many shades of vendor-manufacturer relationships exist in practice. Regardless of how amicable the relationship promises to be or has been in the past, documented specifications must form the cornerstone of this relationship. The documentation must specify all quantifiable parameters such as:

- Performance criteria
- Reliability requirements
- Quality release/acceptance criteria
- Test requirements including method and test equipment
- Special shipping and handling
- Notification prior to material or process changes
- Identification of critical components, processes, etc.

This specification is usually made part of the overall contract which generates the

procurement. If the component or product is critical, the vendor must be made to understand his role and obligations as a supplier of critical materials.

The manufacturer/user must also have in place, a quality control organization which plays an ongoing role in the maintenance of this important relationship. Some manufacturers of commercial products (such as Motorola, for example) are requiring all of their vendors to compete for National Quality recognition awards such as the Malcom Baldridge award, in order to be even considered as a supplier. Obviously the size of the procurement has a lot to do with the manufacturer's ability to impose such requirements. Small manufacturers can, however, take advantage of this quality awareness trend by dealing with recognized vendors and suppliers where possible. An alternative tactic is to give preference to vendors which supply military grade components and are familiar with the military specification and procurement system. Of course, the customer must have some knowledge of this system also. Far too many avoidable differences between manufacturer and supplier/vendor arise in the form of contract non-performance allegations. Usually both are guilty of failing somewhere during the procurement process.

When the procurement involves selecting a vendor to convert a design concept into a finished product, a classic failing is a tendency to treat such an effort as a simple product development program. In fact, there may be a significant amount of research required to adapt a technology which best meets the products functional requirements. This is due in part to the fact that companies, while encouraging the entrepreneurial spirit, are reluctant to appropriate funds which do not result in a product with immediate market potential. Marketing funds engineering to develop products they can sell, not to do research. Overcoming the inevitable snags invariably results in a joining of scientific talents between the procurer and vendor which ultimately permits each to deny the authorship of the design when the product performs poorly in the market place.

Interestingly, failure to resolve unique technical problems completely before the design is accepted is never recognized as the central issue responsible for the recall of a product from the marketplace. Instead, more easily challenged issues of quality, workmanship, and product performance are substituted into the ensuing quarrel between vendor and procurer.

Two other problem areas may also result in expensive field corrections. The first is vendor-initated changes in materials and in processes which does not effect the component by their criteria but makes the part inappropriate for the medical system in which it is being used. Test methods is a second source of problems. When a part, component or system undergoes qualification by test, it is likely that both the vendor and the procurer will repeat this test on their own at some point in time. One way to guarantee different results is for each to use a different test method.

Vendor selection and control is one of the more challenging management problems which arise in medical device development and when it involves the procurement of a complete device or system, it takes on some really serious proportions.

7. Reliability, Engineering Prediction/Testing

Every development effort should have a design assurance function charged with the responsibility for reliability and knowledgeable and practiced in its application. The function should appear on the company's organizational chart and report to at least the Vice President level in parallel with the engineering function to give it separate authority.

Depending on the company's organization, the function may be called Reliability and Safety Engineering, Design Assurance, or it might fall into the Quality Assurance organization. Whatever it may be called, this group has the responsibility for assessing the reliability of the system. This may be done by utilizing published data, similar device history, supplier reliability data, and prediction algorithms. In some uncertain areas of the design, adequate data simply may not exist. Uncertain areas include: the application of unfamiliar technology or design principles and the adaption of cutting edge technology. All raise a red flag with the banner: Test-Test-Test.

Systems can often be decoupled into subsystems for special parallel testing. Isolating an uncertain area to test as a subsystem requires that designers must take this into account early in design and actually construct examples which can be placed on test under conditions of load or stress which simulate the operating environment. Defining how these tests will be performed in order to yield as much life data as possible is a primary objective of the reliability discipline.

8. Failure Modes and Effects Analysis (FMEA)

Several different kinds of analyses can be performed to evaluate the consequences of equipment failure or misoperation. The most common of these are Fault Tree Analysis (FTA), Sneak Path Circuit Analysis (SNEAKS) and Failure Modes and Effects Analysis (FMEA). Each varies in advantage and degree of difficulty.

The approach most often used is FMEA or one of its slightly different variations. The concept is simple and it can be applied at almost any level from the high order system down to an isolated circuit. In order for the results to be reliable, the entire system must first exist in the form of design drawings and specified parts and materials. All design changes, after the FMEA is performed, must be verified by updating the FMEA to reflect the effect of these changes.

In order to perform a FMEA, all of the possible failure modes for each component must be known or determined in some fashion. Examples of failure modes are valves which fail either open or closed, electrical resistors which fail open, a microcompressor address location bit stuck high or low, or sensors which can drift out of calibration. Also, all electronic component failures are assumed to be random and statistically independent. A typical FMEA worksheet is shown in Figure 3. Each component is listed in columnar fashion and in the adjacent Failure Modes column the known failure modes are listed. The analysis involves tracing each component and associated failure mode through the design to determine the effect which that component's failure mode would have on the function of the system. This determination must be made for each single failure mode. The analysis is limited to single failure modes because of the enormous effort required to trace through and determine the effect of multiple simultaneous failures. For example, if A and B are two failure modes, failures of A or B alone may have no undesirable effect especially if each failure

FIGURE 3
FMEA WORK SHEET EXAMPLE

COMPONENT	FAILURE MODE	EFFECT	ANALYSIS
R32 Pull up (Resistor)	open	Partial loss of data display segments	Continues to operate at last setting - rate of operation not affected - display flashes, will not permit continued use without repair - failure disables critical function but fails safe with alarm
R16	Open	Could cause motor speed to change (increase)	Motor speed changes - display data does not change - disables critical function - motor speed change is detected by software system operation stops with audible and visual alarms - system fails safe
C22	Short	Effects control of line voltage fluctuations	Sensitizes system to voltage fluctuation; could increase frequency of nuisance alarms - condition is safe - can be corrected during routing service
Timer (Watch Dog)	No Signal	No signal is sent to reset watch dog timer	Watch dog must operate or system will fail to reset for continued operation - microprocessor will retry 3 times on mis-compare; processor stops operation and alarms - no restart possible - safe failure, repair required

is detectable. However, if A and B both fail simultaneously, it is possible that the combined effect could be undetectable and also unsafe.

Since the number of single failures is always smaller than the combined number of all multiple failure combinations, it would seem that FMEA accomplishes very little in the way of a comprehensive analysis of effects. The reason this is not true, however, is simple: the individual failure probability of a component is very small, and consequently the simultaneous failure of two such components is statistically remote under normal operating conditions. If designed to be fault tolerant, the system's self diagnostics will detect A or B before another random failure can occur. If the system itself can not detect and respond to such failures, alternative means of periodically checking the correct operation of the system must be incorporated.

In order to assure accurate conclusions, the person performing the FMEA analysis must know, in detail, how the system is to operate. Before microprocessors were in use, the analysis need concentrate only on the hard-wired electronic component portions of a control circuit. It is now common practice, however, to invest much of the design effort in the development of a software program which is incorporated in the integrated circuit in the form of a small microprocessor chip.

The microprocessor has considerably increased the power of the electronics to control the process and assure its safe operation. The hardware circuitry design and the software design is usually done by more than one person. Consequently, if the design is moderately complex, the FMEA requires collaboration between these design engineers.

As the theoretical failure modes are systematically imposed on each of the components the design is traced through to determine the effect of this failure mode. It is at this point where the previously performed System Hazards Analysis again plays an important role. Originally performed to determine the hazards inherent in operating the device and establishing the safe design goals, the failure effects are now systematically examined with regard to how well the designer has achieved his objective of avoiding failures which could cause the operation of the system to become unsafe.

In the event that the designers' best efforts still permit isolated fail-unsafe conditions which cannot be further eliminated, then other strategies such as redundancy, operator-initiated test, and periodic maintenance must be incorporated to assure maximum safe operation. In all cases, vulnerable components must be classified and managed as critical components.

9. Design Reviews

In a complex product development program there are many technical disciplines involved:

software engineering
electrical/mechanical engineering
reliability/safety/quality engineering
materials technology
manufacturing/packaging engineering
marketing/sales

and when the product is a medical device we must add:

label copy review staff
medical staff
regulatory affairs
legal department

In varying degree, all of these functions have a role in the product development cycle beginning with the Requirements Definition or Product Specification.

The Design Review process is a formalized opportunity for all of these functions to review the progress of the design and deliberate issues arising during the course of development. Design review meetings must be planned and prepared for in advance. The responsibility for the orchestration and conduct of the meeting typically falls to the program manager and reliability engineer since the net result of such reviews is to assure that reliability and safety design goals are being met as well as those which include performance and schedule. Formal design reviews are conducted at least at the beginning of the program and near the end when the product design nears completion.

Design reviews must be documented in order to preserve the rationale for design/redesign decisions made over the course of development. This documentation should be made part of the Device Master Record, a necessary element of the FDA's requirement for recording the essential details of the evolving design.

Design reviews are conducted at strategic points throughout the development program. A typical program should allow for at least three design reviews:

1. Preliminary Design Review
2. Intermediate Design Review
3. Final Design Review

In addition, there may be several informal design reviews which are confined to the engineering and technical functions to review issues related to software/hardware integration, reliability testing, design iteration, clinical protocols, and other topics as may arise throughout the program.

A method of recording the proceedings of formal design reviews is important. A summary of action items is distilled from the proceedings and circulated to all those who have an active interest and role in the development effort. The design review also serves another important function; today's corporations are highly turbulent environments. A lengthy development program could have numerous changes of key personnel before its completion. Although not a solution, the documented design review does buffer this all too often unfortunate restive corporate syndrome.

10. Design Execution

Eventually, the paper design must take the form of operating hardware. Naturally, the designed function must follow that intended on paper, and by the time the product reaches this stage its performance characteristics are reasonably well known through laboratory test and evaluation.

The Design Execution study provides the development engineers with an opportunity to examine the product for a different type of failure which will not show up in a FMEA. If, for example, a sensor is located such that it can sense the presence of a tubing segment to assure that it is in a physical location where it can be pinched closed by a safety clamp when triggered, then the security of the sensor location must also be guaranteed. Attaching the sensor within the physical configuration of

the device by any means which could cause the product to become unsafe should the sensor become detached, will deceive the instrument into a false assumption that the tubing is still within control of the safety clamp. This is obviously a problem associated with converting the safe design requirement from paper into the physical hardware.

The quality of design execution may also be verified by the application of physical stresses, such as temperature cycling and vibration. Such testing is designed to show up any weakness in the way the product is put together by forcing failures to occur. While similar to certain tests involved in the validation of the product's environmental resistance, this type of stress testing is much more abusive to the product and in some respects runs parallel to the objectives of accelerated life testing. As with any testing of this kind, a program to analyze and correct the origin of such failures is necessary to assure that the testing results in improved product reliability.

11. Design Freeze

During every product development, the design undergoes changes to improve its function, performance, and reliability. These design changes occur more frequently early in the program and are generally made during a period of volatile engineering activity. Ultimately, however, this somewhat informal process becomes counter-productive due to the number of prototypes which clutter the laboratory, the rudimentary condition of the documentation, and the accumulating complexity of the design details.

At this point, the design should be frozen, which is to say that the design drawings, product specification, software, and all associated documents are assigned to a document control center. Changes to the design can then only be made by issuing an engineering change notice (ECN) which must be circulated for review and approval. On approval, the change is entered on the design drawings and the revision block on the drawing is appropriately annotated. Once the product is in production, the changes must be transmitted to the manufacturing plant to be incorporated into the production process.

Controlling the product design in this manner is referred to as configuration control. It becomes especially important in the manufacture of medical devices since it provides traceability to changes during manufacture by linking the design change to the serial number of the device itself.

This information may become an important key to the understanding of the origin of some product failures which occur while in use. The medical device system must include the post-design freeze changes in the **D**evice **M**aster **R**ecord and **D**evice **H**istory **R**ecord in order to be in compliance with the good manufacturing practices (GMP) specified by the Food and Drug Administration. Recalls are often conditioned by bracketing the affected products design configuration by serial number.

12. Fault Simulation

The system hazards analysis establishes the safe design goals. The safety program plan establishes the safe design approach, and the FMEA checks the effectiveness of the safe design approach. These techniques are primarily paper studies. Fault simulation is a procedure which is performed on hardware, usually a pilot production unit. Faults are selectively introduced into the actual operating system in order to verify the predicted failsafe response of the device.

It is almost never possible to simulate physically all of the fault conditions which are theoretically studied during the FMEA process. Consequently, they must be intelligently selected to yield the kind of assurances that this kind of testing intends.

13. Environmental Stress Testing

All products must live in an environment which places a certain level of stress on its operation and survival. While related to the qualification test of the product to properly function in the extremes of its environment, stress testing plays a more fundamental role in product development. By designing to even more stringent environments than the product can ever reasonably expect to be exposed, the designer can build in an extra measure of resilience which will assure failure-free operation under normal circumstances.

In a similar manner stress testing can be used to force out early failures due to weak components or latent manufacturing defects. In some instances environmental stress may be added to an accelerated life test. There are in fact numerous ways in which environmental stress testing can be incorporated in the development program. The objective is always the same, however, regardless of the stress factor, its level of severity or its combined use with other tests. That is to locate and strengthen any aspect of the product design which shows susceptibility to premature failure.

The normal operating environment is the source of a variety of failure precipitating stresses: temperature, pressure, humidity, electromagnetic radiation, vibration, and corrosive elements. Stress testing involves the controlled application of these stressors either singly or in combination, and measuring their effects on the product's performance. The use of such testing almost always must be customized to the specific product and the general class of failure phenomenon which are under investigation. Products may be "soaked" for a period of time at high temperature or cycled between high and low extremes to produce thermal shock. Each may reveal a different form of latent defects.

If the failure produced is permanent, the device may simply be examined after the test is complete. Analyzing intermittent failures is more difficult and may require that the product be operated and monitored during the stress testing.

When stress testing is used to "proof test" the product, that is, to demonstrate its robust qualities without producing failure, the levels must be carefully selected so as not to weaken the product or use up any of its available useful life.

14. Product Specifications Compliance Testing

Before full-scale production begins, the product, representative of the production methods to be used and the latest design configuration, should undergo a comprehensive test and evaluation to assure that it meets the current version of the product specification. Some of the development testing may be sufficient to satisfy some of the requirements for specification compliance. However, many other tests such as splash resistance, EMI/RFI protection, cleanability, maintainability, etc., are best performed on a pilot production unit.

Since many medical hardware devices have electronic control systems which utilize microprocessors, the validation of the software logic becomes an important aspect of

specification compliance testing. This is an area which calls for the application of skills involving both test and analysis. Due to its complexity and history of overlooked software logic errors, the FDA is giving software validation high priority.

The results of specification compliance testing is an item which must be considered during the final design review process. Variances between the specification and actual product must be reconciled before full-scale production can begin.

Conceptually, production should not begin until after the Final Design Review (FDR). It is sometimes impossible to treat the final design review as the simple event which triggers full-scale production because of the demands of the factory to remain productive. The company may choose to risk a possible rework of manufactured product by beginning production before the specification compliance testing has been reviewed and signed off during the FDR. If production begins before the FDR, accumulated product must be quarantined in a holding area while waiting for authorization to release.

As can be imagined, the pressures which are involved in this process are enormous and strong management control is required to avoid the release of product which may not be quite ready for the market place, an action which could result in regulatory sanctions.

15. Market/Clinical Evaluations

In order to conduct market or clinical evaluations, the company must have product available. Every medical device manufacturer must deal with the problem of initially producing a limited number of devices which are representative of those which would be produced by full-scale production. These "limited edition" devices are distributed to strategic market accounts or to clinical investigators to gain further information about the use and acceptance of the device before committing the full resources of manufacturing to its production. This inevitably places great stress on the marketing and engineering functions within the company.

Marketing wants the evaluations to begin as soon as possible; after all, the competition is usually not far behind. Engineering almost always believes the product is not ready and would have to be released lacking certain performance/reliability validation studies. Engineering eventually agrees to complete the final details concurrent with field trails, and everyone agrees that the information returned from the field evaluation will offset the disadvantages inherent in releasing the product too soon.

The two major problems which always make field evaluation decisions difficult are:

1. Someone, usually manufacturing, must produce a limited number of product without turning on production all the way; and
2. The Final Design Review which issues the final go ahead, having been convinced of the safety and efficacy of the product, must occur before the product is produced - that is, after the engineers have completed all of their design studies.

The only practical solution to this situation is to hold two final design reviews; the first to review the design status of the product with a conditional approval to produce and release for evaluation, the second after the evaluation is complete and suggested design changes have been incorporated and validated by engineering. There is an advantage in that the second final design review benefits from having the results of field trials available for review. If field evaluations and design changes occur more than once at this point, it is usually the first indication that the future of the product is in serious technical trouble.

Often companies fail, or refuse to recognize, that the product development effort may entail a significant amount of research, that the solutions to certain key aspects of the product design may not be fully known at the outset. The schedule is therefore drawn around too much marketing desire and too little engineering reality. Technical failures during marketing or clinical trials usually follow, accompanied by a few ambitious careers. When these problems occur, it takes a strong and wise management to revise a new schedule and invoke the discipline and rigor necessary to evolve the product to a successful outcome.

There is also another vulnerable point in the life cycle of medical products. Post-market introduction engineering changes usually do not receive as much critical attention as during design. Product improvements and other later changes are often made later by engineers and others who were not part of the original development team. There are other factors as well but the net effect is that the control over the engineering change tends to be less rigorous, accompanied by less testing, less analysis, and less attention to detail when the corporate eye is not riveted on the product's initial success or failure. The result can be a costly recall.

16. In-Process QC Test and Inspection

It is a required practice in all medical device manufacturing facilities to perform a quality inspection of component parts as they are received. From this point they are sent to the work stations where they are assembled into the product. In the process of using these components, some form of fabrication must be employed.

At each stage of assembly the operations are performed in accordance with a manufacturing specification. In order to assure that these operations have been carried out satisfactorily at each stage, the product of that work station is checked by an in-process quality control (QC) inspection or test procedure. If the QC inspection requires the use of standard measuring devices then each device must be placed on a calibration schedule which periodically assures its accuracy.

An in-process QC routing sheet follows the product throughout the assembly process. This sheet certifies that each assembly has passed the QC examination at that point. It is stamped and signed by the QC inspector for that operation. These in-process QC sheets become part of the device history record and are filed at the facility under the serial number of the device with which they are associated.

It is not uncommon for manufacturing process methods to be changed in response to field failures, indirectly pointing to manufacturing or design deficiencies. In addition to the in-process QC inspection/test procedures which are product specific, most manufacturing organizations will have a set of workmanship standards which address assembly/fabrication/finish operations which are common to all products.

FDA inspectors are especially sensitive to the possibility that components or subassemblies which have been removed from

the production lines for scrap or rework might find their way back into the assembly line before being discarded or reworked. The methods by which the plants handle this detail must be as nearly foolproof as possible. Documented methods by which scrap and rework is managed during production is essential.

17. Final QC Test, Inspection, and Release of Product

Both the manufacturing and the design engineers collaborate on the development of a final test and inspection protocol or checklist which the product must pass before it can be released. This checklist is again product specific and may include some mild environmental stressing such as burn in, power on/off cycling, vibration, and temperature cycling. Finish, decals, labels, and general workmanship are always included. In some instances a brief test simulating use may be prescribed before the product is ready for release. Proper packaging and the inclusions of instructions for use must be verified.

The final QC Test department is the first customer for the product and can be helpful in feeding back beneficial product improvement data both to manufacturing and design engineers. As with the in-process QC sheets, the final QC records also become part of the device history file. Looking through these records will usually reveal if the birth of this specific product serial number was difficult or routine and uneventful since they must contain all pass/fail/rework information by product serial number.

VI. TYPICAL PROBLEM AREAS

Several areas of development do not fall neatly into the time line of the development process. They do, however, figure prominently into the Quality Reliability and Safety of the final product. These areas are:

1. designation of a central program authority
2. designing for manufacturability
3. designing for servicability
4. compatibility assurance with other components and systems
5. design assurance of post-market engineering changes
6. quality assurance of field service actions

1. Designation of a Central Program Authority

The military refers to this person as the System Program Officer or, in the parlance of the military, the SPO. Development of products in the private sector often lacks a similar, well defined, central program authority. The person designated for this role must be highly placed and familiar with the company, its operation and its products. Properly selected, this central authority will be knowledgeable of all of the primary disciplines involved and unbiased with respect to each.

2. Designing for Manufacturability

Designing a product to work and designing it to be producible are separate problems which must be considered together. Sometimes the designers best efforts at designing for reliability and safety can be undone in the manufacturing process. It also makes simple economic sense to address the issue because ease of manufacture not only assures a more reliable and consistent result, it also yields lower production costs and a more competitive product.

In order to accomplish this a manufacturing expert must be a member of the design team to plan production methods and influence the physical structure of the design to make it compatible with these methods.

3. Designing for Serviceability

Maintainability is a recognized part of product reliability. Every product which requires periodic service should be designed in a manner which minimizes the time required for maintenance actions and assures a consistent and correct result. Many service operations which were initially performed in the factory, perhaps by an automated method or process, must be done by hand. Skill on the part of the service man will always be required. However, the easier it is for him to service the product, the higher the quality of the resulting repair will also be.

4. Assuring Compatibility with Other Components and Systems

When products are required to interface with a variety of other components or systems the variables involved in the nature of this interface must be identified along with a strategy for their control. Two conditions are most often present:

1. the product incorporates hardware, a disposable element and perhaps other connected components all of which are designed and produced by the same manufacturer, and
2. the product must interface with other products designed and produced by another company.

Obviously, a medical device designer has more control over his own product than those of others. However, each interface deserves special attention to assure that design and procedural strategies are devised to yield a product system which will perform reliably and safely. The design must attempt to control or compensate for possible variations in the interface parameters and, where it cannot, consideration should be given to the development of instructions which appropriately cover these circumstances of use.

Connected components, especially those of a disposable nature, are often the product of a manufacturing process which requires good process control. Since process control limits are also related to the performance of the system, the product must be designed to accommodate these variations as they manifest themselves in the resulting system.

5. Design Assurance of Post-Market Engineering Changes

Field experience often suggests design changes in the product after it has been approved and marketed. Unless a serious problem arises, the changes are considered to be routine improvements. The original frantic team activity has long abated and key designers may be gone or on to other assignments. Therefore, the routine engineering change falls to a junior engineer who may not have even been part of the original development effort. The nonchalance often present when making routine changes in products which are regarded as mature provides the stage upon which a major disaster may occur. Moreover, even when changes are more than just routine, companies are motivated to defend them as routine lest the entire FDA submission process be set into motion all over again.

Companies may argue to the FDA that certain product changes do not change the essential nature of the product due to its similarity to other existing products of their own or other companies manufacture. The success of this argument lessens the de-

gree of effort involved in validating the product change and permits getting into the market faster. The argument may even be a legitimate one. However this should not preclude taking the time to fully validate engineering changes in the mature product.

6. Assuring the Quality of Field Service Actions

The need for quality assurance in manufacturing is well recognized. This same need, however, is not fully appreciated when it comes to field service actions. Field service is actually a mini-manufacturing process without benefit of automation. Many, if not all, operations are performed by hand with a skill which may not be generally prevalent on the floor of the manufacturing plant. Service men are engineering technicians, it might be argued, not your usual assemblers found on the production line. None the less, published procedures and workmanship standards must be on the shelf of the service facility and standard operating procedures (SOPS) followed in order to assure a uniform quality of repair.

An especially critical procedure is that of calibration. Often, special fixtures and instrumentation are used in the factory. Field servicemen, however, are left to improvise a method of calibration which will hopefully achieve the same results.

When a field problem involving performance reaches such proportions that everyone becomes involved in searching for its source, discrepancies in calibration methods can usually be found. This sometimes takes a curious twist when customers undertake to verify certain calibrated parameters on their own and are unable to duplicate the published performance data. Their first complaint is often to a sales or marketing person whose next response is to call in field service. Consequently the methods which the service engineers employ, and the quality of their workmanship, is important to the success of the product in the market place.

VII. CONCLUSIONS

The primary focus of this discussion about medical devices has been on the design and development activities required to bring these products to the point where they can be turned over to manufacturing. All medical device designers and manufacturers are required to register their facility with the Food and Drug Administration. As a registered facility they are subject to the Good Manufacturing Practice (GMP) regulations as set forth by the FDA.

The historical objectives of these regulations were to introduce controls over the manufacturing process which would assure the "safety and efficacy" of the product. These objectives are still true; however, many product failures have been traced back to deficiencies of design or manufacturing. These are, of course, most vexing to the FDA and the manufacturer alike because all of the product which has been released to the field is affected and must be recalled.

Furthermore, when the correction cannot be phased in as part of a field retrofit program, the products removed from service usually cannot be replaced from available inventory since that, too, must be quarantined.

The FDA requires prompt action on the part of the manufacturer. The FDA is placed in an awkward position on occasion, if forced removal of medical devices works greater hardship on the patient population than the risk itself imposes. The FDA is suspected also of treading a little more lightly when dealing with smaller firms because they are disinclined to be in part responsible for the financial ruin of a company with smaller reserves.

The design side of medical device development invites more interesting discussion than the manufacturing side because of the challenge involved in standardizing this process.

It may never be possible to specify an approach to a particular design because there is always more than one "correct" solution. It is possible, however, to specify the elements of a correct design process. This is what has been attempted here in a manner which avoids getting mired in the technical detail which must be present in all product development programs.

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ELECTROMAGNETIC INTERFERENCE AND ELECTROSTATIC DISCHARGE TESTING ON MEDICAL PRODUCTS: INTRODUCTION

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INTRODUCTION

There is a class of product or process failures which are particularly elusive. They are transitory, often leave no evidence, and testing never reveals any hardware problems.[1, 2] Sometimes operator error is mistakenly suspected. Sometimes other equipment subject to the same environment also exhibits erratic behavior.

Transient failures which cannot be traced to hardware faults or operator error by usual investigative techniques are often caused by an environmental effect called electromagnetic interference (EMI). Some examples of typical EMI problems include the following:

1. In the early 1980's there were many reports in the medical literature of erratic performance of implanted cardiac pacemakers due to interfering signals emitted from industrial and consumer microprocessor controlled devices such as microwave ovens, television sets, elevators and library security systems. Perhaps the most memorable is that of the consumer who complained to the FDA that the automatic cruise control in his new automobile caused his pacemaker to function erratically.[3]

2. Recent accounts[4] have been given of electromagnetic compatibility problems with certain U.S. Army aircraft, despite the often exaggerated accounts of exemplary performance during the invasion of Panama and the Persian Gulf War. Most notable are those that involve the Apache and Black Hawk Helicopter Programs. Apparently the susceptibility of electronic governor circuitry to low level emitters such as commercial microwave, television and airport radar has resulted in the triggering of an overspeed condition and subsequent double engine destruction. Other reported areas of susceptibility for these aircraft include uncommanded stabilator movement, automatic flight control system irregularities, and anomalous uncontrolled operation of vertical instrumentation display systems, AC and DC power systems, fire detector systems, blade de-icer system, command instrument system, as well as other systems.

3. Anne Scully, who lives in Hull, Massachusetts, reports that she can hear nearby WBZ's 50 Kw transmitter broadcasting through her radiator. Things are even worse for her neighbors, who claim they can hear "Maynard in the Morning," broadcasting from their toilets. Powerful transmissions are apparently exciting conductive structures and producing audible signals through audio rectification. The trials of Ms. Scully have been covered by the New York Times (Jan. 17, 1988) and Microwave News (Jan/Feb 1988).[5]

4. There are many examples of the hazards of electromagnetic radiation to ordnance or explosives. Here the problem manifests itself not by inadvertently jamming or causing disturbance to a receivers information output but rather by sufficiently high ambient electromagnetic energies to ignite ordnance devices. Ordnance devices, which are triggered electrically are known as electro-explosive devices (EED) or squibs. They may be used to actuate switches, to separate fastenings between structures, to set off blasting explosives or to ignite explosive rocket motors. Because of the violent consequences either of failure to operate or premature operation, the susceptibility of such devices to electromagnetic influences, is a serious concern. Consider for example the military fighter aircraft pilot on approach to landing who tunes his communications radio to the local control tower frequency and keys his microphone. At that point the carrier signal emitted by his transmitter triggers the ordnance device attached to his ejection seat and he is immediately and without warning separated from his airplane. Incidents of this type were fairly common in the 1950's and instrumental in the development of some of the current electromagnetic compatibility standards.

What characteristics do all of the above examples have in common? For one thing they all represent unexpected electromagnetic energy being coupled from a source (emitter) to a susceptible receiver. For another, they are generally transient in nature and not easily repeatable unless conditions are exactly right. For this reason they often go unrecognized and are attributed to a "bug" or "glitch" etc. Quite often a user will be blamed rather than an electronic circuit because when the device is examined under "normal" circumstances, it performs flawlessly.

HISTORY

EMI testing arose as a result of World War II and the recognition of the fact that the detonation of nuclear weapons creates very strong electromagnetic fields that can instantly disable electronic equipment hundreds of miles away. Radar was also found to cause localized disturbances. It was necessary to develop theories on how electromagnetic fields propagated from these devices and how they caused equipment malfunctions.

In the early 1970's it was recognized that the same theories developed in World War II could be applied to the problems of localized disturbances which affected computers and televisions. There were complaints by the public that television reception was being interfered with by CB radios, computers, vacuum cleaners and a large variety of other devices. The broadcasting industry petitioned the FCC to regulate electronic equipment to reduce the levels of interference and provide for clear reception of programming. This was the beginning of large scale regulation of all electronic emitters whose frequencies were greater than 10 KHZ.

TESTING FOR EMI

There are two ways in which a specialized EMI testing laboratory can help. First, testing a device for EMI emissions before it goes into production allows design modifications necessary to meet all applicable standards. Agencies typically require regulation to acceptable levels of noise in the broadband and narrowband categories.

Second, testing the device for susceptibility to EMI radiated from other sources will help increase reliability by adding whatever protective measures may be necessary. The science of fortifying electrical equip-

ment against the effects of EMI interference is called susceptibility engineering.

Military Testing

The Department of Defense regulates EMI testing of military equipment. Testing in accordance with Military Standard 46IC[6] usually requires security clearances and is very intensive. Submission of data is very meticulous and detailed and the government may require special certification.

Medical Testing

Presently, testing of medical devices is voluntary and is covered by FDA Standard MDS-20I-0004[7], issued in 1979. Special testing expertise and equipment are required to do these tests. Although testing to MDS-20I- 0004 is not presently required by the FDA, it is highly recommended for the benefit of the end user. The testing is very specific to conditions that could arise in the field.

PREVENTING EMI AND ITS EFFECTS

A variety of techniques and standards have evolved to analyze EMI disturbances. Specialized antennas, spectrum analyzers and a host of other apparatus can measure simulated or actual EMI effects. Agencies such as the FCC and the European VDE organization routinely regulate commercial equipment. IEEE and ANSI have also written numerous protocols.

There are many sources of interference that can cause EMI problems, among them unshielded cables and PC board traces carrying high frequency clocks.

ESD

It has been found that electrostatic discharge (ESD) is a major source of factory and field failures. Preventive engineering using the appropriate shielding has been found to significantly reduce field complaints. New European requirements (IEC-80I)[8] require ESD testing. It is particularly important to perform this test on equipment as it is related to failsafe design.

Electrostatic discharge is one form of electrical interference which does produce hard failures traceable to a specific cause. Conditions for ESD are optimal when the weather is cold and dry. Walking across a carpet or sliding from a chair can produce a high surface potential which will discharge, usually through the hand or finger, to any other surface of lower potential. When this surface is the key pad of an electronic instrument the discharge, which can often be felt and seen as a spark, occurs near the point of contact. This discharge, which may be from ten to fifteen thousand volts, follows electrical pathways to components in the control and logic circuitry.

For the remainder of this paper I would like to focus on medical EMI and ESD testing.

NUISANCES DUE TO ESU MAGNETIC RADIATION

One of the primary sources of EMI in the hospital operating room is the electrosurgical unit (ESU) used to control bleeding during surgery. Until recently there was no reliable method to make equipment immune to ESU nuisance alarms. The inducement of alarms comes primarily from high near-field magnetic emissions in the operating room. To understand why please refer to Figure 1 which shows the derivation of the simple case of a magnetic loop. As can be seen, the equivalent electric field intensity of a magnetic loop increases in intensity by the square of loop radius. The RS-0I loop from Mil Std 46IC is commonly used as a reference for magnetic field calculations as shown for a simple example. Also shown is the Faraday Law by which interference voltage may be induced in the equipment through inductive means. The near/far field distance is easily calculated to be 1.59 meters at 30 MHz, hence all ESU emissions are considered near field. The electric field strength increases as the inverse square of distance and the magnetic field strength increases as the inverse cube of distance. It is therefore magnetic fields resulting from the long looping ESU wires that cause the greatest nuisance potential.

Figure 2 shows a power curve for a typical ESU (Valleylabs SSE2L). At peak power the current in the ESU wire is approximately one ampere but can be much higher if the load approaches a shorted condition. For effective cauterizing action the carrier is strongly modulated. The resulting magnetic field noise spectrum of this typical ESU is also shown in Figure 3.

If we assume a somewhat realistic loop diameter of one meter, an RF current of one ampere, a one turn loop, a one MHz interference frequency and distance to the equipment of one meter then the resultant field strength orthogonal to the loop is 47 V/m, which is well above MDS-20I guidelines. As an example, if we assume that an untuned four- inch diameter loop is inside the unprotected case of the victim receiver, then such a field could generate a broad band noise voltage of 5.6 millivolts RMS common mode on a susceptible sensor component.

In practice the power levels of older ESU's are much higher and the leads are draped much more closely in the cramped OR environment so that the apparent field effect is magnified greatly as the distance decreases to the equipment. If the equipment has a gain stage or multiturn inductor then the disturbance is also amplified. The ESU may be activated in several modes during procedures to perform cutting, fulgarization, dessication and coagulation each of which has a different modulation.

Measurements of critical biological parameters can be altered while the ESU is active through:

1. Magnetic coupling to inductors
2. Injection locking to oscillators
3. Noise induction onto the data lines causing alarm, and
4. Audio rectification in op amps or diodes in the equipment.

Since the ESU wires need to pass through sterile fields in the OR, they are close to infusion pumps and other devices, which in turn, are very close to the patient. Some hospitals mount the ESU in the ceiling or under the patient to minimize loop area and lead length and keep other equipment tangential to the loop which substantially reduces coupling. Biological signals measured while the ESU is active become "fuzzy" in appearance and amplitude modulation of signals is commonly observed. Effects observed in the laboratory include blinking display of biological indicators, and disrupted communications. ESU wires cannot be shielded because it would restrict surgeon mobility. The ESU is used during procedures to control bleeding and prevent tissue infection.

ESU CASE HISTORY

In an isolated complaint we investigated several years ago, a hospital indicated that

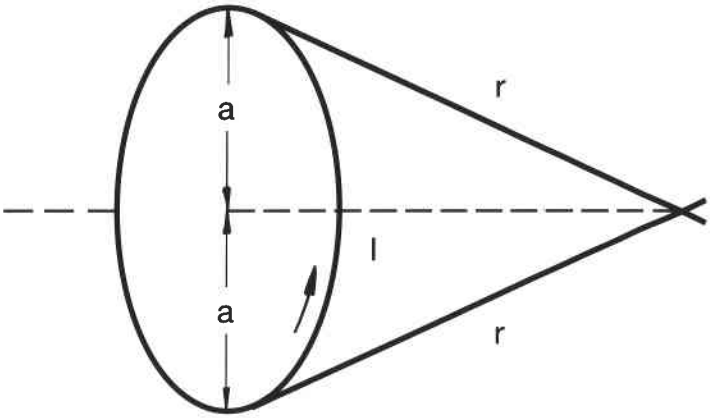
FIGURE 1
ESU LOOP MAGNETICS

- ***TERMS***

1 Tesla = 3×10^8 V/m = 289.5 dBuV/m
= 10^4 Gauss = 240 dBpT

- ***ELECTRIC FIELD STRENGTH EQUIVALENT, B Tesla***

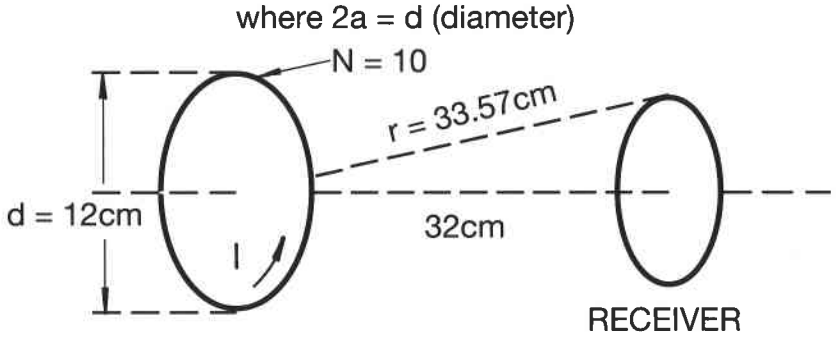
$B = \frac{Uo}{2} \times I \times \frac{a^2}{r^3}$, B in Tesla, a, r in meters, I in amps



- ***ELECTRIC FIELD STRENGTH EQUIVALENT, B VOLTS/METER***

$B\ (V/m) = 188.5 \times I \times \frac{a^2}{r^3}$

$= 47.12 \times I \times \frac{d^2}{r^3}$



- ***EXAMPLE RS-01 LOOP***

Assume r = 33.57 cm, d = 12 cm, N = 10, I = 1 AMP

$B\ (V/m) = \frac{47.12 \times 10 \times .12^2 \times 1}{(.3357)^3}$ = 179.35 V/m or 165 dBuV/m

- ***VICTIM RECEIVER NOISE VOLTAGE (FARADAY'S)***

$E = 4.44 \times f \times B \times A \times 10^{-8}$

where A = loop area, sq cm
f = frequency, Hz
B = Field Strength, Gauss
E = Open Circuit Voltage

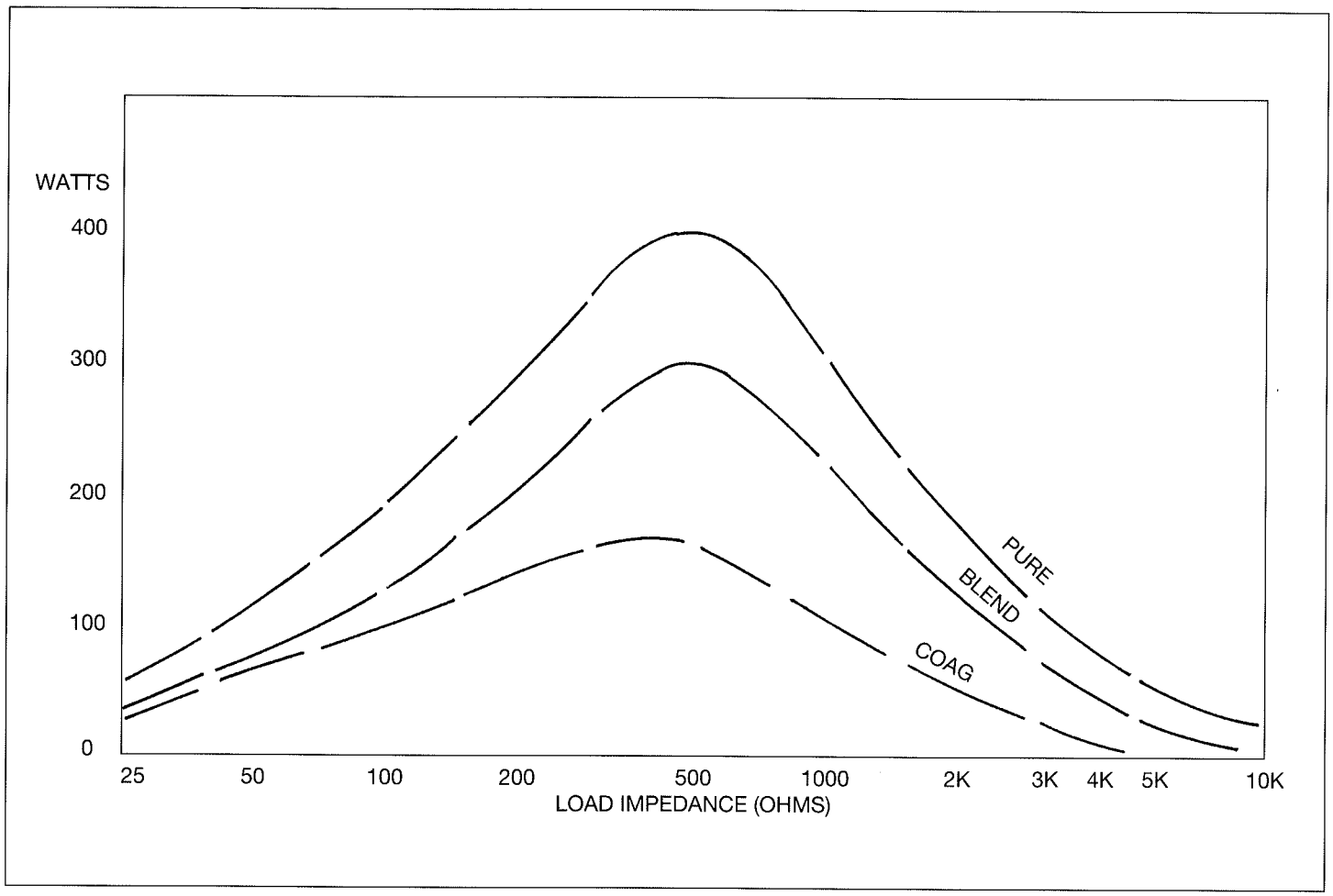


Figure 2. Typical Output Impedance Curves

a Bovi CSV electrosurgical unit had caused nuisance occlusion alarms in an infusion pump in the OR during open heart surgery.[9] By watching the procedure we noted the wires were draped through sterile fields directly behind the infusion pump with the return lead draped to the floor. This condition was seen to present maximum coupling for magnetic flux into the pump and its sensors. In a brief study we found that in the extreme the Bovi could injection lock the occlusion sensor of the pump and simulate an occlusion if we placed a four-turn 9 cm. loop of ESU wire directly upon the front panel and also could induce an air sensor alarm using the same method. (Please note that draping of an ESU wire in front of the front panel of any medical device is a highly unusual procedure).

Although we could not economically change the design to suit the circumstances in this hospital, we recommended a change in the Bovi orientation which lessened the nuisance potential. In a subsequent design the sensitive exposed sensors were redesigned to a higher frequency with improved circuit "Q" factor and moved inside a protective EMI case which further reduced the interference potential.

This case study also caused our company to adopt a strategy of standardly testing against ESU's during qualification testing of new medical devices. Because ESU's are common to the hospital environment and emit intense near-field radiation, a second strategy used was to design medical equipment robustly from an EMI standpoint to the rear of the enclosure. The problem of ESU interference is compounded because different proprietary cut/blend techniques, atmospheric conditions and humidity, power levels and frequencies are employed and the equipment is expensive to purchase from a test standpoint. Our criterion of acceptance is safe failure with alarm and ideally no degradation. Because magnetic fields are present in many other biological measurements (MRI machines), we also standardly test to Mil Std 461, RS0l and use an eleven-inch diameter Helmholtz coil pair to generate a 60Hz field of 145 microtesla for simulation purposes. Large static magnetic fields are produced by MRI machines that may cause mechanical movement of iron-based sensor components causing nuisance alarms.

WIRELESS COMMUNICATIONS

Many manufacturers are now introducing ambitious and economical wireless products into hospitals. Because UL testing limits 60Hz leakage current severely in patient-connected equipment, the wireless method would look attractive for monitoring and feedback purposes. Unfortunately electrical interference is a significant problem to be overcome. In the latest EMC record[10,11] some McGill University researchers performed site surveys at several hospitals in Canada and found a peak level of interference of 135 dBuV/m and recommended mandatory compliance with the FDA specification. Since interference cannot be reduced, either power levels must be raised, bandwidths reduced, or special modulation and decoding techniques employed. Some manufacturers are employing microwave frequencies for communi-

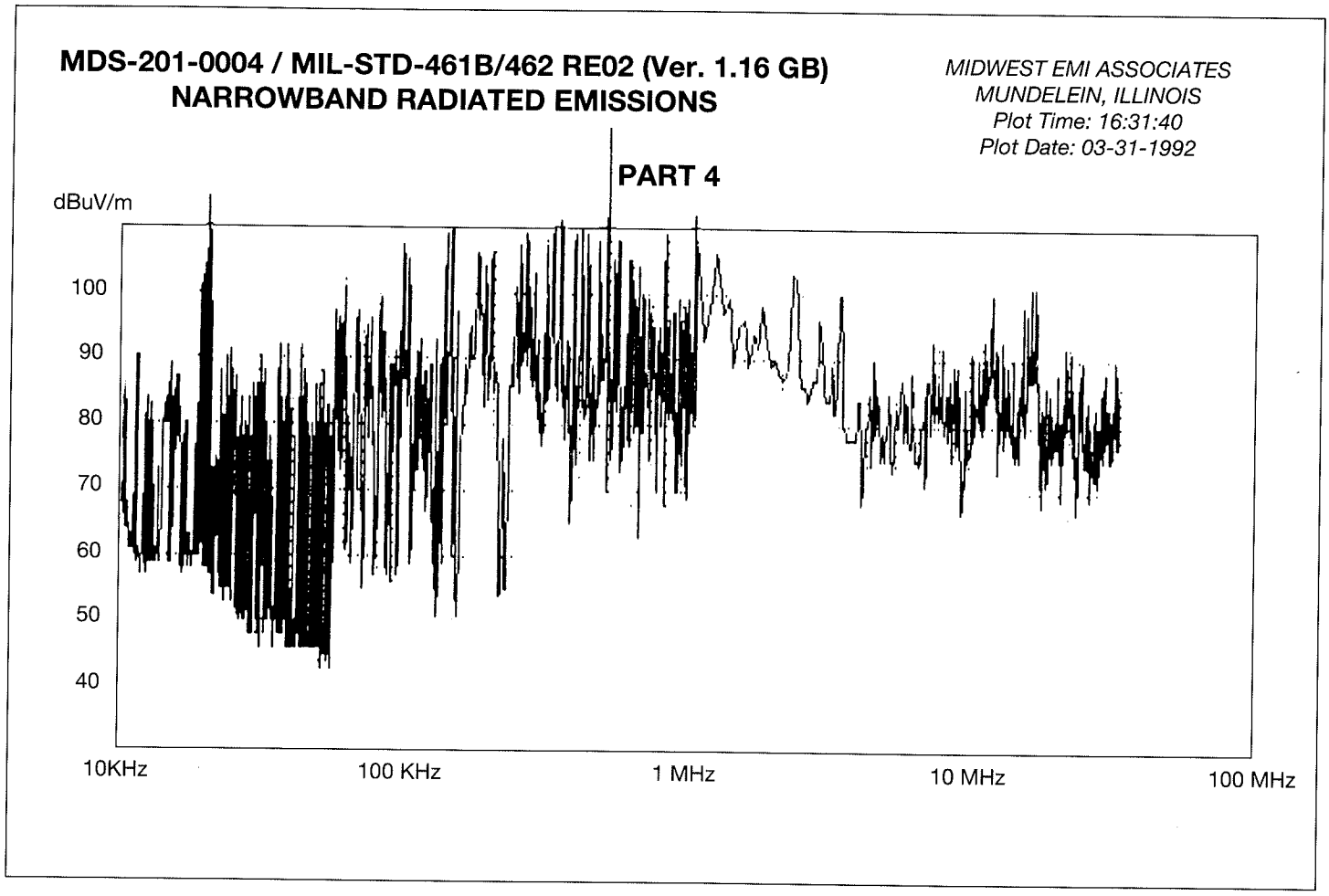


Figure 3. Valley Labs SSE2L ESU 3 meters using EMCO 6502 magnetic antenna.

cations which creates a curious dilemma because the performance of medical devices are not typically tested in these ranges.

We investigated the complaint of one hospital situated in a hilly region concerning the unexpected operation of an infusion device on the hospital's upper floors. We performed a quick site survey using an HP8590B analyzer, support EMCO biconical and log periodic antennas and a Holladay probe. The highest continuous signal measured during our brief stay was 112 dBuV/m due to the hospital paging system at 524 MHz; however, the broad band isotropic probe measured a 2V/m continuous peak level due to a wireless system installed on the upper floors. Several FM transmitting towers were visible from the upper floors and a microwave dish was nearby, pointing away from the hospital.

After we had investigated the MRI area and some X-Ray machines, a security guard was asked to activate his Motorola Radius P-50, Model H44CNU7I20AN, portable transceiver. At a range of one foot it generated a 22 V/m field and at one meter it emitted an 11 V/m field. The transmission did not cause our customers device to malfunction because we knew the device had been qualified to the higher susceptibility levels of Mil Std 46IC Part 4. Although an EMI cause of this hospital's complaint was not found and was later attributed to lack of training in use of the product, this case nevertheless illustrates that mobile wireless transceivers with ever increasing radiation efficiencies may potentially be used by security, fire, police and hospital personnel in close proximity to patients and equipment especially in emergency situations. At present MDS-20I-0004 only tests to levels of .5-7 V/m but IEC 801 recommends 3-10 V/m (to I GHz).

BATTERIES AND ESD: DESIGN STRATEGY

The topic of ESD has been addressed objectively in many excellent articles[10] and books[12-15]. ESD provides only slight sensations in humans but can be fatal to unprotected electronics that employ low voltaic threshold semiconductors for operation. The real life complication that can arise is that unsafe ESD failures can go unnoticed because the front panel display indication becomes frozen or alarms do not sound. When ESD breaches the defenses of a medical product, the currents travel to the closest earth ground. If a semiconductor device such as an EPROM is part of that path, the ESD pulse will turn many semiconductor junctions into metal junctions which act as short circuits to the battery or power supply. In the extreme ESD effects are so severe that no alarm is given and the affected semiconductor component suffers degenerative avalanche breakdown causing rapid heating and instant battery depletion.

Since a safe failure is of paramount importance, it is an effective strategy to provide two paths for supplying power to the medical product which are fused, one of which is dedicated solely to the alarm circuit. The alarm or watchdog must also deactivate safely all motorized functions or relays. The

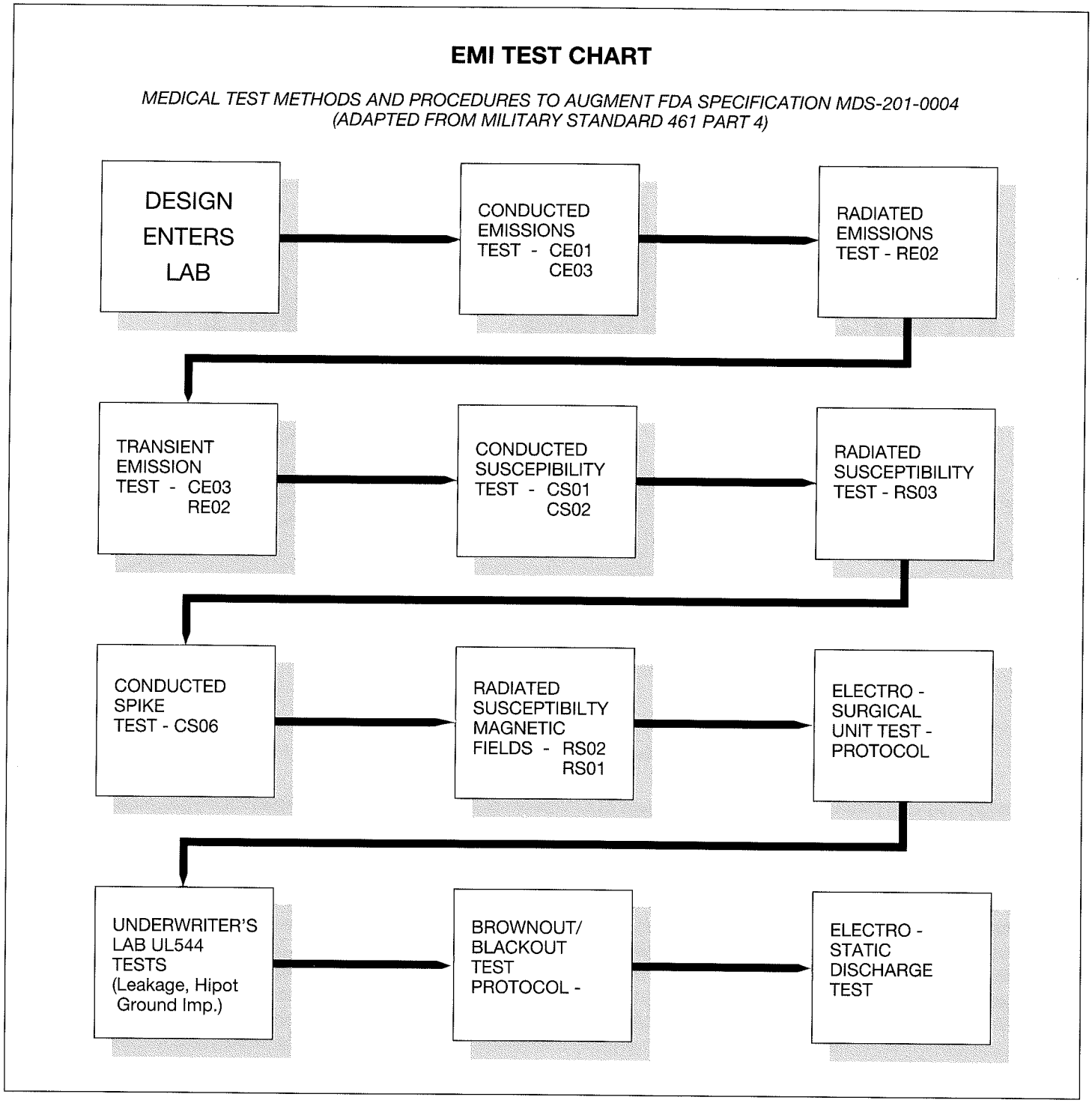


Figure 4. Life Standard

dry atmosphere of winter is a worst case for discharge and 15 KV air discharge and 8KV contact are possible levels of disturbance according to IEC 801. ESD effects are cumulative on equipment and may occur only within certain levels of applied voltage so extended study time is required. Failures noted in other tests are often linked to those which occur during ESD testing.

Although at first glance battery selection may not be considered an EMI issue, it has been a major recall problem for manufacturers. It is the primary protection against brownouts and blackouts. The discharge characteristic of a battery is a critical consideration in design because it affects time in alarm. As batteries age the discharge cycle shortens and becomes sharper and several years ago a battery that was used by many hospital manufacturers was found to degrade seriously after 25 deep discharge cycles. Another manufacturer provided a battery that would not degrade substantially even after 250 deep discharge cycles under identical discharge conditions.

Lead acid is still preferred to nickel cadmium despite its weight because of a more gradually sloped discharge characteristic. The sulfuric acid component of lead acid batteries is a serious concern because of electrical corrosion and the possibility of fire due to overcharging. Batteries must be physically separated and vented from elec-

tronic components and charging must be carefully controlled.

Although hotly debated, lithium batteries are perceived to have high internal resistances, steep end of life curves and can be unstable under high discharge currents that make them unsuitable for motorized medical applications. Unusual behavior observed when lithium cells have been employed include false microprocessor resetting and motor failures. For light duty applications such as CMOS memory standby or real time clocks, lithium cells are excellent candidates but may still suffer hazardous rapid discharge due to the ESD breakdown phenomenon described. Memory which might be compromised by ESD or other EMI effects should be checksummed at least on power up and preferably continuously with critical parameters stored in at least two memory locations.

MEDICAL EMI TEST PLAN STRATEGY

The previous issues are addressed in a newly introduced medical EMI test plan, Figure 4. This test strategy is based on MDS-20I-0004, Mil Std 46IC Part 4 and IEC 801 standards which, in combination, can be used to define the simulated worst-case hospital environment. The advantages to the plan are that the hospital environment is defined objectively and ordinary simulations and stresses are created which allow observation of the response of the medical product before it is used in clinical trials. The plan is improved by surveys at hospitals and from hospital complaints that appear generic. The test results are examined by product managers and cost-effective solutions are implemented.

In most cases the most effective solutions are ones that address susceptibility problems as opposed to emissions problems. In particular, due to the relaxed limits of MDS-20I-0004, radiated emissions are seldom suppressed. The resulting cost effective EMI strategy is to endow medical equipment with great strength to the rear of the enclosure and moderate protection to the front. Panel displays are usually never EMI protected.

The hospital plant should employ auxiliary protection if needed against high frequency stimulus, lightning, and transients that exceed IEC 801 guidelines. Powerline semiconductor transient suppressors are undesirable for use in medical devices because:

1. Catastrophic failure and fire may occur if not fused
2. Nuisance failures are easy to induce in testing if fused, and
3. The devices are too large in size to be effective.

Gasketing for EMS purposes must have the ability to withstand new cleaning chemicals which are presently needed to destroy potent viruses. The chemicals are often highly electrically conductive and may short out batteries, AC lines and keyboard switching functions. If "O ring" seals are used, the case half flanges of the product should be protected from decorative paint overspray during fabrication to prevent the paint from becoming a deleterious insulator. Solution spills are the most common threat to medical electronics in the hospital environment. Sterilization using autoclaving is usually not possible for electronically based medical products.

SELECTED REFERENCES

1. Bowman, G.A. and R. M. Bilof, "Medical Hardware Design and Suitability of MDS-201-004 Conducted Limits," *EMC Technology* v. 8 #2 (March 1989): 19-25.

2. Bowman, G.A. and R. M. Bilof, "Medical Instrument Susceptibility to Power Line Problems," *Biomedical Instrumentation and Technology* v. 23 #3 (May/June 1989): 234.

3. U.S. Food and Drug Administration, *Experience Network Monthly Reports*, Access No. 13754, August 1980.

4. Von Achen, William, "The Apache Helicopter: An EMI Case History," *Compliance Engineering* v. 8 #5 (Fall 1991): 11-17.

5. "News Watch: EMI - You Think You've Got EMC Problems," *Compliance Engineering* v. 5 #2 (Summer 1988): 35.

6. "Military Standard: Electromagnetic Emission and Susceptibility Requirements for the Control of Electromagnetic Interference," *MIL-STD-461C*. Washington, U.S. Department of Defense, AMSC No. N3903, 4 August 1986.

7. "MDS-201-0004: Electromagnetic Compatibility Standard for Medical Devices," *FDA/BMD-80/71*. Silver Spring, MD, Food and Drug Administration, 1 October 1979.

8. "Electromagnetic Compatibility for Industrial-Process Measurement and Control Equipment, Part Two: Electrostatic Discharge Requirements," *IEC-801*. Geneva, SZ, Commission Electrotechnique Internationale, 1984.

9. Bowman, G.A., "Medical EMI Control Strategies," Paper presented at the EMI Control in Medical Electronics Conference, Ramada Renaissance Hotel, Washington Dulles International Airport, 15-17 June 1992.

10. "Preliminary Survey of the Electromagnetic Interference Environment in Hospitals," *Proceedings of the 1991 IEEE International Symposium on Electromagnetic Compatibility* (12-16 August 1991): 214.

11. Workshop on Electromagnetic Interference (EMI) and Electromagnetic Compatibility (EMC) in Health Care Facilities. Edmonton, Alberta, CN, June 1987.

12. Rhoades, W.T., et al., "Electrostatic Discharge," in *Proceedings of the Symposium on Electromagnetic Compatibility*, Session 4A, 8SCH2623-7. New York, IEEE Press, 1988.

13. Dash, Glen, "ESD Testing and Design at the System Level," *Compliance Engineering* v. 6 #1 (1989): 164.

14. Boxleitner, Warren, "Electrostatic Discharge and Electronic Equipment," *PC 0235-2*. New York, IEEE Press, 1989.

15. Mardiguian, Michel, Electrostatic Discharge, *Interference Control Technologies*. Gainesville, VA, Interference Control Technologies, Inc., 1986.

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What is a Defect?

The definition of a defective product in a state may be found in the case law of that state. In our Safety Briefs, we explore leading product liability case law for one or more states. Triodyne Inc. relies on the trial bar for selection of the cases sited.

NORTH DAKOTA

North Dakota first adopted the rule of strict liability in tort in *Johnson v. American Motors Corporation*, 225 N.W.2d ST (N.D. 1974). In *Johnson*, the plaintiff was killed when the Rambler she was driving was struck from behind and immediately upon impact burst into flames. Family members who brought suit on her behalf, claimed AMC was strictly liable, and the court agreed: "The manner in which the public interest in human life and safety can best be protected is by subjecting manufacturers and sellers of defective products that are unreasonably dangerous to strict liability in tort when their products cause harm to users and consumers." The North Dakota Supreme Court specifically adopted the theory of strict liability as set forth in Restatement Second of Torts, § 402(a).

Before the rule of strict liability can be applied, it must be found that a product is defective in design or manufacture, that the defect renders the product unreasonably dangerous to the consumer, and that the defect existed when the product left the manufacturer. *Kaufman v. Meditec, Inc.*, 353 N.W.2d 297 (N.D. 1984). Unreasonably dangerous has been defined by statute to mean that: The product was dangerous to an extent beyond which would be contemplated by the ordinary and prudent buyer, consumer, or user of that product in that community considering the products' characteristics, propensities, risks, dangers, and uses, together with any actual knowledge, training, or experience possessed by the particular buyer, user, or consumer. NDCC, § 28-01.1-05(2).

In *Morrison v. Grand Forks Housing Auth.*, 436 N.W.2d 221 (N.D. 1989), the question was whether a battery operated smoke detector was defective because the instructions contained inside the smoke detector did not inform a consumer that the detector required a battery to operate and also did not warn of danger of removing the battery and leaving it out. The plaintiff admitted that the detector had gone off three or four times when there was smoke in the kitchen and that at each time she had opened the cover and took the battery out until the smoke had cleared before replacing the battery. She also admitted that when the battery wore out, and the detector began chirping, she took the battery out of the detector and failed to replace it with a new one. The court found no defect since danger of removing the battery from the battery powered smoke detector was obvious to a "reasonable and prudent user of the product" and additionally, the plaintiff had actual knowledge that this particular detector did not work without a battery.

Cases selected and text written by Thomas E. Merrick of the Law Offices of Paulson & Merrick, Jamestown Mall, Suite 200, Jamestown, ND 58402-1900.

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